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Towards the Circular Soil Concept: Optimization of Engineered Soils for Green Infrastructure Application

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Abstract: At conventional construction sites, the removal of soil and other excavated materials causes enormous mass movement, with a significant climate impact and contribution to global CO_2 release. This study aimed to generate a Circular Soil concept for reusing excavated materials by creating engineered soils for landscape construction at large building sites. Engineered soils act as a substitute for natural soils and fulfill vital technical and soil functions when installing an urban green infrastructure (GI). In a field study, the vegetation performance on engineered soils was evaluated to establish a methodological approach, to assess the applicability of the Circular Soil concept. First, the technical specifications (grain-size distribution) were modeled for intensive green roof and turfgrass applications. Then, the soil components were optimized, mixed, installed and tested for greenery purposes, focusing on plant growth performance indicators (vitality, projective cover ratio and grass-herb ratio) to assess the vegetation performance. The results showed that the engineered soils match the performance of the reference soil alternatives. In conclusion, the Circular Soil concept has a high potential to contribute considerably to sustainable on-site soil management and the circular economy. It can be applied on a larger scale for urban GI development and sustainable resources management in the landscaping and construction sector.

Keywords: green infrastructures; circular soil; engineered soils; vegetation performance; sustainable resources management; circular economy; sustainable soil management

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1. Introduction

The global building sector (28%) and the building construction industry (10%) are responsible for an immense climate impact, accounting for 38% of total global energy-related CO_2 emissions [1]. The high impact is also a result of the massive resources consumption for buildings and infrastructures. Aggregates like sand or gravel, intended for construction purposes, especially for the cement industry, are extracted at an unsustainable rate, most likely exceeding the current level of 50 billion tons per year in the near future [2], making humankind the most decisive geological factor of the present time.

The proportion of secondary raw materials increased globally between 1900 and 2015 by a factor of 20, while materials that were returned to their biotic or natural cycles decreased from 43% to 27% [3]. The ongoing construction boom contrasts with the need to protect valuable soil resources and their ecosystem services [4,5], especially in urban areas where the degree of impervious surfaces is high [6,7]. The continuously growing stock of created materials is not compatible with the natural limits of our planet [3]. While sand for concrete production has become rare [8], excavated materials, such as soil, sand and gravel, are being transferred to landfills [9]. For example, in the EU, 530.6 million tons of excavated soil were classified as waste in 2018 [10]. This contrasts with the fact that most excavated soils are healthy and should be reused, according to the novel EU Soil Strategy for 2030 [11].

1.1. Soil Management at Large Construction Sites

In urban areas, the most prominent soil types are Technosols, which comprise soil from technical, anthropogenically influenced origins and include engineered soils, wastes and technical, hard materials [12]. The recycling or reuse of mixed or potentially contaminated excavated materials come with their own challenges [13].

A standardized quality assessment assures the geotechnical and constructional applicability of the excavated material for the intended purpose [14,15]. The excavated material can be separated into fractions of organic material, sand and gravel and into the desired grain sizes. Depending on the quality and grain size, the excavated material is assigned for building construction (as aggregates for concrete, (lower quality) backfill of foundations, buildings, trenches or banks), for landscape construction (plant substrate development, terrain modeling, banks and dam establishment) or simply for terrain modeling with mass balances [16,17].

When the quality of excavated materials is assessed in the beginning stages and assessment is included throughout the whole lifespan of a building project, the materials can either be reused for building purposes (e.g., sand for concrete production) or landscape construction (e.g., soil for plant substrates) according to their technical specifications and degree of contamination [18,19].

1.2. Toward the Circular Reuse of Soil Resources in Landscape Construction

The reuse of excavated materials is a notion that can be traced back to the turn of the 20th century. In 1914, the architect Otto Wagner thought about how the terrain modeling of an area could be carried out in such a way that the excavated earth and the backfill would be completely congruent, so that not the slightest degree of transport by wagon would be necessary [20]. The landscaping of the "Donauinsel" in Vienna, an artificial island for flood protection used as a recreational area, was also built using fills of excavated material from the construction of a spillway for the Danube [21].

The excavated material is either removed from the construction site or processed on-site with mobile equipment (in-situ concrete plant) [15]. Removal can lead to deposition and the loss of valuable soil resources. Further usage on another construction site is another promising option. However, logistics between different large construction sites as a way to share soil for green open spaces is not state-of-the-art [22].

The topic of the circular reuse of excavated materials from construction sites has not, to our knowledge, been addressed in research on landscape construction so far. In this article, we focus for the first time on the sustainable allocation of excavated materials for the optimization of soil substitutes.

1.3. Engineered Soils in Landscape Construction

Currently, the concept of using excavated materials on-site with the primary purpose of creating new engineered soils for landscape construction is rarely discussed and implemented [13,19]. Engineered soils, also called technical soils or constructed soils [13,23,24], are defined here as artificially installed soil layers applied for vegetation establishment. For this purpose, excavated materials and technical soil amendments are (re-)used as a substitute for essential soil functions and to provide plant growth functions for vegetation technology applications. So far, engineered soils have been introduced as artificially built soils to perform specific soil functions [25], especially in the context of green infrastructures (GI) [13], to adapt hydrological parameters [26] or hydraulic conductivity [19,27], to promote tree stability [28], and to analyze dissolved organic matter changes [29] or microbial compositions in various engineered soil types of different (urban) GI types [30].

Big construction projects are often built on brownfield sites or on land formerly used for agriculture, as has been done in Vienna for the construction projects of Wildgarten or Biotope City [22,31]. At the Wildgarten site, the quality of the excavated materials was suitable for the reuse and production of engineered soils for landscape construction. The building project at Wildgarten was accompanied by research collaboration and analysis by a construction logistics expert to apply the new concept of circular soil [32]. In accordance with the needs of the building project at Wildgarten, two types of GI were selected. Turfgrass and intensive green roof applications were those most required on-site.

The widespread establishment of GI in urban surroundings has become a crucial strategy in urban development to counteract urban heat and to support climate change adaptation [33,34]. This implies an increasing demand for engineered soil and plant substrate substitutes for future property projects. Engineered soils can contribute to highly functioning GI measures with the provision of improved soil functions. In an effort to reduce the wastage of valuable soil resources, this publication proposes a new approach to support the circular economy: the Circular Soil concept.

1.4. Research Aim

In terms of the circular use of valuable soil resources, this study aimed to test engineered soils and their modification for application as soil substitutes for open-space design and GI installation. The sustainable basic principles of circularity [35] were applied as the underlying motivation. In accordance with the principles of a circular economy, the Circular Soil concept, introduced here for the first time, aims to fulfill the need to reuse as many resources as possible while securing and enhancing the ability of those resources to deliver essential ecosystem services [18]. This specifically addresses the problem of soil excavated from large construction sites and suggests reinstalling it for landscape construction, GI and open-space design, preferably at the same location.

The presented research was part of a collaboration with the Wildgarten building project in Vienna (Austria), which tested the circular reuse of excavated soil and sandstone for its applicability in landscape construction.

Before the field experiment, the current problems of soil management at large construction sites were analyzed to document efforts regarding the circular reuse of excavated materials. Based on these findings, the Circular Soil concept was developed and tested with the excavated soil material of the Wildgarten building project in Vienna. The excavated material was modified for turfgrass and intensive green roof applications and compared to standardized reference horticultural soils. To assess these engineered soil substitutes for greening purposes, the plant growth was analyzed for the performance of vitality, projective cover ratio and grass-herb ratio.

Within the realm of the Wildgarten study project, since it was not subject to external funding but was fully based on self-funded research, not all aspects of circular soil application could be covered. As this study aimed to establish a framework for circular soil use, it did not examine detailed aspects on, e.g., the cooling performance of green roofs, their prefabrication, or maintenance for preserving performance.

In this paper, the following research questions shall be answered:

(RQ1) How is plant growth performance characterized on engineered soil substitutes based on excavated materials, compared to horticultural soils?

(RQ2) How can excavated soil material be used as an engineered soil substitute for landscape construction in a systematic and coordinated setup?

(RQ3) How can the Circular Soil concept, based on excavated materials, be expanded to become a standard approach in urban and Green Infrastructure development?

In this study, we chose two commonly applied green infrastructure types in large construction projects as an underlying experimental mock-up setting for engineered soil installation.

2. Materials and Methods

2.1. Site Description

A field experiment was set up at the test site of the Institute of Soil Bioengineering and Landscape Construction (University of Natural Resources and Life Sciences, Vienna, Austria) in Groß-Enzersdorf, Austria. Groß-Enzersdorf is located to the east of Vienna in Lower Austria (48°12′0 N 16°33′0 E), has a warm temperate climate (Cfb, according to Köppen–Geiger climate zones [36]), with an average temperature of 11.1 °C and average annual precipitation of 688 mm [37].

2.2. Field Study Design

The field study was designed to test engineered soil alternatives, based on the excavated materials from the Wildgarten construction site (12th district, Vienna, Austria; 48°9′22 N 16°17′38 E; Cfb) and to compare them to standardized reference horticultural soils (for details on materials and soil properties, see Section 2.3). Engineered soil alternatives, based on the Wildgarten material, were optimized for (1) turfgrass (T) and (2) intensive green roof (R) application and were compared to standardized plant substrates (turfgrass reference material (TR), intensive green roof reference material (RR)). All materials were established as vegetation and sub-base layers (see Figure 1). As the research focus was on the soil substitutes, we simplified the structure for turfgrass and intensive green roof application within the legal reference frame [38,39].

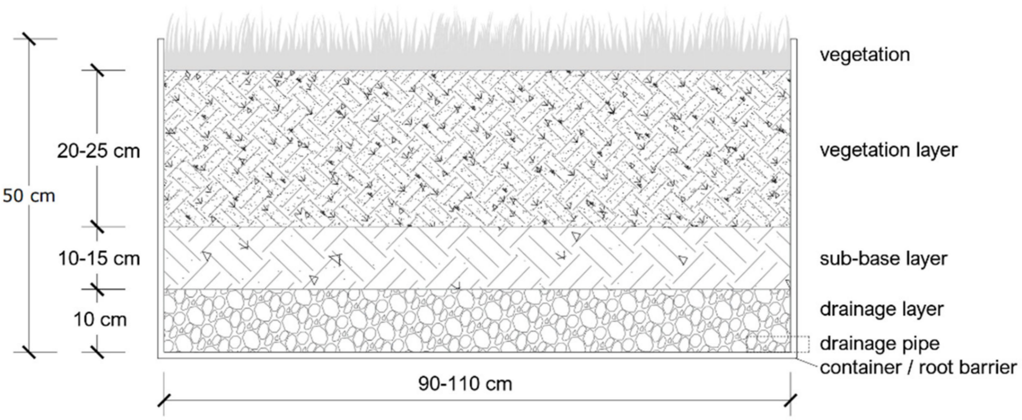


Figure 1. Applied standard profile of the mock-ups' setup for all tested applications.

Mock-ups were installed in three replicates for each tested application (2 engineered soils, 2 reference materials, 3 replicates each; n = 12). The engineered soil alternatives were installed in intermediate bulk containers (IBC) (surface: 90 cm × 110 cm, height: 50 cm) according to the standard profiles shown in Figure 1 (drainage layer: 10 cm, sub-base layer: 10–15 cm, vegetation layer: 20–25 cm [38,39].

The same standard seed mix (RSM 2.4, [40]) was used for all mock-ups to compare the vegetation performance (see Appendix A Table A1 for a detailed species list). The standard seed mix, RSM 2.4, with an 83% share of grasses and 17% of herbs, finds its main application in public green areas and residential developments, due to its low maintenance needs [40].

An automated irrigation system (Hunter® I-CORE®) was installed with 12 micro sprays for each IBC, to guarantee the initial growing success (irrigation interval: 10 min, 2 ×/day for one month) and throughout the test series if required, after three consecutive heat days for the duration of the heatwave or after a prolonged dry period of two weeks.

2.3. Material Properties and Mixing Ratios of Components

Organic and mineral components were mixed for the individual layers for turfgrass and green roof applications. Whereas the reference materials were mixed with standard components, the engineered soils were modified using excavated materials and soil additives. The mixing ratios were specifically generated, based on volume-based grading curves (see Section 3.1) to allow easy mixing and installation at the construction site. Table 1 gives an overview of the tested soil alternatives and the mixing ratios of the engineered soil components.

Table 1. Mixing ratios of the individual components to construct each engineered soil layer for all tested applications.

Engineered Soil Substitutes		Components						
		Wildgarten Topsoil B-Horizon	**Wildgarten Sand 0/8**	**Compost**	**Perlite (Agroperl K1)**	**Expanded Clay (Leka 0/8)**	**Turf Sand 0/4**	**Standard Topsoil**
T	vegetation layer (T1)	2	2	1				
	sub-base layer (T2)	1	1					
TR	reference vegetation layer (TR1)			1			3	
	reference sub-base layer (TR2)						1	1
R	intensive green roof vegetation layer (R1)	2	2	1	1	1		
	intensive green roof drainage layer (R2)	1	1		1			
RR	reference intensive green roof vegetation layer (RR1)			1	1	1	2	
	reference intensive green roof drainage layer (RR2)				1	1	2	

Soil additives were compost, perlite, turf sand (0/4) and expanded clay. While compost is a standard additive for soils to provide nutrition to the plants [41], expanded clay and perlite are added to enhance pore volume, water-holding capacity and nutrient storage, as well as to reduce weight [42].

The excavated materials used were the soil of the B-horizon (silty loam) and crushed sandstone (sand 0/8) from the Wildgarten site. The grading curves of the Wildgarten material (topsoil and crushed sandstone (see Figure 2)) were the initial starting points to modify engineered soil alternatives. The mass-based grading curve of the grain-size distributions (in mm) was established by referring to the Austrian Standard [43] and shows the cumulative relative mass percentage (grain-size intervals: silt < 0.02–0.063, sand 0.063–2; gravel 4–32 mm).

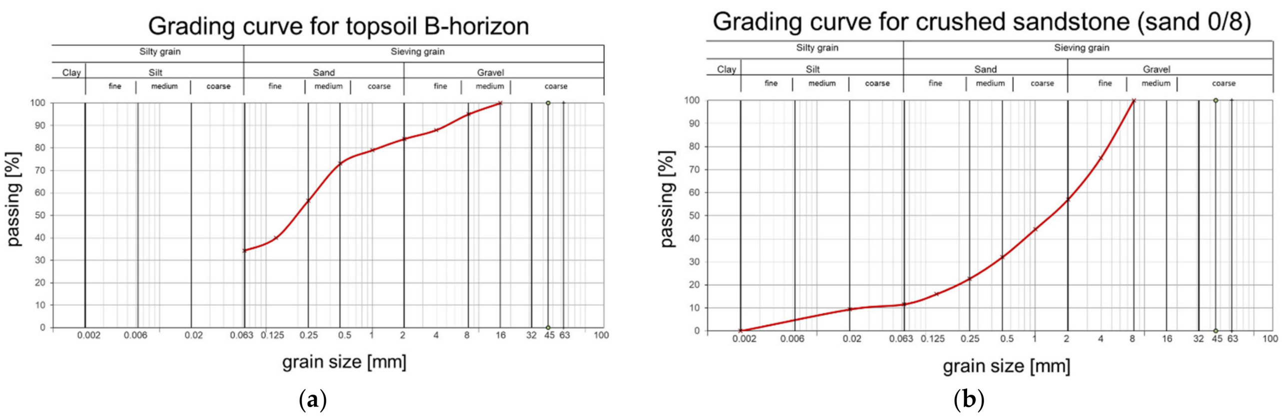


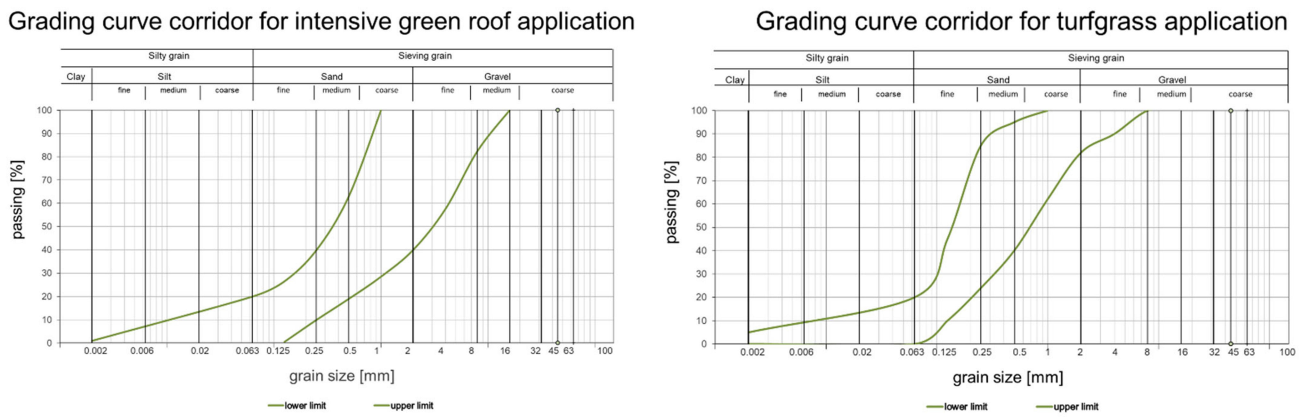
Figure 2. Grading curves of the excavated Wildgarten material: (**a**) topsoil B-horizon, (**b**) sandstone C-horizon (sand 0/8).

Chemical material specifications of the engineered soil substitutes are shown in Appendix A Table A2 (analysis for pH [44], electrical conductivity [45], total nitrogen [46], total organic carbon [47], chloride and sulfate [48], total potassium and total phosphorus [49]).

2.4. Modelling of the Grading Curves

The optimization process of the engineered soils was based on modifying the grading curves for intensive green roof and turfgrass applications.

The Austrian Standard L1131 [38] and the FLL Guideline on green roofs [50] define grading curve corridors (minimum to maximum array per grain size, regarding its mass proportion) for green roof substrates. The grading curve corridor for intensive green roof substrate (see Figure 3a) served as the basis for the respective optimization processes.



(**a**) (**b**)

Figure 3. Grading curve corridors for the application as (**a**) an intensive green roof, according to FLL [50]; and (**b**) turfgrass, according to Austrian Standards B 2606-1 [38]; green lines indicate the upper and lower limit.

There is no standard reference for the grading curve corridor in place for turf areas in open spaces. Therefore, the grading curve for sports fields according to Austrian Standards B 2606-1 [39] was chosen as the basis for the optimization process (see Figure 3b for the grading curve corridor).

First, the grading curves of the Wildgarten materials (soil B-horizon and sand 0/8 (see Figure 2)) were plotted against the grading curve corridors, according to the respective standards for an intensive green roof [50] (Figure 3a) and turfgrass [39] (Figure 3b).

Second, soil additives (compost, perlite, expanded clay and turf sand 0/4) were added to the excavated materials until the grading curves sufficiently matched those of the grading curve standards. For this purpose, data on specific weight [t/m^3], pH value and water holding capacity [volume %] were collected for the potential soil additives such as compost, perlite, expanded clay and finer turf sand (technical data provided by the individual producers and previous internal research projects).

Lastly, the masses (g) and respective volumes (mL) of grain-size components were calculated and modeled as grading curves.

2.5. Plant Data Collection and Analysis

The vegetation was monitored for two vegetation periods (July–October 2019, May–October 2020). Every two weeks, throughout the vegetation period, the plant growth performance indicators of (1) vitality, (2) projective cover ratio, and (3) grass–herb ratio were monitored in each IBC, over an area of 1 m^2 (for a detailed species list, see Appendix A Table A1; for a detailed monitoring plan, see Appendix A Table A3). Each square meter was subdivided into four quadrants, to facilitate monitoring and to guarantee enough replicates for statistical analyses. A margin of 10 cm from the edge of the container was omitted to exclude the possibility of any influencing effects on plant development.

The indicator of "vitality" was assessed and rated according to the visual vegetation assessment [51], as shown in Table 2.

Table 2. Rating of vitality performance, based on the descriptive visual vegetation assessment method, through qualitative criteria [51].

Rating	Vitality
9	healthy, vital, coverage well above specified target, vigorous growth, no effects of pest infestation, disease, deficiency or mechanical damage evident
7	healthy, vital, coverage above specified target, hardly any dead or impacted plants, hardly any impact from pest infestation, disease, deficiency or mechanical damage evident
5	weakened, stagnant in growth, sufficient coverage, dead or impaired plants, effects of pest infestation, disease, deficiency or mechanical damage if any is visible
3	heavily weakened, puny growth, insufficient coverage, many dead or impaired plants, visible pest infestation and/or disease and/or deficiency and/or mechanical damage
1	dying plants, very low cover, predominantly dead
0	dead, composting

The projective cover ratio (expressed as a percentage) describes the relative projective area the plants cover to absorb the light, compared to the total bare soil area [52,53]. At least two persons estimated the projective cover ratio in 5% increments, where 0% indicated bare soil and 100%, total coverage. According to the Austrian Standards for landscaping and landscape construction, the projective cover ratio needed to be at least 80% after approval of the follow-on care period [54].

The grass–herb ratio (expressed as a percentage) shows the distribution of grasses and herbs in a given area [51,55]. As with the projective cover ratio, at least two persons estimated the grass-herb ratio in 5% increments, where 50:50 indicated an equilibrium of grasses and herbs.

The statistical analysis included an ANOVA with a Tukey post hoc test, which compares all group combinations to show differences between the soil alternatives. Post hoc tests, such as the Tukey test, are used when there is a significant result but no precise hypotheses are available as to which groups differ. This test examines the differentiation of the individual group means [56]. The Tukey test compares all possible group combinations and is recommended for variance homogeneity and an equal group size. The Spearman rank correlation was used to identify the strength of the reciprocal relationship between two variables. The Spearman rank correlation coefficient examines the presence of a correlation, as well as the extent of the correlation (ρ is between −1 and 1) between two ordinal scaled variables. The Spearman coefficient determines correlations via ranks [56]. Both tests used $p < 0.05$ (n depended on the year and indicator) to denote statistical significance. Furthermore, a descriptive statistical analysis was performed using bar charts and box plots.

3. Results

3.1. Verification of the Grading Curves

The modeled mass- and volume-based grading curves of the engineered soils were verified after mixing to check their compliance to the required grading curve corridors (Figure 3). The striped grey lines indicate the grading curve for mass-based and the dotted grey lines indicate the volume-based grading curve. The green lines specify the upper and lower reference limits of the FLL Guideline on green roofs [50] (see Figure 4 [38]) and of the Austrian standard for sports turf (Austrian Standard B 2606-1 [39]) in Figure 5.

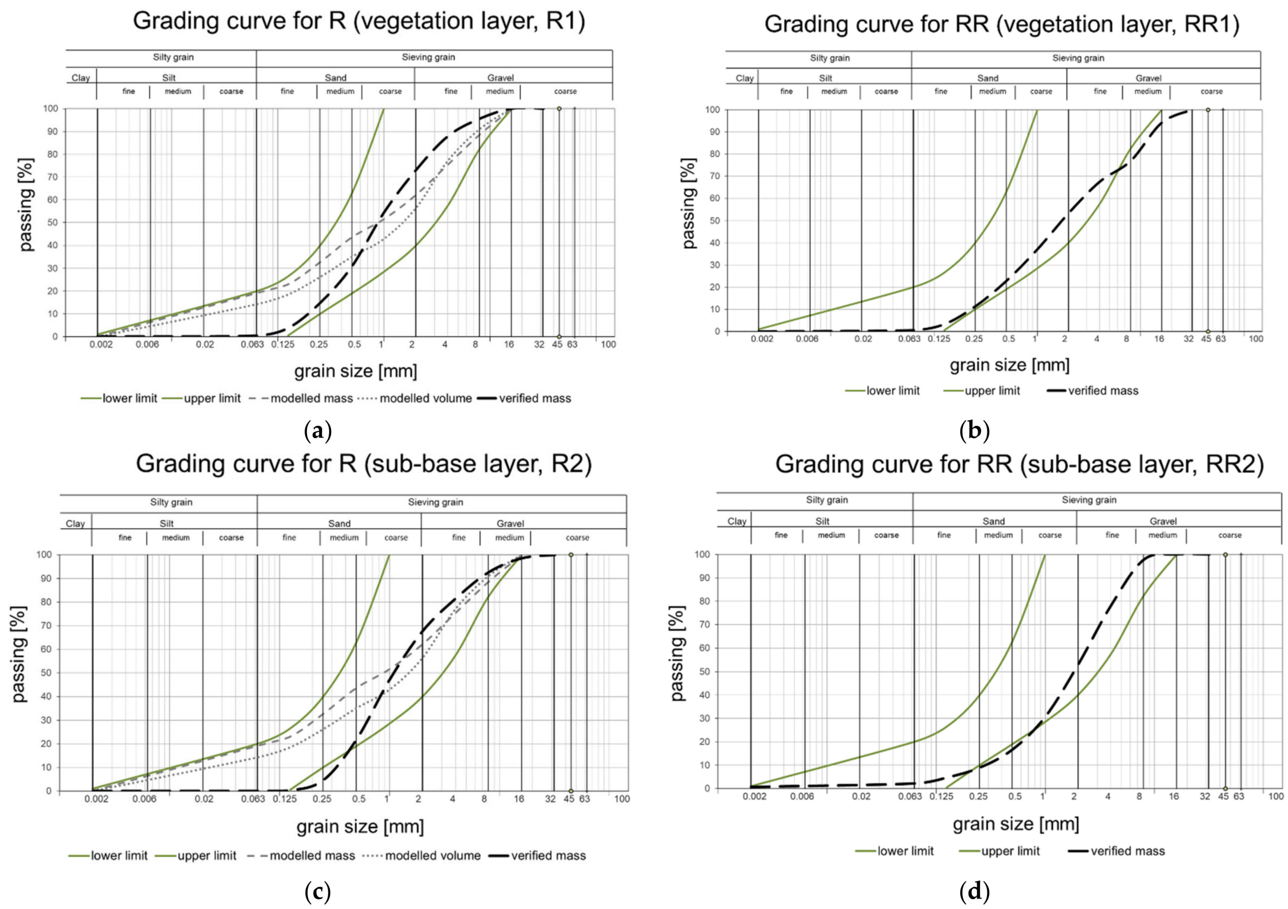


Figure 4. Grading curves of the tested engineered soils for intensive green roof application in the vegetation layer (**a**,**b**) and the sub-base layer (**c**,**d**). (Horticultural reference soils (RR1, RR2) were not modeled).

All grading curves of the tested engineered soils for intensive green roof application fell mainly within the reference frame of the FLL guideline [50] (see Figure 4). However, all alternatives deviated slightly from the corridor as they all showed grain sizes larger than 16 mm.

In comparison with the tested engineered soil for green roof application, the grading curves of all soil layers for turfgrass application were slightly beyond the reference frame of the Austrian standard [39], as shown in Figure 5.

3.2. *Analysis of Plant Growth Performance*

3.2.1. Indicator: Vitality

The indicator of "vitality" showed seasonal variations corresponding to the dry and moist periods (see Figure 6). The vitality rate was not significantly different ($p > 0.05$; 2019: n = 96; 2020: n = 168) between the soil alternatives.

3.2.2. Indicator: Projective Cover Ratio

In 2020, the projective cover ratio was significantly different ($p < 0.05$; 2019: n = 96; 2020: n = 168) between R and RR, as well as T and TR, but not in 2019 (see Figure 7). The projective cover ratio had a wider range during the 2019 season compared to 2020. The vegetation period included four months for 2019 (July–October), compared to seven months for 2020 (April–October), and started after an initial growing period of two weeks. In 2020, R was lower than RR but still above 80%, which is the required projective cover ratio needed for performance approval after an initial care period, according to ÖNORM B 2241 [54].

The alternative T, on the other hand, had a higher projective cover ratio than TR, closer to 90% than 80%, complying with the requirements for sports turf [54].

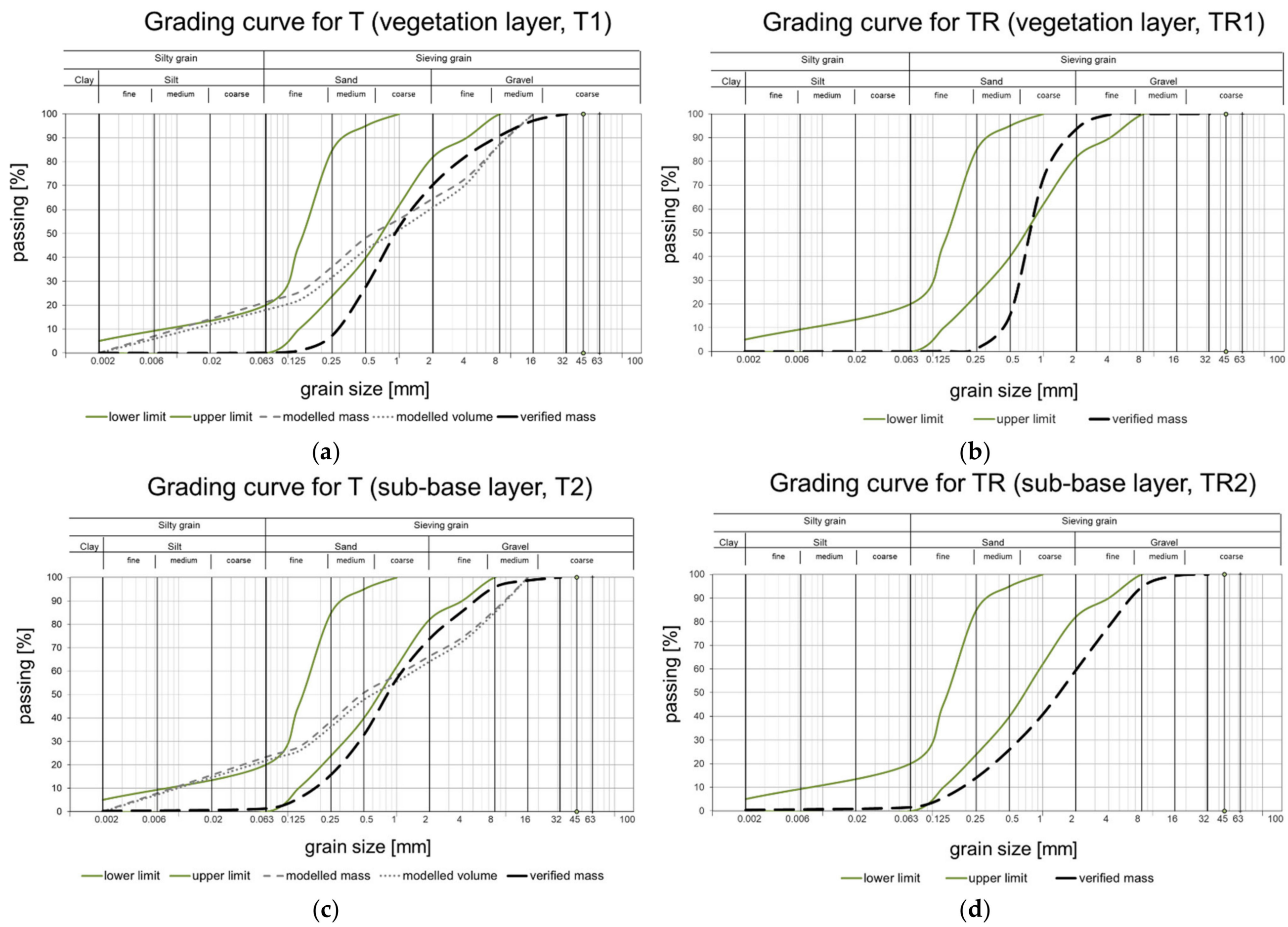


Figure 5. Grading curves of the tested engineered soils for turfgrass application in the vegetation layer (**a**,**b**) and the sub-base layer (**c**,**d**). (Horticultural reference soils (TR 1, TR 2) were not modeled).

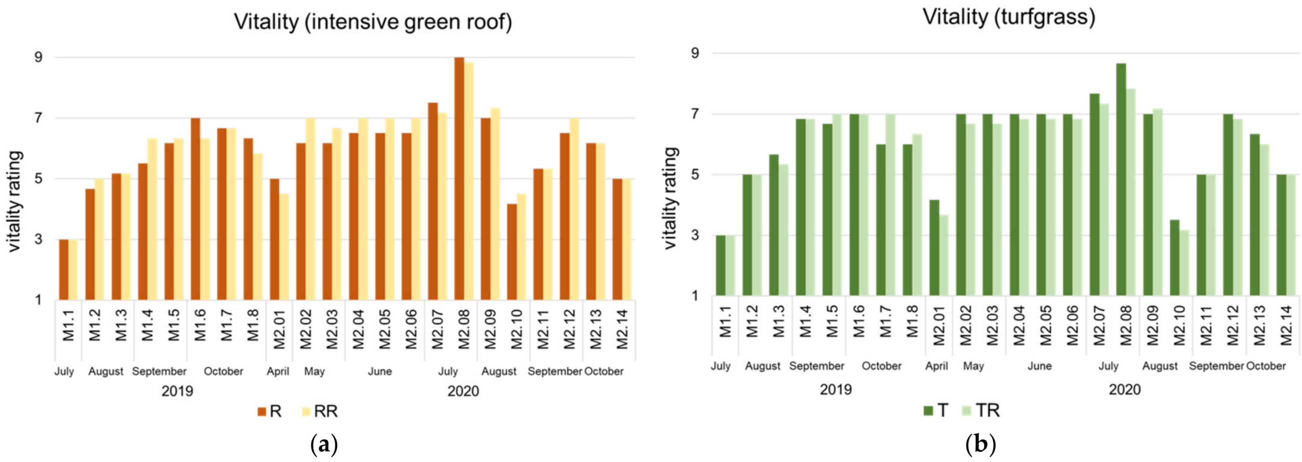
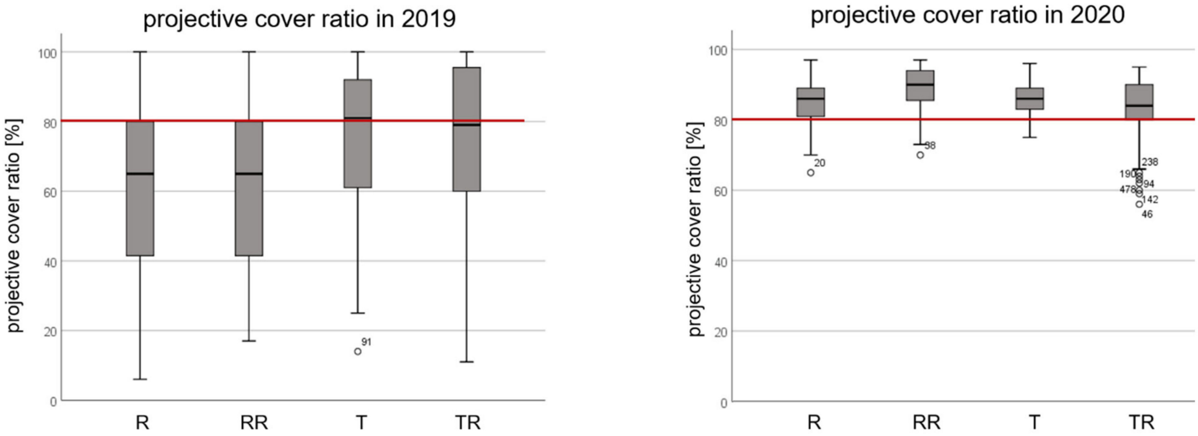


Figure 6. Overview of the average vitality performance on the tested alternatives for (**a**) intensive green roof (R, RR) and (**b**) turfgrass (T, TR) applications in 2019 (n = 96) and 2020 (n = 168).

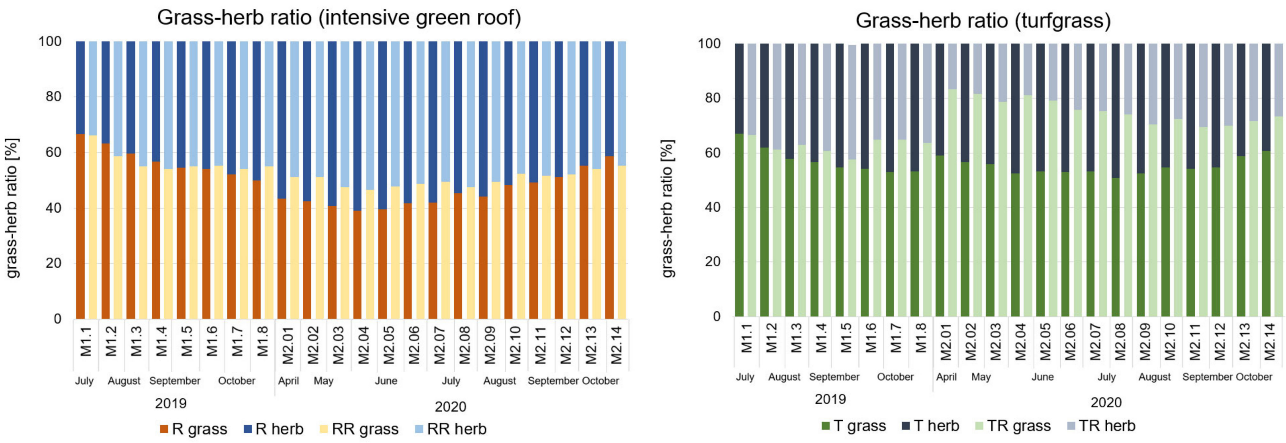


(**a**) (**b**)

Figure 7. Box-plots of the projective cover ratio of the vegetation on the tested alternatives for intensive green roof (R, RR) and turfgrass (T, TR) application in (**a**) 2019 (n = 96) and (**b**) 2020 (n = 168). The red line indicates the minimum projective cover ratio required, after the inspection and approval of the follow-on care period (according to the Austrian Standards [54]).

3.2.3. Indicator: Grass–Herb Ratio

The grass–herb ratio was significantly different ($p < 0.05$) for T and TR in 2019 (n = 96) and in 2020 (n = 168), but not for R and RR. Although the seed mix (RSM 2.4 (see Section 2.2)) only had 17% of herbs included (see Appendix A, Table A1), the grass–herb ratio for R and RR varied between 60:40 and 50:50 over both vegetation periods (see Figures 8a and 9). In comparison, TR substantially deviated from the 60:40 ratio at the beginning of the second vegetation period. Then, TR showed a clear tendency towards an 80:20 grass–herb ratio, whereas T remained at 60:40 (see Figures 8b and 9).



(**a**) (**b**)

Figure 8. Overview of the grass–herb ratio (%) on the tested alternatives for the intensive green roof ((**a**) R, RR) and turfgrass ((**b**) T, TR) applications.

3.2.4. Correlations between the Indicators

For further analysis, Spearman rank correlations ($p < 0.05$) were applied to the indicators of vitality, projective cover ratio and grass–herb ratio. There were significant positive correlations between the projective cover ratio and the vitality rate for all tested alternatives (Spearman rank correlation: $p < 0.05$; for detailed values refer to Appendix A, Tables A4 and A5). This result indicates that with an increasing projective cover ratio, the vitality rate increased as well. Significant negative correlations occurred between the projective cover ratio and the grass–herb ratio for all alternatives except TR in 2020 (see Appendix A, Tables A4 and A5). Vitality rate and the grass-herb ratio correlated negatively and only significantly in 2019 for R, RR and T (see Appendix A, Tables A4 and A5).

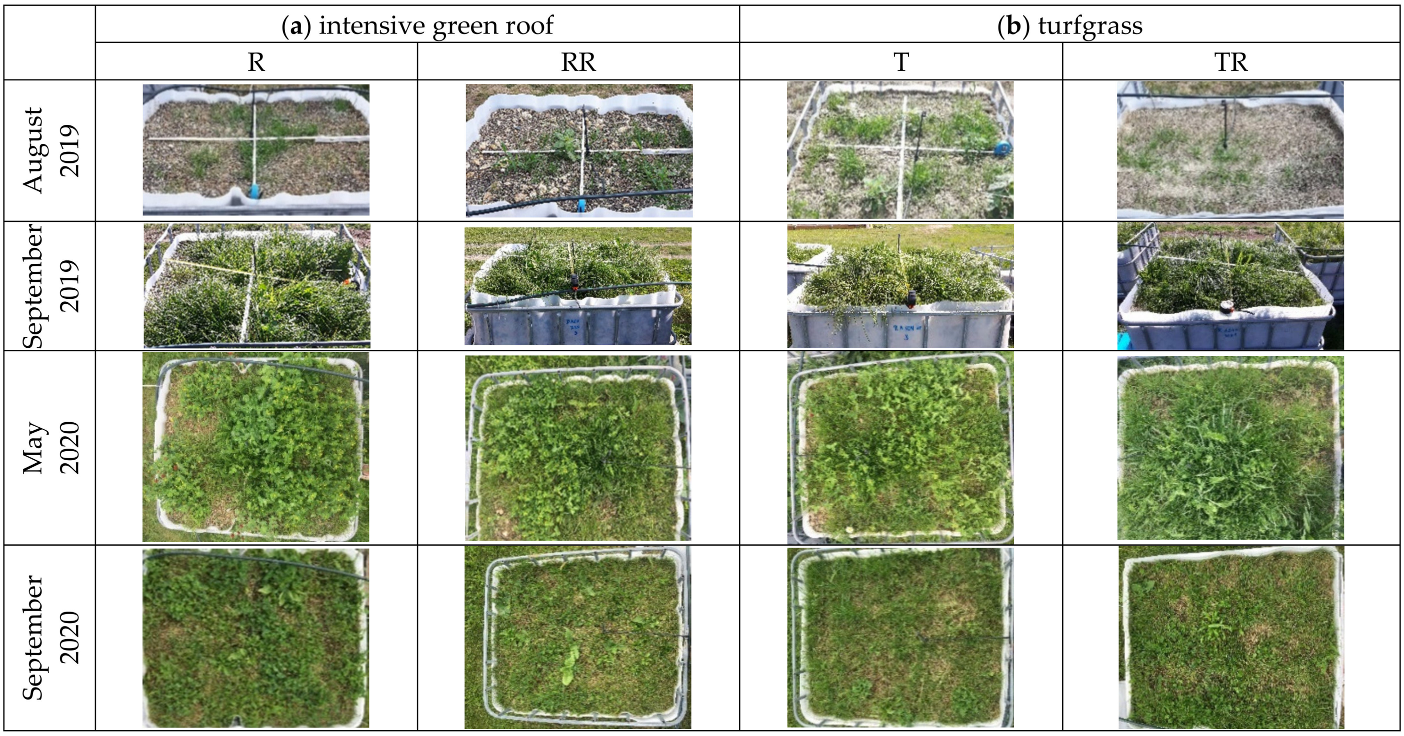


Figure 9. Examples of the vitality performance on the tested alternatives for (**a**) the intensive green roof and (**b**) turfgrass application in 2019 and 2020.

3.3. Stepwise Approach toward a Circular Soil Concept

The results of the field study promise a profound basis for the novel approach presented in the Circular Soil concept. A preliminary six-step approach was derived from the field experiment described in the following sections, to implement the circular use of excavation materials for landscape construction (see Figure 10).

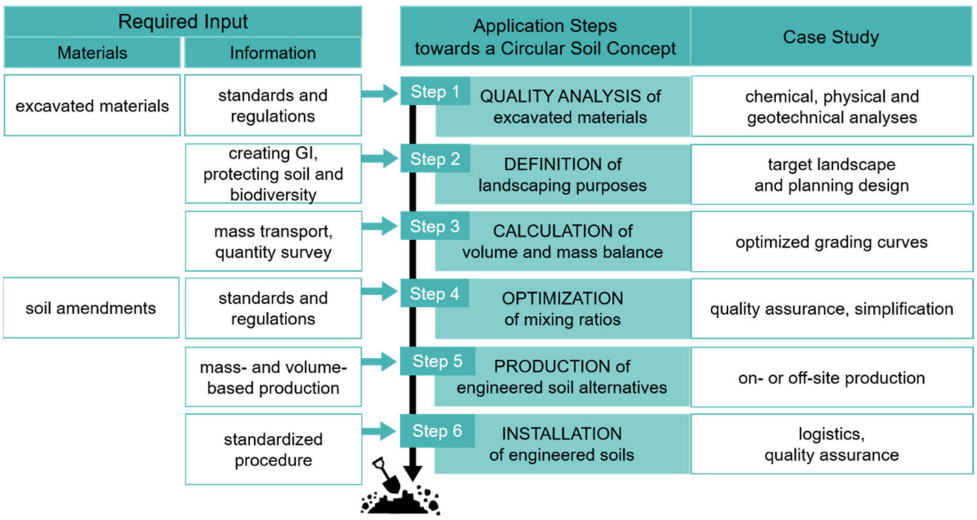


Figure 10. Stepwise approach toward a Circular Soil concept for landscape construction.

3.3.1. Step 1: Quality Analysis of Excavation Materials

The first step covers the quality assessment of the excavation materials from the construction site to produce engineered soils (see Section 2.3). The excavated materials need to comply with (national) norms and regulations to work in terms of installation on a larger scale [22]. It has to be established that the pollution and toxification load is below the required limits and the soil's physical and geotechnical characteristics allow further processing of the materials. In this step, recovered building residuals, such as bricks or concrete, can be analyzed and included in the optimization process of engineered soil alternatives [13,19,57].

3.3.2. Step 2: Definition of Landscaping Purposes

The final mixture of the engineered soils must be in accordance with landscaping purposes, planned greenery and vegetation typologies (e.g., sports turf, intensive green roof, flowering meadows or other use). First, landscape planners need to define the target landscape design, consider the ecological targets, aesthetics and cases of application [22]. Then, the requirements for the soil's structural stability can be determined for the engineered soil alternatives (see Sections 2.3 and 2.4).

In this step, various aspects of soil protection can be addressed (e.g., storage, biodiversity). Soil can be protected in the short term during the construction phase, as well as in the long term during the usage phase. In the short term, the quality of the excavated soil can be increased with the appropriate construction site planning and management, e.g., temporary storage [58]. For example, topsoil should not be stored in a pile deeper than approximately 2.00 m, to prevent compaction, and temporary greening ensures good aeration [59,60]. In the long term, the usage phase is strongly dependent upon the chosen landscaping purposes. Landscape planners can choose greenery typologies with higher biodiversity (e.g., flowering meadows instead of sports turf) to increase the ecological benefits of the green and open spaces in the construction project and biodiversity by design [61] (see Section 4.1). Higher plant diversity will also benefit soil biodiversity [62], which can be notably high in engineered soils [30].

3.3.3. Step 3: Calculation of Volume and Mass Balance

Based on the planning design and the landscaping purposes (see Section 3.3.2), the number of engineered soils and individual components matching the required soil performance should be determined.

As the logistics, specifically the mass transport, at the construction site define the success of the Circular Soil concept [22], all the soil structural analyses (see Section 3.3.1) shall be tendered in a concerted manner to assure optimized volume and mass balances. The preparation of a quantity survey is necessary to ensure that the temporary storage of material after excavation from the construction site and needed components is congruent with the demand. The different soil layers shall be stored individually to allow a quality-secured production and tailored use of the different soil layers for specifically engineered soils. An uncontrolled and mixed storage of different soil layers will reduce their applicability for different specific engineered soils and thus diminish the Circular Soil concept. Additionally, more excavated material can be reused [63] when the individual soil layers (or horizons) are separated for storage. The mixing ratios can only be optimized if it is known how much excavated material is available and how much, in terms of masses and volumes, is needed for construction.

3.3.4. Step 4: Optimization of Mixing Ratios

The available amount and the grain size distribution expressed in the grading curves of the excavated materials (see Section 2.3) are the basis for the processing and optimization of the engineered soils (see Sections 2.4 and 3.1).

Apart from adjusting the grading curves to comply with the applicable (national) standards and directives as amended, the production (see Section 3.3.5) and installation (see Section 3.3.6) of the engineered soil need to be planned. Therefore, it is recommended to simplify the materials used for the mixing ratios as much as possible, to reduce the mixing effort and risk of production mistakes while maintaining the quality (see Section 2.3). In the example of the Wildgarten project, the variation of engineered soil alternatives was restricted to two different landscape typologies (namely, intensive green roof and turfgrass application, out of eight potential variations) based on the intended use. Soil amendments were limited to four components (see Table 1).

3.3.5. Step 5: Production of Engineered Soil Alternatives

Mobile equipment can be used to prepare the excavated materials on the site, e.g., crushing sandstone or mixing the excavated materials and soil additives [17]. For example, the mixing and homogenization of mineral and organic components can be done on-site with a wheel loader, as was done on the Wildgarten site. If the production takes place off-site (which scenario has been applied for production of the mock-ups (see Section 2.2)), keeping this as local as possible will reduce transport emissions [15,22]. Then, the engineered soils can then be delivered ready-mixed. Homogenous mixing of the components is strictly required in either case.

3.3.6. Step 6: Installation of Engineered Soils

The installation of the engineered soils will follow standardized landscape construction procedures [64]. Additionally, the installation needs to comply with the standard soil protection measures on construction sites, such as the prevention of soil compaction or coordination of the construction measures, according to the levels of soil moisture [58–60].

In large construction sites, coordinated mass balances increase the amount of (re-) used excavated materials. The individual project-related construction sites have the ability to meet their needs from this stockpile of optimized engineered soils. The scope and time of the removal must be given to the construction logistics team and documented.

On-site production of the engineered soils (see Section 3.3.5) according to the simplified mixing ratios (see Section 3.3.4) allows for milling in individual components, such as compost or brick chippings, layer by layer.

4. Discussion

4.1. Vegetation Growth Performance of the Engineered Soil Alternatives

The engineered soil alternatives were assessed for their applicability regarding their soil structural stability (see Section 4.1.1) and vegetation performance (see Sections 4.1.2 and 4.1.3) to answer RQ1: How is plant growth performance characterized in engineered soil substitutes, based on excavated materials, compared to horticultural soils?

4.1.1. Geotechnical Accordance and Soil Structural Stability Performance

Vegetation growth depends on the growing material, such as soil or plant substrate. Therefore, the tested alternatives were evaluated regarding their grain-size distribution as this is a key parameter for the durability of the installed GI measures [13,19].

Standard mass-based grading curves provide mass-based information (proportion in weight). However, specific weights of soil components can vary between 90 kg per m^3 to 1.600 kg per m^3 [65,66], which affects the compaction rate of the individual components. Therefore, volume-based grading curves provide information on the composition of the soil aggregates based on their specific density, rather than just the proportion in terms of weight. This is relevant as in landscape construction, besides mass weights, the actual volume for the individual GI measures is essential for planning and installation [13,19]. If the engineered soils keep their intended volume, this prevents problems regarding stability due to shrinking soil layers, or rainwater management due to compaction [67,68].

The tested grain-size distributions varied between the modeled and mixed alternatives, as is evident in the grading curves (see Figures 4 and 5). The grading curves of the tested engineered soils of the vegetation and sub-base layer for intensive green roof application were mostly within the standard corridor of the guideline [50] as a result of modifying and optimization processes, as were the reference materials (see Figure 4). However, no tested alternative met the requirements referring to the largest possible grain-size share, as all alternatives contained gravel larger than 16 mm.

The grading curves of the engineered soil mixes for turfgrass application were slightly outside the reference frame of the Austrian standard for sports fields for sand and gravel [38] (see Figure 5a,c). This Austrian standard was used within the field study because there are no other standards available for durable turfgrass or comparable loads and stresses. The reference materials showed the same slight deviations in the grading curves (see Figure 5b,d), indicating that the engineered soils tested exhibited an equivalent performance to the reference materials. As this research on engineered soil from excavated material is pioneering work, to our knowledge, no comparable analyses can be found in the scientific literature.

Other parameters for soil structural performance (e.g., infiltration rate, pore volume, water-holding capacity) will be essential for the applicability and application decisions of engineered soil alternatives. Future research should address the water-retention curves additional to the grading curves, to assure the long-term functionality of the optimized soil alternatives for applications in sustainable rainwater management [69].

Additionally, soil aeration and, hence, adequate pore volume, is necessary to establish long-lasting plant growth [70]. In previous research projects, the pore volume and water-holding capacity were statistically analyzed, showing that the pore volume correlated positively with plant vitality [51]. However, other soil parameters that are important for plant growth, e.g., biological properties and the nutrient content of engineered soils, were rarely analyzed [29,71]. Neither the effects of GI features on the nutrient cycle, e.g., soil dissolved organic matter [29], nor the effects of the soil construction process on the soil fauna, e.g., earthworms, have hitherto been sufficiently included in studies on engineered soils [71]. However, some studies prove these aspects to be relevant to maintain or even to enhance urban soil biodiversity and the provision of ecosystem services [71].

4.1.2. Vitality Performance and Projective Cover Ratio

The tested vegetation experienced seasonal variations in its vitality rate, corresponding to dry and moist periods, and only decreased in very dry periods (see Figure 6). The vegetation's vitality performance revealed similar variations between the tested alternatives and showed, furthermore, no significant differences between engineered and reference soil alternatives (see Section 3.2.1). Based on the indicator vitality alone, all alternatives can be recommended. However, when using the seed mix RSM 2.4, a low-maintenance plan with infrequent cutting and irrigation is recommended. Additional irrigation during drier summer months would increase the vitality rates.

All alternatives showed a significant positive correlation between the vitality rate and the projective cover ratio (see Section 3.2.2). The mean projective cover ratio reached the threshold of 80% at the end of the first vegetation period in 2019 for all tested soil alternatives (see Figure 7), which conforms to the required projective cover ratio, according to the Austrian standards [54]. Due to the absence of plant diseases or the occurrence of droughts, the vitality performance increased, in accordance with the projective cover ratio and depending on mowing interventions.

However, the projective cover ratio was significantly different ($p < 0.05$) between the engineered soil alternative for the intensive green roof application (R) and its reference material (RR), and for the turfgrass application (T) and its reference material (TR), respectively, in 2020, but not in 2019 (see Figure 7). This might be the result of the very short growing period in 2019. RR performed significantly better than R. However, as the standard requirements were fulfilled, R is still applicable for recommendation. In the second growing period, T had an overall significantly higher projective cover ratio than TR as the variability was higher for TR. This can be linked to the grass–herb ratio performance, as addressed in the next section.

4.1.3. Grass–Herb Ratio Performance

The grass–herb ratio is a common indicator for biodiversity as the presence of herbs is substantial in terms of the ecological and biodiversity aspects [72]. A low grass–herb ratio is a desired target for the ecological upgrading of any large-scale biodiverse vegetation area. A higher herb ratio enables a higher inflorescence rate and, therefore, higher biodiversity [72]. Furthermore, seed mixes with a higher share of herbs and greater species diversity simplify the maintenance regime because herbs can self-seed and self-renew when cut at the appropriate seed maturity [72,73]. Additionally, herbs can prevent erosion [74].

In the initial seed mix, RSM 2.4, the share of seeds was at 83% of grasses and 17% of herbs. However, the first grass–herb ratio recorded was closer to 70:30 in July 2019, indicating non-homogenous mixing when seeding. Furthermore, the germination rate of the herbs (see Appendix A Table A1) was lower than that of the grasses.

Over the total test period, the grass–herb ratio was not significantly different for R and RR, with variations between the alternatives of only 5–10% (see Figure 8a). However, the grass–herb ratio for turfgrass was significantly different ($p < 0.05$) for T and TR with ratio variations between the alternatives of up to 20% (see Figure 8b). With the start of the second growing period, the grass–herb ratio was about 60:40 for T and almost 80:20 for TR (see Figure 8b). This changed only slightly until the end of the growing period, when TR decreased to a grass-herb ratio of 75:25. The lower herb ratio when on the reference material for turfgrass application (TR) might be a result of the higher content of mineral soil components [75] compared to T (see Table 1). More soil chemical analyses are recommended in future research projects, as this was not the focus of this field study.

The grass–herb ratio correlated negatively with the vitality rate (significantly for R, RR and T in 2019) and the projective cover ratio (significantly, except for TR in 2020). A lower grass–herb ratio is associated with a higher herb presence and fewer grasses [55]. Especially in drier periods, grasses are more affected by water shortage than herbs and are less drought-resistant [76]. When grasses are already withered, herbs are still vital [51]. The projective cover ratio is decisive for such vital functions as erosion protection or transpiration rates and is also strongly determined by leaf area [77]. Often, the larger leaf area of herbs compared to grass leaves, therefore, increases the projective cover ratio.

4.2. The Circular Soil Concept: Systematic Use of Excavated Materials for Optimizing Engineered Soils

Regarding the assessed indicators focusing on vegetation performance, the tested engineered soil alternatives were proved to qualify for installation at the Wildgarten site for intensive green roof and turfgrass applications. Hence, the results of the field study led to the development of the Circular Soil concept, which addressed the defined RQ2 (How can excavated soil material be used as engineered soil substitutes for landscape construction in a systematic and coordinated setup?). Figure 11 gives an overview of the derived six steps of the Circular Soil concept, described in detail in Section 3.3, as they might be implemented in large construction projects, additionally considering their long-term use.

The chemical, physical and geotechnical quality analysis (Step 1, Section 3.3.1) of the excavated materials, according to standards and norms [22,44–49], provide the basis for the optimization process. Then, the target landscape and planning design can be defined (Step 2, Section 3.3.2) for a specific building project, focusing on the landscaping purposes required and various GIs [22,30]. This information is essential to calculate the volume and mass balance (Step 3, Section 3.3.3) and optimize the grading curves [38,39,43,50]. In the next step, the soil amendments used and the mixing ratios can be optimized (Step 4, Section 3.3.4) to improve the overall performance of the engineered soils [30,41,42]. Based on these calculations, the mass- and volume-based production of the engineered soil alternatives can proceed on- or off-site (Step 5, Section 3.3.5) [17,22]. With an emphasis on quality assurance, the installation of the engineered soils can follow standardized landscape construction procedures (Step 6, Section 3.3.6) [64].

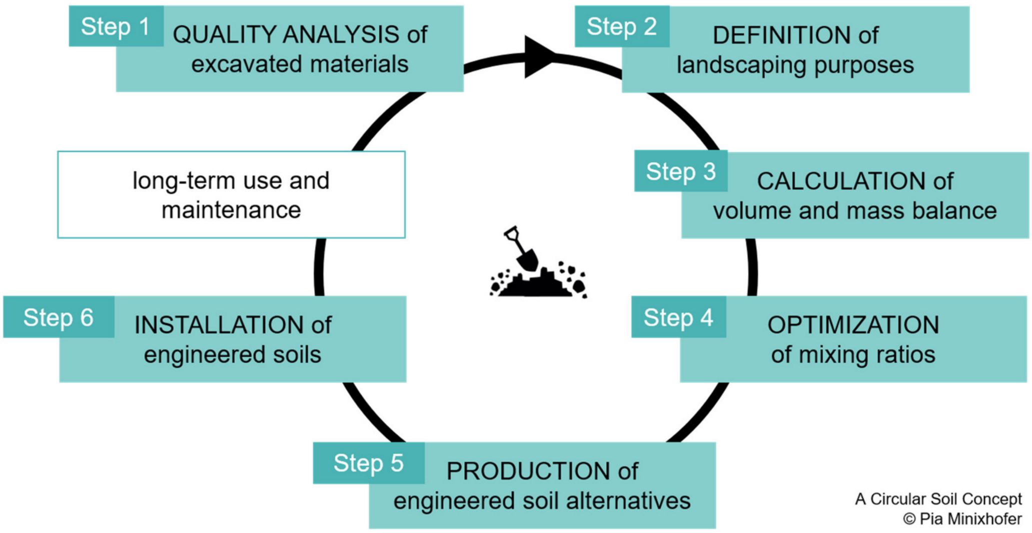


Figure 11. A new Circular Soil concept for landscape construction and GI application.

The Circular Soil concept can be implemented in a full circle, in line with the conceptional idea of the circular economy [3,9,35]. In addition to the six steps, long-term use has to be considered for sustainable implementation of the Circular Soil concept. Once installed, the vitality and survival of the vegetation are dependent on the maintenance regime. We propose extensive landscape maintenance, when possible, as intensive landscape maintenance reduces biodiversity, increases costs and carbon emissions [78], as well as diminishing the capacity of carbon sequestration in vegetation [6,79]. The field test results indicate that the grass–herb ratio is favorable to herbs on the optimized engineered soil alternatives applied in this study (see Figure 8b), and an overall acceptable vitality rate can be maintained for at least two seasons (see Figure 6).

Based on our experience, it is recommended to verify the technical properties of the engineered soils after optimization (Step 4), such as grain-size distribution or pore volume, using small-scale prototypes before going into large-scale production. This can be performed on-site or by a local landscape construction business. The optimization process should focus on the long-term structural stability of the installed engineered soil aggregates, in order to guarantee long-term buffer and storage functions, water-holding capacity and well-balanced pore volume for optimal plant conditions, hence using volume-based grading curves (see Section 3.1).

If the whole life cycle of the engineered soils is considered, the engineered soils could be excavated due to, e.g., extinct vegetation vitality or the implementation of new building projects after long-term use. The excavation would lead straight into Step 1 of the Circular Soil concept, and circularity would be kept (see Figure 11). In addition, cost savings are also part of the whole life cycle. In the course of the accompanying research work for the construction projects in Wildgarten and Biotope City, an average cost saving of 17% was calculated for engineered soil substitutes when following the Circular Soil concept, compared to industrially produced horticultural soils [22]. In another model calculation for an urban development area in Vienna, cost savings of approximately 30–40% were determined, depending on the landfill class of the soil and the recultivation target (unpublished data). In future research projects, a financial cost-benefit analysis will be assessed in more detail.

4.3. Recommendations for Transferability to Standard Application in Urban Development

This section addresses RQ3: How can the Circular Soil concept, based on excavated materials, be transferred to becoming a standard approach in urban and green infrastructure development? So far, the Circular Soil concept is not a common idea within a circular economy (see Section 4.3.1), lacking profound scientific studies and publications, guidelines (see Section 4.3.2) and legal regulations (see Section 4.3.3) to be routinely implemented. The following recommendations are deduced from the experiences gathered in the mock-up experiment presented herein and in the Wildgarten Project.

4.3.1. Contribution to a Circular Economy

The underlying objective of a circular economy in terms of construction is to make the best possible use of resources on-site to minimize material flows from or to the construction site, as far as possible [3,9]. With the Circular Soil concept, this principle is extended to the soil. The target is no longer to have materials transported from the construction site and deposited in landfills while reusing and recycling routes are promoted on-site or within the city. Intelligent logistics can reduce the environmental burden of traffic emissions. For example, in Vienna, one-third of the fine particle emissions recorded are attributable to construction [15]. If less material is transported to and from the construction site, fewer fine particles and CO_2 emissions occur.

The Circular Soil concept is a novel approach in the realm of the circular economy [9,35], one that needs to be established on an urban planning level to fully explore its transformative potential. Particularly regarding the loss of valuable soil resources, the Circular Soil concept will have the strongest impact at the city level, where the highest management responsibility can be found to reduce urban soil sealing [4]. The Circular Soil concept can contribute to the goal of the City of Vienna to reduce the consumption-based material footprint per capita by 50% by 2050 [80].

At the EU level, the presented Circular Soil concept complies with the aim of the EU taxonomy for sustainable activities (7.1) [81] that at least 70% of non-hazardous construction and demolition waste can be reused or recycled. In the Circular Economy Action Plan 2020, the European Commission specifically acknowledged the need to promote initiatives that reduce soil sealing and "[. . .] increase the safe, sustainable and circular use of excavated soils" [35] (p. 11). The EU Soil Strategy for 2030 [11] (p. 7) clearly states that "[s]oil is a major partner in a resource-efficient and circular economy since it is arguably the planet's biggest recycling machine".

The Circular Soil concept is a promising tool to contribute to the goal of zero net land-take in cities [82], and this target can only be reached if urban development focuses on the regeneration of brownfield sites and abandoned, uncontaminated industrial sites, such as the Wildgarten area [9]. In such low-density areas, the soil carbon pool is highest [6], as urban areas generate high CO_2 emissions and affect the carbon cycle of the city itself and its linked footprint [6]. The reuse of soil and recycled construction materials assures that CO_2 emissions are avoided. The Circular Soil concept aims at preserving the ecosystem functions of cultural and natural areas as well as possible and keeping soil as undisturbed as possible [18].

Following the 9R framework for circularity [83], the Circular Soil concept falls into category R3 of reuse, whereby all lower R rankings (R9 recover, R8 recycle, R7 repurpose, R6 remanufacture, R5 refurbish, R4 repair) are achieved. The potential benefits of reusing excavated resources are evident. Not only is a valuable, non-renewable resource kept in circulation but also emissions are reduced, climate change adaptational measures are promoted and the costs for construction are decreased [18,22].

4.3.2. Guidelines and New Routines for Construction Logistics

Construction logistics play a crucial role in the Circular Soil concept. The persons responsible for construction logistics must coordinate the on-site storage, preparation, mixing and installation of the reclaimed materials. If the Circular Soil concept is applied over multiple large-scale construction projects and sites, these processes become more complex and have to be coordinated and closely intertwined.

The Circular Soil concept aims to create a network between construction sites, in the sense of a cooperative, optimized mass balance. The logistics can be improved if the local resources are quantified and included in a quality plan or even a building information modeling (BIM) approach [22]. This has to be agreed on, in terms of quantities, and be as time-specific as possible before the start of construction, via communication between developers, general contractors, landscape planners and executing contractors [22]. The ecological and economic outcomes are improved with a decentralized, or dislocated, nearby temporary storage site for the excavated materials and with mobile construction equipment onsite for production of the materials [22]. The transferability prospects of the Circular Soil concept on an urban level increase when these new routines are established.

A well-known and successful large-scale example is the New York City Clean Soil Bank [84], where clean soil from construction sites is repurposed at public and private sites, e.g., urban gardening or land elevation [24]. Thus, in the first three years of the pilot phase, 2300 tons of CO_2 were saved through the avoided transportation of 600,000 tons of excavated material [84]. In line with this example, municipal structures are needed to ensure the exchange of recyclable (excavated) materials as such coordinative tasks are difficult to manage individually by a single construction management body. The establishment of the job profile of a Land Mass Coordinator, comparable to the one in Helsinki [85], a role that coordinates the logistics of urban mass flows from earthworks in a superordinate manner, could be a role model.

4.3.3. Adaptation of Regulations and Legal Requirements

The implementation success of the new Circular Soil concept strongly depends on the conditions for legal regulations, logistical conditions, and landscaping purposes at ground level (e.g., turfgrass) and higher up the buildings (e.g., intensive green roofs) [86]. For example, the main drivers for the implementation of green roofs can be identified as policy pressure, market pressure and technical innovation and development [86]. If these drivers are fostered with, e.g., the adaption of regulations, financial savings or improved engineered soils, the chances of the Circular Soil concept being implemented will increase.

The use of optimized engineered soils has to comply with federal and state law, building law, permits, norms and regulations; in short, with a variety of legal regulations. It depends on the locality if the excavated materials fall under the legal definition of waste, as they do in Austria [87] if they leave the construction site. Then, they have to be treated as waste, have to comply with strict regulations and may potentially be going to landfills, incurring higher costs.

Currently, no processes and quality requirements have yet been defined for the reuse of topsoil for the production of engineered soils. Therefore, processes such as the addition of soil amendment materials or mixing must be transparent and comprehensible [22]. The production of engineered soil alternatives must be verifiable, traceable and proven to be standard-compliant. To put the Circular Soil concept into practice, there is a need for standards, defined performance profiles and descriptions for planning and comprehensible step-by-step instructions. Further research on the implementation process will be necessary to optimize putting the Circular Soil concept into practice.

5. Conclusions

The Circular Soil concept presented herein has a high potential to contribute to climate change adaptation measures as it protects valuable soil resources. At construction sites, engineered soils can be produced on-site, reusing excavated matter and demolition materials. Its great benefits include a significant contribution to a sustainable circular economy, saving on emissions and costs. The engineered soils tested in this study were applicable and feasible in a mock-up trial and showed promising results for large-scale implementation. Further research opportunities include (1) the implications for rainwater management (especially the contribution to water-retention capacity, infiltration rate and filter performance), (2) its applicability for other landscaping purposes (e.g., tree-planting substrates), and (3) the use of recycling materials (e.g., brick chippings or sand).

Future challenges include the establishment of a logistical guideline for the implementation and optimization process, the acceptance of new routines along the entire construction process (from developers to general contractors) and the adaptation of legal regulations to allow the reuse of the excavated and demolition materials.

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Appendix A

Table A1. Germinability rate (%) for individual species in the seed mixture.

Species	Germinability Rate (%)	Species	Germinability Rate (%)
Agrostis capillaris	99	*Achillea millefolium*	88
Festuca trachyphylla/ovina	82	*Bellis perennis*	69
Festuca rubra commutata	75	*Centaurea jacea*	80
Festuca rubra rubra	75	*Crepis capillaris*	70
Lolium perenne	92	*Dianthus deltoides*	49
Poa pratensis	89	*Galium* sp.	53
		Leontodon autumnalis	53
		Leontodon hispidus	64
		Leucanthemum vulgare	75
		Lotus corniculatus	63
		Medicago lupulina	85
		Plantago lanceolata	31
		Prunella vulgaris	48
		Salvia pratensis	25
		Sanguisorba minor	62
		Thymus pulegioides	30
		Trifolium incarnatum	100
		Trifolium pratense	94
Average grass: 85.33		Average herbs: 63.28	

Table A2. Analysis of the chemical soil properties.

Chemical Soil Properties	TOC Total [%C]	+/−	ph-Value	+/−	Electrical Conductivity [mS/m]	+/−	Chloride [mg/kg TS]	Sulfate [mg/kg TS]	+/−	Kjeldahl-(N) Solids Modified [mg/kg TS]	+/−	Potassium Total [mg/kg TS]	+/−	Phosphorous [mg/kg TS]	+/−
T1	1.30	0.19	8.37	0.23	12.00	1.20	<10.6	13.37	1.45	1386.67	277.33	2363.33	591.00	1270.00	245.00
T2	0.96	0.14	8.37	0.27	10.57	1.06	<10.43	18.60	1.87	903.00	348.00	2886.67	722.00	935.33	187.00
TR1	1.32	0.20	8.00	0.20	8.96	0.89	<10.23	10.43	1.10	1556.67	311.00	1208.00	302.67	803.00	160.67
TR2	1.29	0.19	8.23	0.20	10.99	1.10	<10.5	11.07	1.15	1420.00	284.67	2060.00	515.33	979.67	196.00
R1	1.30	0.20	8.27	0.23	10.74	1.06	<11.0	13.57	1.37	1440.00	288.33	1124.00	281.00	1140.00	227.67
R2	0.84	0.13	8.40	0.30	11.30	1.13	<11.27	25.27	2.53	754.33	150.67	2820.00	705.00	725.00	145.00
RR1	2.46	0.37	8.27	0.20	13.13	1.33	<12.0	19.73	2.00	3163.33	633.00	1906.67	476.33	2506.67	500.67
RR2	1.41	0.21	8.23	0.20	11.17	1.13	<11.87	29.67	2.97	1576.67	315.00	1700.00	425.33	1733.33	346.67
Wildgarten topsoil	0.16	0.02	8.60	0.30	7.68	0.77	<9.8	9.85	0.99	215.00	43.00	2710.00	678.00	874.00	169.00

Table A3. Monitoring plan.

Month	2019		2020	
April			M2.01	20.04.2020
May			M2.02	04.05.2020
			M2.03	18.05.2020
June			M2.04	01.06.2020
			M2.05	15.06.2020
			M2.06	29.06.2020
July			M2.07	13.07.2020
	M1.1	25.07.2019	M2.08	27.07.2020
August	M1.2	08.08.2019	M2.09	10.08.2020
	M1.3	23.08.2019	M2.10	24.08.2020
September	M1.4	05.09.2019	M2.11	07.09.2020
	M1.5	19.09.2019	M2.12	21.09.2020
October	M1.6	03.10.2019	M2.13	05.10.2020
	M1.7	17.10.2019	M2.14	22.10.2020
	M1.8	31.10.2019		

Table A4. Spearman ρ correlations for the intensive green roof (R) and reference (RR) alternatives in 2019 and 2020.

Spearman's ρ—Correlations	R 2019			RR 2019			
	Vitality	**Projective Cover Ratio**	**Grass-Herb Ratio**	**Vitality**	**Projective Cover Ratio**	**Grass-Herb Ratio**	
vitality	1	0.749 **	−0.576 **	1	0.779 **	−0.265 **	Correlation Coefficient
	.	0	0	.	0	0.009	Sig. (2-tailed)
projective cover ratio	0.749 **	1	−0.534 **	0.779 **	1	−0.279 **	Correlation Coefficient
	0	.	0	0	.	0.006	Sig. (2-tailed)
grass–herb ratio	−0.576 **	−0.534 **	1	−0.265 **	−0.279 **	1	Correlation Coefficient
	0	0	.	0.009	0.006	.	Sig. (2-tailed)
	R 2020			**RR 2020**			
	vitality	projective cover ratio	grass−herb ratio	vitality	projective cover ratio	grass-herb ratio	
vitality	1	0.383 **	−0.245 **	1	0.351 **	−0.196 *	Correlation Coefficient
	.	0	0.001	.	0	0.011	Sig. (2-tailed)
projective cover ratio	0.383 **	1	−0.233 **	0.351 **	1	0.033	Correlation Coefficient
	0	.	0.002	0	.	0.674	Sig. (2-tailed)
grass–herb ratio	−0.245 **	−0.233 **	1	−0.196 *	0.033	1	Correlation Coefficient
	0.001	0.002	.	0.011	0.674	.	Sig. (2-tailed)

2019: n = 96; 2020: n = 168; significant correlations indicated in grey. * Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table A5. Spearman ρ correlations for the turfgrass (T) and reference (TR) alternatives in 2019 and 2020.

Spearman's ρ—Correlations	T 2019			TR 2019			
	Vitality	**Projective Cover Ratio**	**Grass-Herb Ratio**	**Vitality**	**Projective Cover Ratio**	**Grass-Herb Ratio**	
vitality	1	0.602 **	−0.394 **	1	0.721 **	−0.114	Correlation Coefficient
	.	0	0	.	0	0.268	Sig. (2-tailed)
projective cover ratio	0.602 **	1	−0.605 **	0.721 **	1	−0.389 **	Correlation Coefficient
	0	.	0	0	.	0	Sig. (2-tailed)
grass–herb ratio	−0.394 **	−0.605 **	1	−0.11	−0.389 **	1	Correlation Coefficient
	0	0	.	0.268	0	.	Sig. (2-tailed)

Table A5. *Cont.*

Spearman's ρ—Correlations	T 2019			TR 2019			
	Vitality	**Projective Cover Ratio**	**Grass-Herb Ratio**	**Vitality**	**Projective Cover Ratio**	**Grass-Herb Ratio**	
	T 2020			TR 2020			
	vitality	projective cover ratio	grass-herb ratio	vitality	projective cover ratio	grass-herb ratio	
vitality	1	0.426 **	−0.170 *	1	0.471 **	−0.033	Correlation Coefficient
	.	0	0.027	.	0	0.67	Sig. (2-tailed)
projective cover ratio	0.426 **	1	−0.161 *	0.471 **	1	−0.061	Correlation Coefficient
	0	.	0.039	0	.	0.437	Sig. (2-tailed)
grass–herb ratio	−0.170 *	−0.161 *	1	−0.03	−0.061	1	Correlation Coefficient
	0.027	0.039	.	0.67	0.437	.	Sig. (2-tailed)

2019: n = 96; 2020: n = 168; significant correlations indicated in grey. * Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

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