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Recycling of selected fraction of municipal solid waste as artificial soil substrate in support of the circular economy

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Abstract: Regions with warm climate are poor in organic matter or have a deficit of soil. The purpose of the work was to select the optimal mix from biodegradable wastes such as cardboard (Cb), natural textiles (Tx) newspaper (Np), colored newspaper (Cp), and office paper (Op) for creating artificial soil by combining these materials with compost and sand. To select the optimum mix, 15 samples were taken (3 from each type of waste in the following proportions: 25%, 50% and 75%). The optimum mix was analyzed for grass germination rate and root development. Tests were performed in the laboratory with conditions similar to those of regions with warm climate and soil deficiency in a specially designed testing spot (bioterm). The effects of particular mixes on plant germination rate and growth were measured. Out of all mixes, the textile compositions Tx50 and Tx25 supported best the plant propagation. During the whole experimental process, the grass showed various growth tendencies. The best results for grass height were observed for mixes with textiles and colored newspaper. Based on this data and subsequent laboratory research, the best substrate composition was selected. For the whole period of the tests, germination rate in the pot with the mix was higher than the germination rate in the control sample with compost. Considering the experimental conditions of this research, the tested substrates can be used to aid in plant propagation, especially in regions with warm climate and soil deficiencies, and for restoration of damaged land areas.

Introduction

As consumerism increases, so does the production of wastes. Production of municipal waste is an inevitable result of human activity in both the domestic and the industrial sectors (Singh and Raj 2018, Mannheim 2022). Economic development carried out in an unsustainable way, with no respect for the environment, may result in excessive exploitation of natural resources and increased emission of pollution to the environment. Part of the negative impact may be managed, but at the moment when some limits are exceeded irreversible changes may happen, which may threaten the stability of the functioning of the Earth (Alam et al. 2021). The continuously increasing stream of wastes poses an ethical problem and results in the waste of natural resources. Wastes that are reused, recycled, or recovered constitute potential resources. Rational waste and natural resources management will maximize reclamation and use of these resources, while unmanaged wastes could be trated as symptomatic of an ineffective economy.

At the same time, as municipal waste grows with economic growth, there are areas in the world where the soil is insufficient to grow crops (Avató and Mannheim 2022). These areas are poor in organic matter (Lederer et al. 2015). Consequently, it is often necessary to improve soil properties by adding organic corrections (Achiba et al. 2009, Bustamante et al. 2011, Hargreaves et al. 2008).

The European Directive 2018 addresses the need for changing waste management practices – improved materials and better management should be employed to protect, maintain, and improve the quality of the environment, protect human health, assure sustainable, effective, and rational use of the natural environment, and propagate the circular economy rules. The purpose of these actions is to assure that the use of resources, products, and wastes contributes to saving energy and decreasing greenhouse gas emissions.

The Agenda on Sustainability 2030, including the Sustainable Development Goals, was agreed upon by all 193 members of the United Nations General Assembly. The agenda describes, among other matters, 17 goals for various social, economic, and environmental aspects, which together constitute a path to the achievement of the sustainability assumptions. One of the goals is "life on land," which asks 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."

Wastepaper products are suitable for a few cycles of recycling until the material loses its properties, at which point paper waste needs to be neutralized through various methods. Furthermore, not all paper waste can be transformed into recycled paper because of, for example, contamination or excessive moisture content. Textile wastes are heavy and difficult to recycle and manage, thereby require a significant attention for sustainable management. These wastes are characterized by fast decomposition given an appropriate population of microorganisms and suitable environmental conditions. Therefore, it may be justifiable to use these wastes as a component of the soil substrate for plant production. The substrate may be used in areas of soil deficiency to establish city greenery, where the plants from the very beginning need to have proper conditions for growth and development, especially in degraded areas and wherever phytoextraction (of pollutants from soil by plants) is recommended.

Although there are some studies that have been performed on paper waste recycling (Lei et al. 2019, Si et al. 2016, Rajput et al. 2012, Pelegrini et al. 2010), cardboard (Espinosa et al, 2019, Asdrubali et al. 2019, Ayrilmis et al, 2008), and textile (Çay et al. 2020, Homem and Amorim 2020, Haslinger et al. 2019, Awwad et al. 2012, Tatariants et al. 2019, Zhou 2010, Kymäläinen and Sjöberg 2008, Aspiras and Manalo 2008) which have large different application areas, a review of the literature has not produced a single reference to the use of these wastes for creating artificial soil substrate by combining these materials with compost and sand. Thus this research was performed to evaluate the potential use of selected fraction of municipal solid waste as artificial soil substrate in support of the circular economy.

The main research aim of this scientific work was to determine the optimal mixture and compare different mixes by using biodegradable wastes. In the first step, we performed laboratory tests to determine physicochemical properties, fertilizing properties, and contamination with heavy metals of the wastes used for the substrate mixes. In the second step, we analyzed the properties of compost used for the mix and investigated additional tests. Additional tests included vegetation pot experiments, tests of the impact of additives on the germination rate and plant growth, and tests of the optimum mix of the substrate for plant production.

Experimental procedure

Materials and preparation of the samples

The main components of the artificial soil substrate for plant production were wastes obtained from the selective collection process: grey or colored newspaper, cardboard, natural textiles, and office paper (printed). The collected material was crushed in a mill manufactured by Trymet type T4-5.5 SW of capacity 5.5 kW. An 8 mm mesh was used for crushing. To produce the mix, the following materials were used: Cardboard (Cb), natural textiles (Tx), newspaper (Np), colored magazine paper (Cn) and office paper (Op) with the admixture of compost and sand for the production of the artificial soil substrate. To select the optimum mix, 15 samples were constructed (3 with each waste in volume percentages 25%, 50%, and 75%). Mixtures were classified according to the type of waste added and its percentage: Cb_{25}, Cb_{50}, Cb_{75}, Tx_{25}, Tx_{50}, Tx_{75}, Np_{25}, Np_{50}, Np_{75}, Cn_{25}, Cn_{50}, Cn_{75}, Op_{25}, Op_{50}, Op_{75}.

Preliminary basic tests

Physicochemical tests

All measurements were performed in triplicate and calibrated with the appropriate standards.

Total moisture content, bulk density, and phytotoxicity measurements were made for solid fractions, and aqueous extracts were made from each tested fraction of the material. The tests, methods and standards applied for the physicochemical tests of solid fractions are presented in Table 1.

Physicochemical tests on aqueous extracts of the tested fractions consisted of pH, alkalinity, acidity, hardness, electrolytic conductivity, chlorides, and sulphate. Also, phytotoxicity tests for aqueous extracts were performed. The scope of determination, method and standards applied for the physicochemical tests on aqueous extracts are presented in Table 1.

Fertilizing-substance tests and heavy metal composition

Tests of solid fractions for substances contributing to soil fertility included total particulate organic matter, organic carbon, total nitrogen, potassium, calcium, phosphorus, and humic substances. Determinations on the aqueous extracts included phosphorus and ammonium nitrogen content. The methods and standards applied for tests of solid fractions and aqueous extracts related to soil fertility are presented in Table 1. The test results were compared to statutory requirements (Ordinance of the Minister of Agriculture and Rural Development 2008, Ordinance of the Minister of Environment 2006, Ordinance of the Minister of Environment 2014).

Tests of heavy metals concentrations in the wastes were performed with flame atomic absorption spectroscopy (FAAS). The tests included the determination by flame atomic absorption spectroscopy of cadmium, chromium, cobalt, copper, lead, nickel, and zinc in the extracts of solid wastes with aqua regia. Test results are presented in Table 2.

The results of the tests were compared with the requirements for quality and contamination with metals for manures included in (Ordinance of the Minister of Agriculture and Rural Development 2008).

The data show that the organic content in the tested wastes was much higher than the value specified in the Ordinance. The concentrations of the fertilizing elements in the tested fractions were much lower than the relevant values listed in the Ordinance. For these reasons, compost was added to the applied waste fractions. In the case of heavy metals, it was noted that none of the values of the fractions exceeded the permissible limits specified in the Ordinance.

Vegetation pot experiments

Orchard grass (*Dactylis glomerata*) and tall fescue (*Festuca arundinacea*) were sown as indicative species with respect to the tolerance for soil. The selection of species was based primarily on the resistance to water stress, high and low temperature tolerance, propagation rate, and germination ability.

Experimental stands and results

In order to conduct the experiment, a research apparatus called 'bioterm' was designed and constructed. The structure is made from PVC hard slabs. The front wall is plexiglass 5 cm thick. The whole box is covered with tempered glass, as necessary to avoid deformations or melting due to the high temperature emitted by heating lamps. The pot was strengthened with angle bars. The bottom of the bioterm has openings that allow drainage of water. The agro-textiles are spread at the bottom to protect against washing out of the testing material from the pot. The bottom of the bioterm is divided into 9 chambers, each subdivided into 3 smaller chambers. Each chamber is 30 cm high. In order to control humidity and temperature, a controller for humidity and temperature (NINOO model TR-3) was used. Final data concerning temperature and humidity were input into the controller. The temperature at the research post was maintained at 40°C. After the set temperature was exceeded, the controller started up the fans (adapted from egg incubators).

Table 1. The scope of tests, methods and standards applied for physicochemical tests and fertilizing tests of solid fractions and aqueous extracts

Methods and standards applied for physicochemical test		
Test	**Method**	**Standard**
Solid fractions		
Total moisture content	Weighing	
Bulk density		PN-EN 1097-3:2000
Phytotoxicity tests		PN-ISO 11269-1, 1998
Aqueous extract		PN-Z-15009:1997
Aqueous extract		
pH		PN-Z-15011-3:2001
Alkalinity		PN-Z-15011-3:2001
Acidity		PN-Z-15011-3:2001
Hardness	Versenate test	PN-Z-15011-3:2001
Electrolytic conductivity		PN-Z-15011-3:2001
Chlorides	Argentometric test	
Sulphate	Weighing	
Phytotoxicity		PN-ISO 11269-1, 1998
Methods and standards applied for fertilizing tests		
Solid fractions		
Content of organic elements		PN-Z-15011-3:2001
Organic carbon		PN-Z-15011-3:2001
Total nitrogen	Kjeldahl's method	PN-75/c-04576.17 Titration test
Potassium		PN-EN 14385:2005; ICP-OES
Calcium		PN-EN 14385:2005; ICP-OES
Phosphorus	Spectrophotometric test	PN-Z-15011-3:2001
Organic soil	Czesny's method	
Aqueous extracts		
Phosphorus	Spectrophotometric test	PN-Z-15011-3:2001
Ammonium nitrogen	Kjeldahl's method	PN-75/c-04576.17 Titration test

Table 2. Concentrations of heavy metals (mg/kg) in the tested wastes

Sample	Cadmium	Lead	Copper	Chromium	Zinc	Nickel	Cobalt
Cardboard	2.23±0.24	<9.9	58.0±6.1	<11	59.8±9.9	<11	<11
Textiles	1.8±0.2	<9.9	14.5±1.5	<11	26.3±4.3	<11	<11
Office paper	3.4±0.4	<9.9	12.9±1.4	<11	18.9±3.1	<11	<11
Coloured newspapers	2.2±0.2	<9.9	55.2±5.8	<11	10.6±1.7	<11	<11
Grey newspapers	1.5±0.2	<9.9	58.8±6.2	<11	16.5±2.7	<11	<11

One fan injected fresh air from the outside of the apparatus and the other exhausted air to the outside. During the research, it was observed that the humidity in the bioterm varied from 50 to 60%, whenever it fell below the limits the controller started an air humidifier which operated until the desired humidity level was achieved.

For the purpose of the experiment, a portable irrigation system was constructed. For its construction, a pump (Elegant Comet 12 V) was installed in a 10 L covered vessel with a capacity of 81 L per minute and pressure of 0.55 bar. In the middle of the tank, a side valve was installed connected to the water supply system. A feeding water pipe of diameter 10 mm was connected to the pump, which was further connected to a pipe of diameter 6 mm. When the pipe was lifted, a tee bar was installed, and each of the pipes terminated in sprinklers. The tested area was irrigated with 5 liters of water daily.

Test of the impact of cardboard on the germination rate and plant growth

The following mixes were tested:
25% cardboard waste (Cb), 70% compost, 5% sand,
50% cardboard waste (Cb), 45% compost, 5% sand,
75% cardboard waste (Cb), 20% compost, 5% sand.

<u>Germination rate of grass of mix with the addition of cardboard</u>

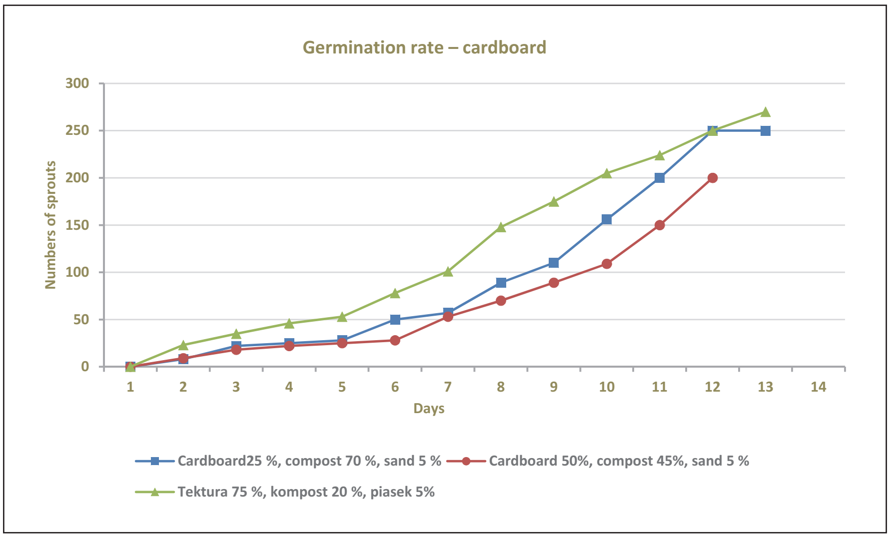
Early in the experiment (Figure 1) germination rates in the pots with cardboard were similar, without large deviations. Noticeable changes were spotted on the 6–7th day after seeding, when pots with Cb_{25} and Cb_{50} were similar, while there were more sprouts in mix Cb_{75}. Figure 1 shows clearly that Cb_{75} produced the most sprouts, Cb_{50} the fewest, and Cb_{25} an intermediate number of sprouts.

<u>Average height of grass in mixes with added cardboard</u>

Figure 1 shows approximately equal growth in mixes with cardboard. The growth rates were similar in all cardboard mixes. Slight differences occurred between days 13 and 23 when the grass in Cb_{25} showed accelerated growth. Finally, the plants in all the mixes with the cardboard reached a similar height of approximately 20 cm.

Tests of the impact of textiles on plant germination rate and growth

The following mixes were tested:
25% textile wastes (Tx), 70% compost, 5% sand,
50% textile wastes (Tx), 45% compost, 5% sand,
75% textile wastes (Tx), 20% compost, 5% sand.



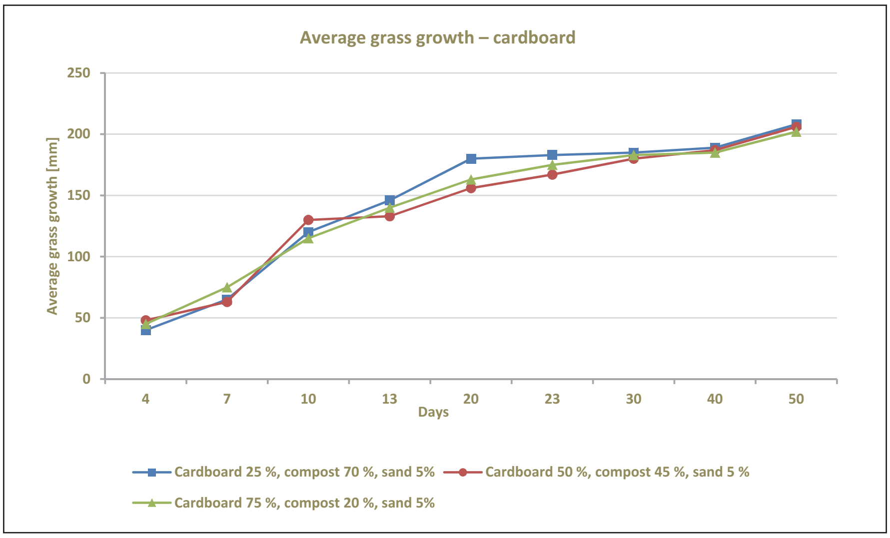


Fig. 1. Germination rate and average grass growth – cardboard

Germination rate in the mixes with added textiles

The results (Figure 2) show that all the mixes were characterized by high germination rates. The high absorption rates, chemical makeup, and morphology of natural fibers in the textiles provide weak resistance to environmental factors, including humidity, fungi, bacteria, and light. These sensitivities result in relatively rapid decomposition of the crushed textiles.

Of all the mixes, the greatest germination and growth rates were achieved in textile-compost mixes Tx_{50} and Tx_{75} (Figure 2).

Differences between the mixes first appeared on the 3rd day after seeding. The germination rate in the first few days did not differ much between the samples, clear differences appeared on the 6th day of observations. Grass grown in the mix Tx_{50} germinated faster that in the other mixes. On the 8th day, the whole testing spot was covered with growing grass, when compared to the mixes Tx_{25} and Tx_{75}. Finally, the mixes Tx_{25}, Tx_{50}, and Tx_{75} produced the same numbers of sprouts, but at different rates.

Average height of grass in mixtures with added textiles

Figure 2 shows grass growth in height, where the biggest differences between textile mixtures were on the 40th day. On the 50th day after seeding, the mix Tx_{50} reached the height of 30 cm. Similar to the germination rate, the largest growth was achieved in the mix Tx_{50}. At the final stage, the mix Tx_{25} achieved better results than Tx_{75}. The grass growth in all of the textile mixes was greater than the other waste product mixes. In each Tx mix the grass reached a height of more than 27 cm.

Tests of the impact of grey and colored newspapers on grass germination and growth rates

The following six mixes were tested:

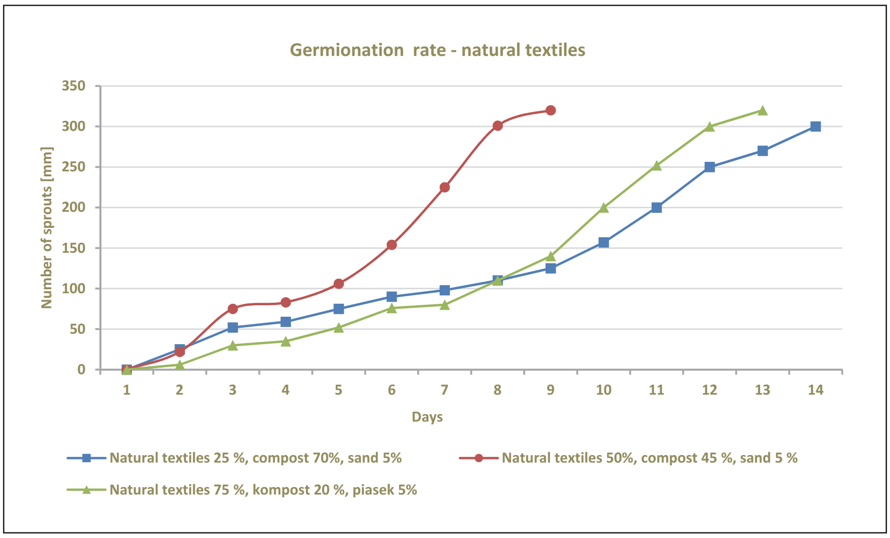
25% grey or colored newspaper waste (Np or Cp), 70% compost, 5% sand,

50% grey or colored newspaper waste (Np or Cp), 45% compost, 5% sand,

75% grey or colored newspaper waste (Np or Cp), 20% compost, 5% sand.

Germination rate in the mixes with added grey newspaper

Germination rates in the mixes containing newspaper are shown in Figure 3. On the second day after seeding, the first differences in the germination rates were observed. The mixes Np_{25} and Np_{50} had a similar number of sprouts within 16 days



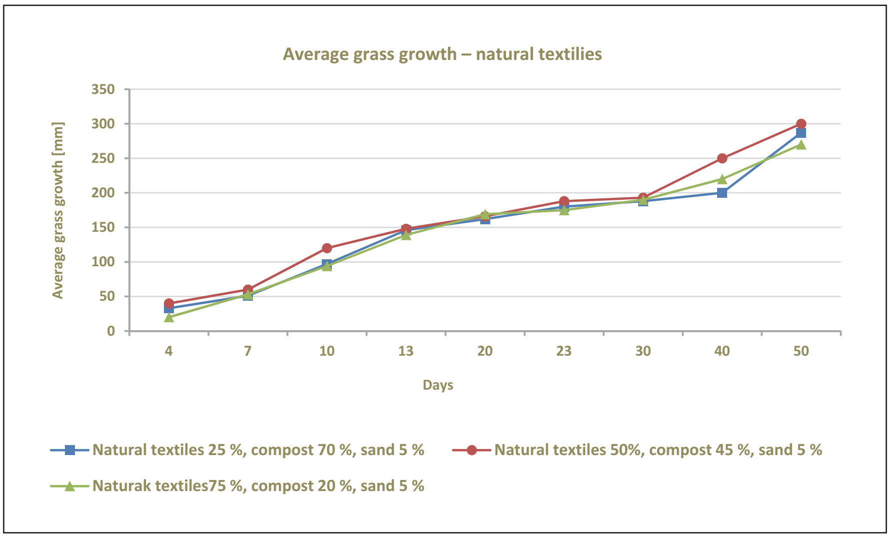


Fig. 2. Germination rate and average grass growth – natural textiles

with minor deviations between days 9 and 14. Mixture Np_{75} produced a dynamic germination rate, with more frequent seed emergences than in Np_{25} or Np_{50}. Np_{75} also showed a higher percentage of sprouting seeds.

Average height of grass mixes with the admixtures of the grey newspaper

Figure 3 shows average grass growth in Np mixtures. Grass growth is similar in all the Np mixes, with faster growth tendency until the 20th day. An average grass growth was 18–19 cm. Np_{25} and Np_{50} attained the greatest heights.

Germination rate in mixtures with colored newspaper

All the Cn mixes had similar germination rates (Figure 4), with some minor deviation in Cn_{75}. Sprouting rates in Cn_{25} and Cn_{50} were similar to each other. Germination rate and the percentage of sprouted seed were higher in Cn_{75}.

Average height of grass with admixtures of colored newspaper

Grass growth in all the Cn mixes was even, without large differences between the mixes (Figure 4). The grass reached a height between 20 and 22 cm. Mixes Cn_{25} and Cn_{50} had slightly higher growth than Cn_{75}.

Tests of the impact of office paper on plant germination and growth rates

The following mixes were tested:
25% office paper (Op), 70% compost, 5% sand,
50% office paper (Op), 45% compost, 5% sand,
75% office paper (Op), 20% compost, 5% sand.

Germination rate in mixtures with added office paper

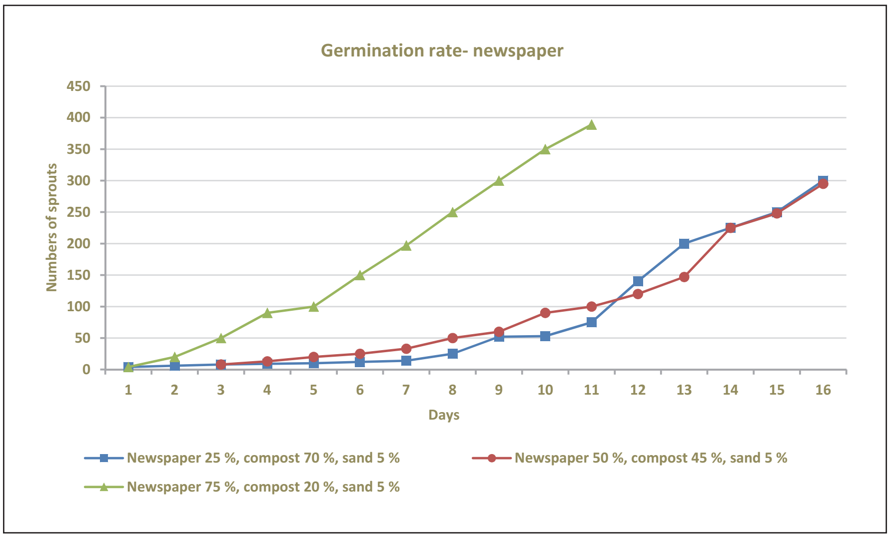
Figure 5 shows even germination rates in all the Op mixes, even though minor differences between the mixes can be seen on the 3rd day. Germination rate in the Op mixes was characterized by a lower growth when compared to other types of waste mixes. Lower results are probably an effect of higher contamination of office paper with chlorides (575.9 mg Cl^-/dm^3) and cadmium (3.4 mg/kg).

The average height of grass mixes with the added office paper

Figure 5 presents grass growth for 50 days after seeding. In all the Op mixes, the growth was even. The height of the grass on the 50th day was 17–19 cm.

Germination rate in all the mixes

The results of the analysis show that in all the mixes applying wastes had a positive impact on the number of sprouts, the



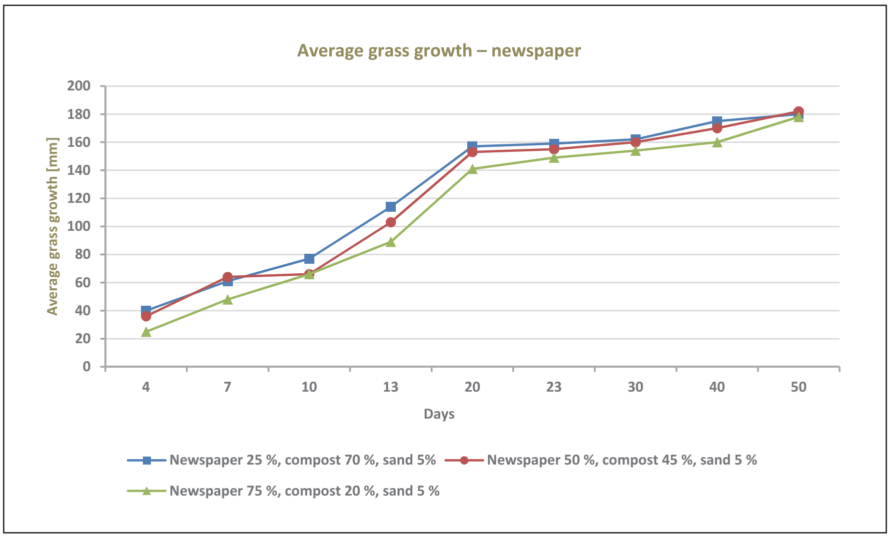


Fig. 3. Germination rate and average grass growth – newspaper

germination rate, and grass growth. The number of grass sprouts was clearly similar for 14 days after seeding. Significant differences in the growth were observed within the first 7 days. With time the differences diminished. Of all the mixes, Tx_{50} and Tx_{25} were the best for grass propagation.

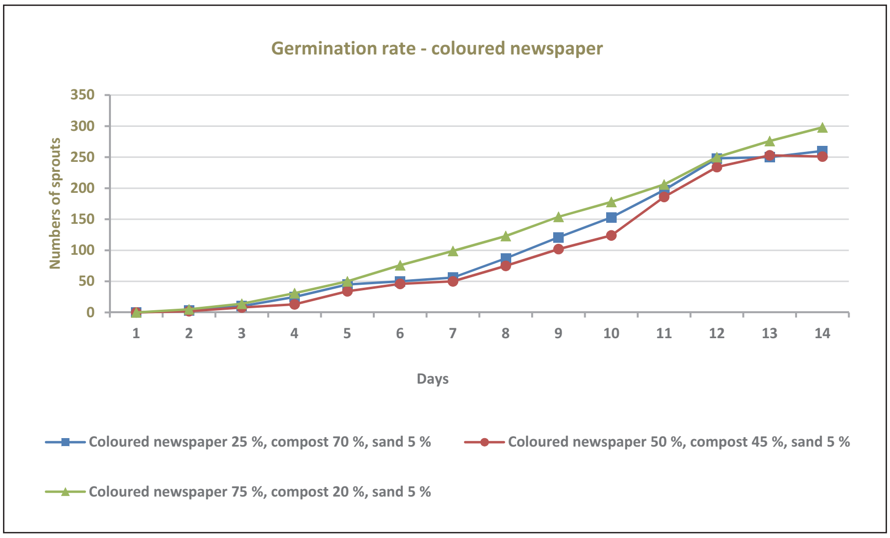
Average grass growth in all the mixes
Large germination energy has a significant impact on seedling emergence. The height of the seedlings in the first days after seeding proves that the plant surface area for CO_2 assimilation (assimilation area) is growing. During the whole period of the pot experiments, the grass showed various growth tendencies. The best results for grass height were observed in the mixes with textile additives. These mixes were characterized by fast germination rate and higher growth when compared to other mixes. Other favorable grass growth results were observed in colored paper mixes where the grass reached 25–26 cm in Cp_{25} and Cp_{50} mixes, compared to 29 cm in the Cp_{75} mix. The growth results for the remaining three mixes were similar, with Cb, Np, and Op reaching 18–22 cm in height.

The type of substrate used modified the intensity of plant propagation. In the mixes with waste as 25% of the total volume, the grass propagated worse than in the mixes with 50% and 75% waste. In the mixes with the 50% and 75% waste, faster growth and more sprouts were observed. It seems from the results that the content of heavy metals in the applied wastes did not affect adversely the development of the grass.

Tests of the optimum mix of substrate for plant production

The scope of the tests covered the germination rate and growth of grass in the optimum mix. The tests were performed also on the control ample, with only compost for comparison of the test results.

Preparation of the optimum mix
The optimum mix is composed of 20% textiles, 20% colored newspaper, 15% grey newspaper, 15% cardboard, 5% office paper, 15% compost, and 10% sand, for a total of 75% waste fractions, with 25% compost and sand. The composition of the substrate was selected on the basis of the analysis which accounted for the content of heavy metals [mg/kg], phytotoxicity tests, physicochemical tests and the vegetation test results of particular mixes. In order to compare the germination rate and the grass growth with the grass seeded on the optimum mix, a control sample was made only with the



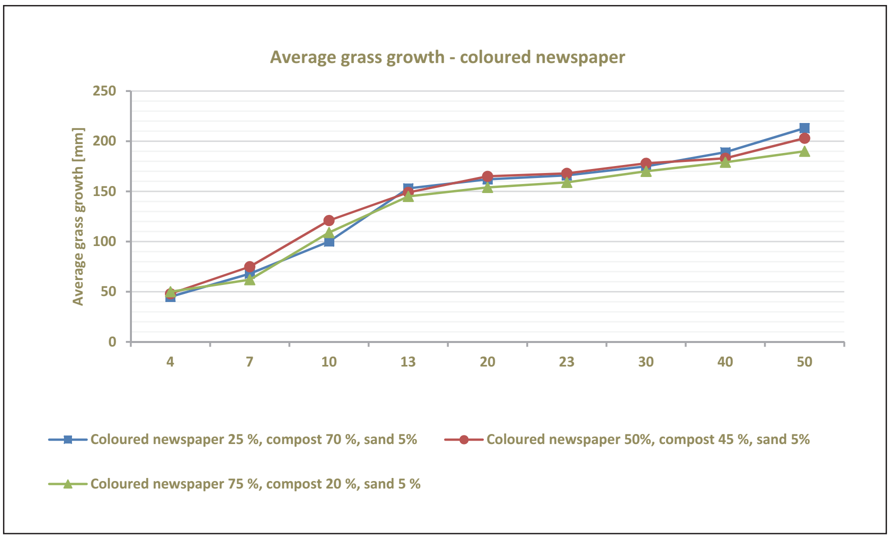


Fig. 4. Germination rate and average grass growth – coloured newspaper

compost. Tests of the impact of the optimum mix were carried out in the bioterm. At the next stage, vegetation field tests were performed. The test results of the germination rate and the grass growth are presented in Figure 6.

Analysis of the impact of the mix on the germination rate and average height of the grass in the bioterm

Figure 6 compares the germination rate and grass growth of the optimum mix with a control sample (compost). The plot clearly shows that the germination rate in the optimum mix was higher than the germination rate in the control sample with compost only. The results show that during the whole testing period, the germination rate in the pots with the mix was higher than in the control sample with the compost.

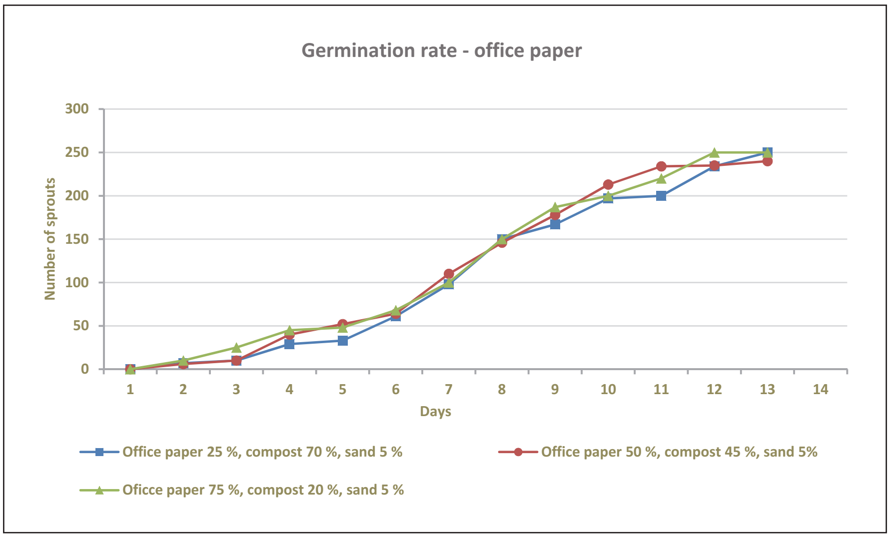
During the experiment, in the pot with the optimum mix, no negative impact of the waste on the grass growth was noticed. Starting from day 4, the pot with the optimum mix was characterized by a higher number of sprouted seeds. After 10 days, the whole testing area was covered with grass sprouts.

Figure 6 presents the grass growth in the pot with the optimum substrate mix as compared with the compost only. The growth in both pots was similar. However, the optimum mix reveals a higher growth of blades. Furthermore, on the surface of the leaves, no discolorations were noted, and the number of sprouts and the height of the grass proves higher assimilation area in both pots.

The microclimate in the bioterm did not have any negative impact on the grass growth during testing. Despite the high temperature, the seeds sprouted by the 4th day. Humidity in the bioterm was maintained at 60% which had a positive impact on the growth of seeds in the growth phase.

Conclusions

The results of pot experiments, carried out in specially simulated conditions, show the ability of the substrate to maintain appropriate moisture under high temperature. Test results for particular mixes show that applying waste in all the mixes has a positive impact on the number of sprouts and germination rate and on the grass growth. Out of all the mixes, the best results for plant propagation were found in the mixes Tx_{50} and Tx_{25}. During the whole period of pot experiments, the grass showed various growth tendencies. The best results in respect to the grass growth were noticed in mixes with the addition of textiles and colored newspaper. In



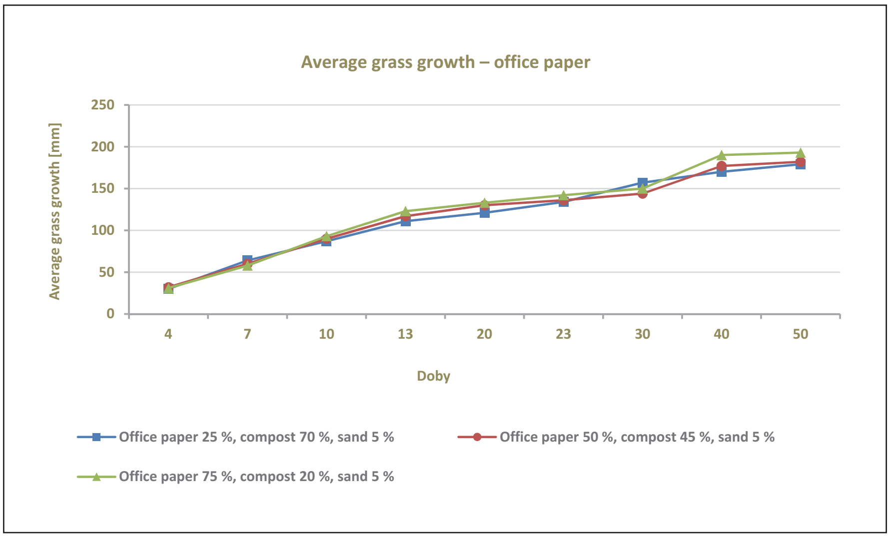
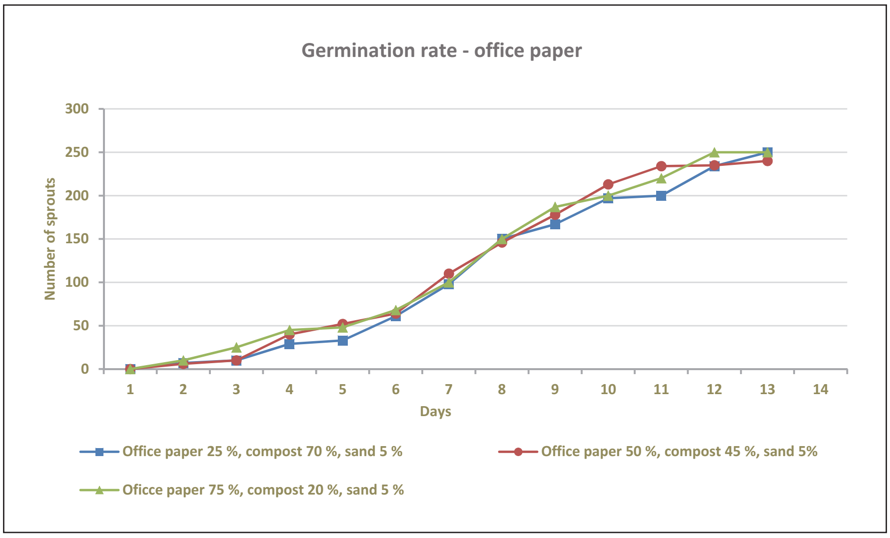


Fig. 5. Germination rate and average grass growth – office paper



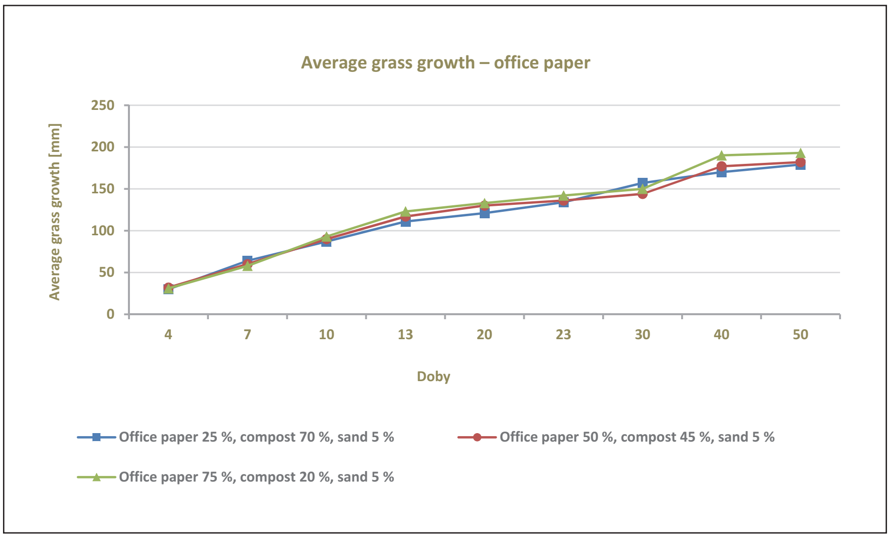


Fig. 6. Germination rate and grass growth – optimum substrate and compost

the optimum mix, 75% mixed waste fractions, 15% compost, and 10% sand were applied. Both in the optimum mix and a compost sample, the experimental area was covered with sprouts. However, the number of sprouts in the optimum mix was higher.

Grass yields in the optimum sample were higher than in the control sample with the compost. The number of sprouts and the height of the grass indicated the increasing assimilation area.

Substrate properties have a direct impact on the height and quality of the obtained yields. The material used to create the substrate is capillary and hygroscopic, absorbs moisture from the vapor in the air, moisture in the soil, or from the dew on the surfaces. Due to these properties, the substrate can maintain humidity and the material used protects the plants (seeds) from drying out.

The results of the tests indicated that the selected wastes used, i.e., natural textiles, cardboard, newspapers, and printed office paper may be used as components to create an optimum substrate for the adaptation of plants. The substrate mix may be used as an agent that improves the properties of the soil, as growth stimulator or substrate for non-agricultural cultivation or soil reclamation.

The substrate applied provides nutrients to the plants, meets the minimum quality requirements, does not contain contaminants that would exceed the permissible limits. The content of heavy metals in the wastes used did not have any negative impact on the development of the grass. Lack of phytotoxic influence on the plants allows for a positive evaluation of the suitability of substrate for natural purposes.

Summary

In regions of warm climate and poor soils, selected groups of biodegradable wastes can be used as soil amendments to improve plant production. Tested substrate may be used in areas of soil deficiency to establish city greenery, where the plants from the very beginning need to have proper conditions for growth and development, especially in degraded areas and wherever phytoextraction (of pollutants from soil by plants) is recommended.

In regions with warm climates, it is recommended to apply the substrate at the end of summer or mid-winter. The winter in these regions is short and characterized by moderate temperatures. Additionally, we recommend adding a super-absorbent or hydrogel to correct substrate moisture.

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