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Compostability and vermicompostability of greaseproof wrapping paper

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ABSTRACT

This study aimed to determine the compostability of greaseproof wrapping paper and evaluate the resulting product according to legislative requirements. The paper with amendments was composted in a GreenGood electric composter and vermicomposted in a Worm Factory vermicomposter. The resulting pH and electrical conductivity (EC) values indicated that the material from the electrical composter was not suitable for fertilization. This was because of the presence of acidic and salted composted substrate from the gastro-waste in the initial mixture. Conversely, an electric composter was suitable for rapidly reducing paper waste. The mixture with paper, apple pomace, and horse manure had 90% of particles smaller than 9 mm and 5 mm after 24 and 48 h of composting, respectively. In vermicomposting, these parameters were reached after two to three months. Vermicompost in comparison with compost showed greater pH (7.4–8.8) and lesser EC (405–1046 μS/cm). The greater macroelements contents in the compost were positively influenced by a 50% proportion of the composted substrate in the initial mixture. Nevertheless, a vermicompost based on paper and horse manure exhibited the greatest nutrient content of all the assessed variants. According to the phytotoxicity test, it was a well-matured compost. Greaseproof paper used for food packaging is both compostable and vermicompostable. The disintegration results can be inferred when the legislative standard was met in all cases.

1. Introduction

Greaseproof paper is the ideal packaging material for food containing fat and water. Greaseproof paper is treated to prevent penetration of fat and moisture into the paper structure and through it, thus preserving the packaged food as well as the packaging and its printing in perfect condition. Oil and grease-resistant papers have a wide application range in the food packaging industry. They are designed and certified for direct food contact. Common use cases include food service wraps (e.g. in fast foods), the manufacture of paper bags, and laminating with other materials, where paper serves as one of the functional layers of composite packaging. Grammage usually ranges between 30 and 70 g/m^2 (Paulapuro 2000). The global greaseproof paper market is estimated to be worth 1.1 billion USD by 2025 (Acumen Research and Consulting, 2019). Before the emergence of plastic films, the paper industry used parchmentizing technology which utilized concentrated sulfuric acid and high levels of fiber refining. But it was not the only approach. Greaseproof paper also has been made for over a century by (a) high levels of refining of chemical pulp (including sulfite pulp and kraft pulp, often combined with (b) surface application of starch or other water-soluble polymers, especially polysaccharides. In such cases what it achieved is a very dense cellulosic sheet (or top layer) that is resistant to the permeation of oils even though it has no

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perfluorinated treatment (Hubbe and Pruszynski 2020). Oil-repellent fluorocarbon paper treatments have substantially displaced these technologies. But per- and polyfluoroalkyl substances (PFAS) are persistent in the environment, bioaccumulative, and some are toxic to humans and other animals. Since the early 2000s, laws, policies, and regulations have been implemented to reduce the prevalence of PFAS in the environment and exposures to PFAS (Brennan et al., 2021). Because of mentioned environmental concerns and regulations, the paper industry needs more options. Some promising directions in published research include advances in chemistry, superoleophobic surfaces, nanocellulose films, and systems to protect nanocellulose films from the effects of moisture (Hubbe and Pruszynski 2020). The greaseproof paper used in this study did not contain perfluorooctanoic acid. The oils and fats from foods make the recyclability of used greaseproof paper into new paper impossible. In most cases, greaseproof paper is part of mixed municipal waste, which ends up in landfills, or in a better case, in a waste-to-energy plant. Composting and vermicomposting could be suitable options for handling.

There are three stages to aerobic composting. The first degradation phase converts carbohydrates and amino acids into simpler compounds, such as CO_2 and water, at high temperatures of over 60 °C. During the transformation phase organic matter is degraded by mesophilic bacteria. Synthesis or maturation is the final phase. Based on various factors, the entire composting process can take anywhere from 3 to 6 months to complete (Meena et al., 2021). Most recent studies concerning biowaste composting and treatment of the compost are published in Sarlaki et al. (2021). Indoor composting is conducted using special composters (Mu et al., 2017). By maintaining proper temperature and aeration conditions, modern composting machines optimise the composting process, thus reducing the time required to complete the process (Pandey et al., 2016; Sangamithirai et al., 2015). The description, technical parameters, and advantages of the electric composter used in this study are given in Kliopova et al. (2019). From the standpoint of research, they can allow relatively low volumes of compost to be evaluated under controlled conditions. Vermicomposting is an efficient tool in waste handling which includes the biotransformation of solid organic wastes into useful products, and therefore holds a great promise towards sustainable waste management (Sharma and Garg 2022; Ravindran et al., 2016). Earthworms can process paper mill or paper with the addition of other materials (cow dung, straw, tea waste) as demonstrated (Ganguly and Chakraborty 2021; Badhwar et al., 2020; Abbasi et al., 2018; Ravindram and Mnkeni 2016). The paper type was not specified in these and other published studies.

This study aimed to determine the compostability and vermicompostability of greaseproof wrapping paper and evaluate the resulting product according to legislative requirements. The novelty is the testing of the biological processing of used greaseproof wrapping paper in the indoor electric composter and in the vermicomposter. This paper waste type is not suitable for conventional material recycling into new paper. However, it could be used to prepare quality soil amendment. Thanks to this, it is possible to move from the current landfilling of this paper type to qualitatively better biological recycling, which is in line with the goals of the circular biobased economy (Tan and Lamers 2021). The results of this research are important and useful for producers, users, and downstream processors of this type of waste.

2. Materials and methods

2.1. Raw material

Greaseproof wrapping paper KH PACK superior was provided by KRPA PAPER, a.s., Czech Republic. The paper was cut into narrow strips using a shredder and soaked for 18 h in excess water, which was subsequently drained from the barrel. For faster and more efficient processing, the addition of apple pomace and horse manure, which came from the Severofrukt, a.s. company, and the Academic Equestrian Club of the Czech University of Life Sciences Prague, respectively, were used. The basic physico-chemical parameters of the raw materials are shown in Table 1. The paper was characterized by low electrical conductivity (EC) and nutrients, mainly nitrogen. Thus, the C:N ratio was very high. The input substrate with microorganisms for the electric composter came from GreenGood composter processed food waste (food residue from a restaurant). Because of this, it was characterized by low pH, and high EC and

Table 1
Basic physico-chemical parameters of the raw materials.

	Paper (moistened)	Apple pomace	Horse manure	Input substrate
Dry matter (%)	45.7 ± 0.06	34.9 ± 0.87	25.2 ± 0.86	96.4 ± 0.15
pH/H_2O	6.8 ± 0.04	3.2 ± 0.03	7.4 ± 0.06	4.4 ± 0.09
EC (μS/cm)	80.3 ± 13.6	1103 ± 199.7	554 ± 32.7	9423 ± 371.7
C:N ratio	1050 ± 74.4	48.7 ± 6.01	15.8 ± 1.83	18.4 ± 1.19
Ctot (%)	42.3 ± 0.10	45.6 ± 0.31	18.4 ± 0.81	46 ± 1.6
Ntot (%)	0.01 ± 0.001	0.1 ± 0.01	1.3 ± 0.11	1.6 ± 0.21
$N_{mineral}$ (mgN/kg)	50.3 ± 1.3	18.8 ± 1.2	114.4 ± 0.7	84.2 ± 3.1
DOC (mg C/kg)	2697 ± 342	30,183 ± 4011	3238 ± 338	88,027 ± 2734
Total Mg (mg/kg)	197 ± 45	67 ± 25.2	4518 ± 450	688 ± 14.4
Available Mg (mg/kg)	51.6 ± 19.1	425 ± 32.8	419 ± 19.1	686 ± 29.6
Total P (mg/kg)	65.6 ± 50	1075 ± 104	4355 ± 507.4	2453 ± 124.7
Available P (mg/kg)	<0.02	468 ± 7.6	370 ± 32.5	1927 ± 104
Total K (mg/kg)	309 ± 236	7423 ± 698.4	8583 ± 241.9	8732 ± 419.6
Available K (mg/kg)	54.5 ± 6.5	4648 ± 231	2644 ± 182.6	7990 ± 217.9
Total Ca (mg/kg)	944 ± 156	1796 ± 37.9	23,889 ± 950	5959 ± 204.6

Values are means, ±SD (n = 3), DOC – dissolved organic carbon.

nutrients. This is in agreement with Kucbel et al. (2019) who used various household food waste types for composting in a GreenGood composter. The pH and EC values in water leachate ranged from 4.2 to 4.6 and from 4.4 to 5.7 mS/cm, respectively.

2.2. Experimental design

There were two experiment types.

2.2.1. Composting in an electric composter

The composting experiment in the GreenGood electric composter (GG-10) took place on the canteen premises of the Czech University of Life Sciences Prague. Three composting variants were prepared.

- substrate 50% vol. + paper 50% vol. (variant I; PAP)
- substrate 50% vol. + paper 25% vol. + apple pomace 25% vol. (variant II; AP)
- substrate 50% vol. + paper 25% vol. + horse manure 25% vol. (variant III; HM)

Variants were inserted in sequence into the composter and monitored. Every 1, 12, 24, 48, and 120 h, 3 samples were taken up for the determination of disintegration. The disintegration was examined by a 2 mm screen mesh sieve, as specified in European standard EN 13432: "After 12 weeks of composting, no more than 10% of the original dry matter of the test material shall pass through a sieve with > 2 mm screen mesh size" according to European Standard EN 13432. It would be appropriate to revise this standard to make it clear that more than 90% of the composted material must pass through a sieve. For full accuracy, it could be mentioned whether it is a 2 mm diameter mesh or 2 × 2 mm mesh. However, a 2 mm mesh size is commonly used to obtain dry fine soil rather than compost. Therefore, the extra sizes of 5 mm and 9 mm were also chosen. The weight of undersized and oversized fractions was determined for both dry and wet samples. Samples taken up after 120 h were divided into two parts.

2.2.2. Vermicomposting in Worm Factory vermicomposters

Three variants were prepared.

- paper 100% vol. (vermicompost I; PAP)
- paper 50% vol. + apple pomace 50% vol. (vermicompost II; AP)
- paper 50% vol. + horse manure 50% vol. (vermicompost III; HM)

There were always two layers in these vermicomposters. In the first bottom layer was an earthworm substrate (about 50 pieces of *Eisenia andrei* earthworms/L), and in the second top layer was the paper itself or the biowaste mixture. The experiment was conducted for four months. A sample was taken each month to determine the disintegration of vermicomposted paper, and the number and biomass of earthworms. The disintegration was investigated for the mentioned reasons using three sieves with mesh sizes of 9, 5, and 2 mm. The weight of undersized and oversized fractions was determined for both dry and wet samples.

Earthworms in vermicomposters were no longer fed, and only moisture was regulated. At the experiment end, 3 samples were taken up from each vermicomposter, only from the upper layers (samples from the earthworm substrate were not collected), which were subsequently analyzed. From these samples, earthworms were removed for number and biomass determination.

From both experiment types, the first samples (30 g of each sample) were stored in a refrigerator at 4 °C, the second samples (100 g of each sample) were dried in an oven at 35 °C to constant weight. The pH and EC values were measured from the first sample. From the second sample, the dry matter, the total contents of C, N, and Ca, and the total and available contents of P, K, and Mg were determined. Furthermore, vermicompost was evaluated according to a phytotoxicity test. This test revealed the maturity and intensity of organic substances' decomposition in vermicompost.

2.3. Agrochemical analyses

The pH value and EC were determined from the aqueous solution. The 10g sample was weighed and subsequently filled with 50 ml of demineralized water. The suspension was shaken using a mechanical shaker. The pH was then measured using a WTW pH 340i pH meter. Subsequently, the suspension was filtered to determine the EC according to EN 15933. The EC was measured using a WTW Cond 730 inoLab® conductometer.

Samples were removed from the oven after drying and weighed to determine dry matter content. Furthermore, the samples were ground for subsequent analyses. The total carbon and nitrogen content were determined using a CHNS Vario MACRO cube analyzer (Elementar Analyser Systeme GmbH, Germany). Approximately 25 mg of each sample was burned in a catalytic furnace of this apparatus, and the desired values were determined using a thermal conductivity detector.

The total contents of macroelements and microelements were determined by wet decomposition using a closed microwave heating system Ethos 1, MLS GmbH, Germany. Furthermore, the available contents of macroelements for plants (K, Mg, P) were determined. The contents were measured in CAT extracting reagent (0.01 mol/L $CaCl_2$ and 0.002 mol/L DTPA diethylentriamine pentaacetic acid) according to BSI EN 13651, 2001. Measurements of total and available element contents were made using inductively coupled plasma optical emission spectrometry (ICP - OES Varian VistaPro, Australia).

Furthermore, vermicompost was evaluated according to a phytotoxicity test (modified from Zucconi et al., 1981). This test revealed the maturity and extent of organic substances' decomposition in vermicompost. The 10g sample was weighed into a flask and 400 ml of demineralized water was added. The mixture was shaken for 2 h and then filtered to obtain clear leachate. The test was performed in 5 cm diameter Petri dishes. Filter paper was placed in each dish and covered with 1 ml of leachate. Eight cress seeds were added to each dish. In this way, 10 replications of each sample were generated. Control samples (demineralized water was used instead of leachate) were set up in 10 dishes. The closed dishes were placed in an incubator at 28 °C for 24 h under complete darkness. After this time, the germinated seeds were counted and the root lengths were measured. The germination index (GI) marked as equation (1) was calculated as a percentage of the measured data:

$$GI\ (\%) = 100*(gs*ls)/(gc*lc) \tag{1}$$

where g_s = sample germination (%), g_c = control germination (%), l_s = average sample root length (mm), l_c = average control root length (mm).

2.4. Statistical analyses

To determine 90% standard compliance, a relative frequency test (U) was used according to the computational relationship (equation 2):

$$U = \frac{p - \pi_0}{\sqrt{\frac{\pi_0(1-\pi_0)}{n}}} \tag{2}$$

where p is proportion of frequency (f) and file range (n). π_0 is the specified standard, in this case 0.9 for determination of 90% standard compliance.

To meet the requirements for parametric testing, a normality test was first performed. In the case of no rejection of the null hypothesis, a Leven test was performed for homogeneity of variances followed by an Analysis of variance (ANOVA) test and a post hoc Tukey's honestly significant difference (HSD) test method. In the case of non-compliance with data normality or variance homogeneity, the Kruskal-Wallis nonparametric test was used, and a Bonfferin correction was performed to determine the relationship between the variables and the significance of the relationship. IBM SPSS Statistics 25 was used for statistical calculations. Auxiliary calculations were performed in Microsoft Excel.

3. Results and discussion

3.1. Composting in an electric composter

3.1.1. Agrochemical properties

Table 2 shows the agrochemical properties measured in the three variants after the composting process in a GreenGood electric composter. The dry matter content varied substantially in each variant. This was due to the varying need for wetting, by the decomposition rate, and by drying of the individual variants. Two of the main principles of an electric composter are mixing and drying. For this reason, it is necessary to moisten the composted material. Therefore, leachate is not created here as in classic composting in outdoor conditions. The pH values were almost identical in variants I and III, and they resembled variant II. These acidic pH values were mainly due to the input substrate used in the electric composter, which originated from acid food waste. This type of electric composter rapidly processes specialty food waste using microorganisms of the genus *Acidulo*, which live in an acidic environment. Electrical conductivity (EC) expresses the content of soluble salts. If the value is greater than 3000 μS/cm (Lazcano et al., 2008) or 4000 μS/cm (Karak et al., 2013), it indicates immaturity and phytotoxicity of the material. Composts from household food waste produced in automatic composters reached values of 5170 and 5660 μS/cm (Kucbel et al., 2019). All three investigated variants in this study exhibited high salinity values ranging from 4870 to 8346 μS/cm. The high dissolved organic carbon (DOC) values in this material also confirmed immaturity. The values found were several times greater than the optimal values for mature compost reported (<0.4% DOC (Zmora-Nahum et al., 2005), <0.5% DOC (Eggen and Vethe 2013), <1.0% DOC (Hue and Liu 1995), <1.7% (Bernal et al., 1998)). The values for pH, EC, and DOC indicate unsuitable material for fertilization, and therefore the phytotoxicity test using seed germination was not carried out.

Nutrient contents, essential for plant nutrition, are a key parameter for compost agronomic value (Barthod et al., 2018). Fig. 1 shows the total and available phosphorus, potassium, and magnesium content of the tested variants. The available phosphorus content ranged from 62 to 84% of the total content. The greatest total phosphorus content in variant I reached an average of 2523 mg/kg,

Table 2
Values of basic agrochemical properties of composts.

	Variant I (PAP)	Variant II (AP)	Variant III (HM)
Dry matter (%)	55 ± 5.9	89.4 ± 0.99	94.4 ± 0,67
pH/H_2O	4.9 ± 0.16	4.7 ± 0.02	4.9 ± 0.01
EC (μS/cm)	4870 ± 138.9	7540 ± 346.9	8346 ± 106.9
C:N ratio	20.2 ± 0.27	21.6 ± 1.55	19.5 ± 1.94
C_{tot} (%)	45.4 ± 0.6	44.8 ± 0.30	43.7 ± 0.72
N_{tot} (%)	2.2 ± 0.11	2.1 ± 0.21	2.3 ± 0.23
$N_{mineral}$ (mgN/kg)	26.6 ± 0.6	70.8 ± 5.9	68.4 ± 2.4
DOC (mgC/kg)	93,319 ± 4156	96,480 ± 6275	76,608 ± 4355

Values are means, ±standard deviation (n = 3), DOC – dissolved organic carbon.

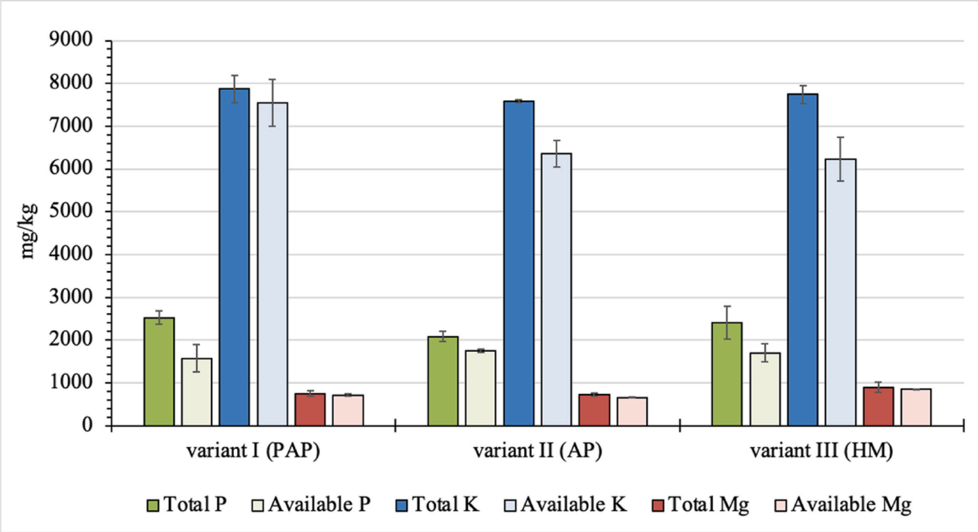

Fig. 1. Total and available contents of phosphorus, potassium, and magnesium in variants from an electric composter. Values are means, ± standard deviation (n = 3).

its available form was 62.6%. The greatest available content was in variant II, its average content was 1750 mg/kg. It was 84% of the total content. In all variants, the total potassium content was similar, ranging from 7576 to 7867 mg/kg. Variant I contained the greatest contents of total (7867 mg/kg) and available (5339 mg/kg, i.e. 95.9%) potassium. In variants II and III the available contents constituted 83.9% and 80.4% of the total content. The available content of magnesium was very great in all three variants, always ranging from 90 to 96% of the total content. Variant III contained the greatest total and available contents of magnesium, where the average total content was 896 mg/kg and the average available content was 853 mg/kg.

Variant III contained the greatest total calcium content (11,182 mg/kg) as illustrated in Fig. 2.

In compost based on biogas residues and spent mushroom substrate composted for 105 d, the available portions constituted 4% and almost 100% of the total contents of P and K, respectively (Meng et al., 2019).

3.1.2. Risk element contents

The contents of risk elements were measured in variants I, II, and III (Table 3). None of the contents exceeds the limit values pursuant to the Decree of the Ministry of Agriculture Czech Republic No. 474/2000 Coll., "On setting requirements for fertilizers" with these limit values in mg/kg of dry matter: Cd = 2, Pb = 100, Hg = 1, As = 30, Cr = 100, Cu = 150, Ni = 50, Zn = 600. The addition of apple pomace 25% vol. (variant II; AP) decreased the total content of risk elements unlike manure, which increased the content of these elements. Nevertheless, even in variant III, the contents of Cd, Pb, Hg, As, Cr, Cu, Ni, and Zn were 33, 55, 100, 20, 12, 32, 26, and 22 times less than the limit values, respectively. Therefore, the compost is suitable for use as an organic fertilizer from this point of view. Previously, kitchen waste from restaurants was composted in a GreenGood electric composter (Kliopova et al., 2019). The 25 cycles were performed, and each lasted 24 h. The contents of risk elements also did not exceed the limit values shown above but were mostly greater than in our study. This could be due to very different input materials, such as boned meat, fish waste, soup, and tea residues.

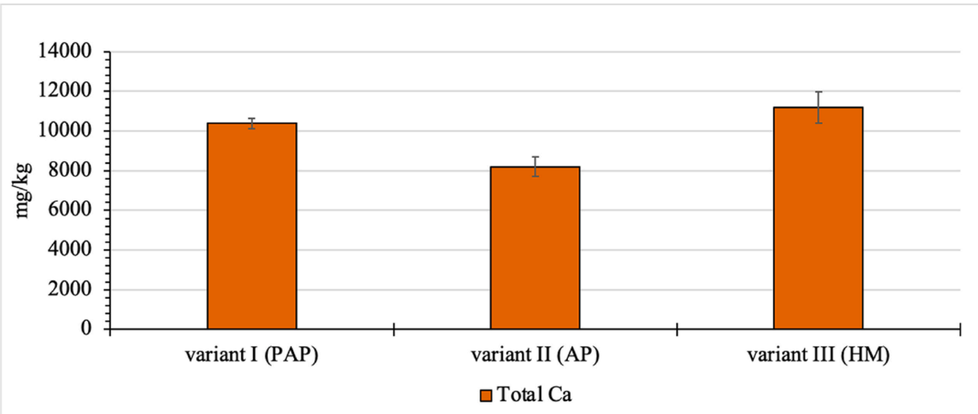

Fig. 2. Total calcium contents in variants from an electric composter. Values are means, ± standard deviation (n = 3).

Table 3
Content of risk elements in composts.

mg/kg of dry matter								
	Cd	Pb	Hg	As	Cr	Cu	Ni	Zn
Var. I	<0.05	0.4 ± 0.35	< 0.01	<1.5	8.4 ± 0.33	3.2 ± 0.56	1.3 ± 0.14	18.3 ± 2.89
Var. II	<0.05	0.5 ± 0.04	< 0.01	<1.5	5.7 ± 0.39	2.7 ± 0.17	1.2 ± 0.79	14.6 ± 0.56
Var. III	0.06 ± 0.020	1.8 ± 0.79	< 0.01	<1.5	8.2 ± 1.18	4.6 ± 0.68	1.9 ± 0.27	27.1 ± 5.15

Values are means, ±standard deviation (n = 3).

3.1.3. Disintegration of the composted material

To determine whether the disintegration requirement was met, a relative frequency test with a set value of $P_0 = 0.9$ was performed. The disintegration of the material must be at least 90%. The upper index and the letter "a" or "b" (Table 4) illustrate whether a null hypothesis can be rejected or accepted according to this 95% probability test. The zero hypothesis for this relative frequency test was: "The disintegration of compostable material is more than 90%." The letter "a" indicates the rejection of the null hypothesis at the level of significance of 5%, the letter "b" denotes the acceptance of the null hypothesis at the level of significance of 5%, or the rejection of the null hypothesis, with the test value being greater than the critical value of the normal distribution at one-sided testing $u_{(\alpha=0.1)} = 1.6448$, so that samples that have a disintegration of, for example, 100% were not rejected. According to the statistical test performed, none of the samples from variant I (substrate with paper itself) met a disintegration requirement greater than 90% with 95% probability (Table 4). However, it was a control variant with a very great one-time paper addition with a wide C:N ratio, and this compliance with the requirement was not expected. According to a statistical test with 95% probability, both wet and dry samples met the variant II requirement after composting 24 h when sieving with 9 mm mesh. The average undersize portions of wet and dry samples after 24 h were 88.3% and 84.3%, but the test evaluated these samples as satisfying the disintegration requirement. Wet and dry samples sieved through a 5 mm mesh screen fulfilled the requirement after composting for 48 h. When sieving wet and dry samples through a 2 mm mesh screen the disintegration requirements were fulfilled in 120 h.

In variant III, where substrate, paper, and horse manure were composted, the dry and wet sample requirements were fulfilled after processing for 24 h (for a 9 mm mesh screen). When sieved through a 5 mm mesh screen the dry and wet samples met the statistical test requirement after 48 h. When sieving both wet and dry samples through a 2 mm mesh screen, the disintegration requirement was also met after 48 h.

Table 4
Disintegration % during composting in an electric composter (variants I, II, and III in wet and dry samples).

Variant I (substrate + paper)					
Wet sample	1st h	12th h	24th h	48th h	120th h
mesh 9 mm	49.7 ± 0.58^a	53.3 ± 2.08^a	63.7 ± 1.15^a	69 ± 1.7^a	70 ± 1.0^a
mesh 5 mm	50.0 ± 1.0^a	52.3 ± 1.53^a	60.7 ± 0.58^a	66.3 ± 2.31^a	68 ± 2.6^a
mesh 2 mm	48.3 ± 2.31^a	50 ± 1.0^a	55.7 ± 2.08^a	58 ± 1.0^a	62.3 ± 1.53^a
Dry sample					
mesh 9 mm	48.7 ± 1.53^a	55.7 ± 2.31^a	62.3 ± 2.08^a	67.7 ± 2.31^a	70 ± 1.0^a
mesh 5 mm	49.3 ± 0.58^a	54.7 ± 0.58^a	60.3 ± 1.15^a	64.7 ± 2.89^a	67.7 ± 2.31^a
mesh 2 mm	46.3 ± 1.15^a	51.7 ± 0.58^a	54.7 ± 1.53^a	60 ± 1.0^a	64.3 ± 2.08^a
Variant II (substrate + apple pomace + paper)					
Wet sample	1st h	12th h	24th h	48th h	120th h
mesh 9 mm	74.7 ± 0.58^a	77.7 ± 0.58^a	88.3 ± 0.58^b	95.7 ± 0.58^b	99.3 ± 1.15^b
mesh 5 mm	53.7 ± 1.53^a	54.3 ± 2.08^a	75.3 ± 0.58^a	93.3 ± 1.53^b	97 ± 1.0^b
mesh 2 mm	44.7 ± 0.58^a	51.7 ± 1.53^a	71 ± 2.65^a	84 ± 1.7^a	94.7 ± 1.58^b
Dry sample					
mesh 9 mm	74 ± 1.0^a	78.3 ± 0.58^a	84.3 ± 0.58^b	94.3 ± 0.58^b	98.3 ± 1.53^b
mesh 5 mm	55.3 ± 3.21^a	58.3 ± 0.58^a	68.3 ± 0.58^a	91.7 ± 0.58^b	95.3 ± 0.58^b
mesh 2 mm	40.3 ± 1.53^a	49.7 ± 0.58^a	58.3 ± 2.08^a	83.7 ± 2.52^a	91 ± 1.0^b
Variant III (substrate + horse manure + paper)					
Wet sample	1st h	12th h	24th h	48th h	120th h
mesh 9 mm	74.7 ± 0.58^a	78.7 ± 0.58^a	87 ± 2.0b	92.7 ± 0.58^b	100 ± 0^b
mesh 5 mm	63.3 ± 4.16^a	69.7 ± 2.08^a	79.7 ± 0.58^a	91 ± 1.0^b	99.3 ± 1.15^b
mesh 2 mm	48 ± 3.0^a	47.3 ± 0.58^a	60.3 ± 1.53^a	84.7 ± 1.53^b	97.7 ± 0.58^b
Dry sample					
mesh 9 mm	75.7 ± 0.47^a	75.3 ± 1.53^a	87.3 ± 1.53^b	94.3 ± 1.53^b	100 ± 0^b
mesh 5 mm	68.3 ± 0.94^a	66.7 ± 1.53^a	78.7 ± 0.58^a	90.7 ± 0.58^b	99 ± 1.0^b
mesh 2 mm	48 ± 2.2^a	49.3 ± 0.58^a	81.7 ± 1.53^a	88 ± 1.0^b	98 ± 1.0^b

Values are means, ±standard deviation (n = 3). The indices show statistically significant differences according to the relative frequency test ($u \geq u\alpha$).

3.2. Vermicomposting in Worm Factory vermicomposters

3.2.1. Agrochemical properties

Agrochemical properties were measured after the vermicomposting process (Table 5). The dry matters of vermicomposts were similar, ranging from 21% to 28.2%. Further, vermicomposters II and III exhibited similar pH values, which reached 8.4 and 8.8, thus slightly alkaline. The electrical conductivity was different in all variants, the least was in vermicomposter I (405 μS/cm) and the greatest in vermicomposter III (1046 μS/cm). C:N ratios were also different, ranging from 13.2:1 (vermicomposter III) to 35.4: 1 (vermicomposter I).

Fig. 3 shows the total and available phosphorus, potassium, and magnesium contents. The greatest total phosphorus content in vermicomposter III reached 5267 mg/kg. In vermicomposter I, the available phosphorus content was 347 mg/kg (61.2% of the total), in vermicomposter II this content was 1024 mg/kg (51.3%), and in vermicomposter III only 650 mg/kg (12.3%). Fig. 3 shows that the total potassium content trends upward the same as phosphorus from vermicomposter I and vermicomposter III. The greatest total content in vermicomposter III reached 16,923 mg/kg. The available potassium contents were greater and reached 73.3% (vermicomposter I), 88.8% (vermicomposter II), and 67.2% (vermicomposter III). Vermicomposter II had the greatest content of available potassium (11,827 mg/kg). In vermicomposter I, the available potassium was 3151 mg/kg, and in vermicomposter III 11,372 mg/kg, which was only slightly less than in vermicomposter II. The total magnesium content was significantly greatest in vermicomposter III (4061 mg/kg). The available magnesium contents were significantly different from the total contents at 70.6% for vermicomposter I, 26.6% for vermicomposter II, and only 7.6% for vermicomposter III. The available magnesium content values were similar at 242 mg/kg (vermicomposter I), 336 mg/kg (vermicomposter II), and 307 mg/kg (vermicomposter III).

Total calcium content was greatest in vermicomposter III (Fig. 4). Total contents were 1434 mg/kg (vermicomposter I), 4848 mg/kg (vermicomposter II), and 24,012 mg/kg (vermicomposter III).

In another experiment, apple pomace was vermicomposted in volume proportions of 25%, 50%, and 75% with straw. The resulting vermicomposts exhibited slightly acidic to neutral pH (5.9–6.9), and optimal EC (1.6–4.4 mS/cm) and C:N ratio (13–14). The total content of nutrients increased during vermicomposting for all treatments with the following average final values: N = 2.8%, P = 0.85%, K = 2.3%, and Mg = 0.38%. Adding straw to apple pomace did not enhance earthworm biomass but increased the

Table 5
Basic agrochemical properties of materials after vermicomposting completion.

	Vermicomposter I (PAP)	Vermicomposter II (AP)	Vermicomposter III (HM)
Dry matter (%)	28.2 ± 1.26	21 ± 0.2	24.2 ± 0.41
pH/H_2O	7.4 ± 0.02	8.4 ± 0.09	8.8 ± 0.07
EC (μS/cm)	405 ± 9.5	980 ± 5.6	1046 ± 13.4
C:N ratio	35.4 ± 4.99	26.6 ± 0.81	13.2 ± 0.52
C_{tot} (%)	42.1 ± 0.52	43.2 ± 0.15	25.6 ± 1.45
N_{tot} (%)	1.2 ± 0.11	1.6 ± 0.14	1.9 ± 0.17
$N_{mineral}$ (mgN/kg)	39.8 ± 1.2	40.1 ± 0.9	31.6 ± 0.4
DOC (mgC/kg)	5354 ± 1351	8026 ± 1283	9335 ± 802

Values are means, ±standard deviation (n = 3), DOC – dissolved organic carbon.

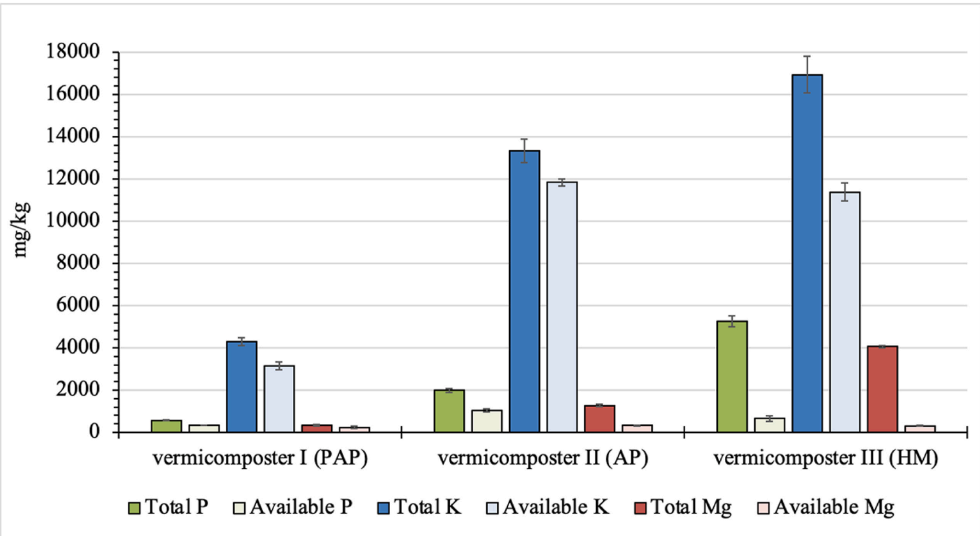

Fig. 3. Total and available contents of phosphorus, potassium, and magnesium in variants from vermicomposters. Values are means, ±standard deviation (n = 3).

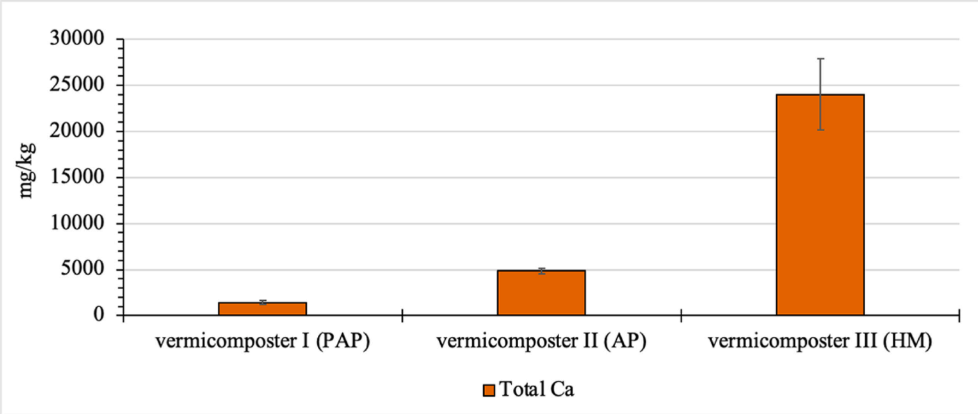

Fig. 4. Total contents of calcium in variants from vermicomposters. Values are means, ±standard deviation (n = 3).

available content of nutrients during vermicomposting. The available P, K, and Mg contents in vermicomposts constituted approximately 16%, 62%, and 15% of the total contents, respectively, and these values were 60%, 45%, and 25% greater than in the control composts (Hanc and Chadimova 2014). The available P and K contents in vermicompost from kitchen bio-waste constituted approximately 50% and 5% of the total contents, respectively. Greater available P contents were found in this material supplemented with woodchips than paper (Hanc and Pliva 2013).

3.2.2. Qualitative characteristics

Table 6 shows the contents of risk elements that were measured in vermicomposters I, II, and III. None of the contents exceeds the limit values pursuant to Decree of theMinistry of Agriculture No. 474/2000 Coll., “On setting requirements for fertilizers”.

Table 7 shows the quality properties of the material in vermicomposters I, II, and III at the process end. According to the requirements of the Czech State Standard 46 5736. “Vermicomposts”, only vermicomposter III fulfilled all requirements. Humidity can be treated later by drying. Vermicomposter I did not meet the C:N requirement and the P and K contents were insufficient. The C:N was 35.4:1 in vermicomposter I and the requirement was a maximum of 30:1. However, variant I was the control with paper itself, where no significant vermicomposting was expected. In vermicomposter II insufficient phosphorus content was reached to meet the legislative requirement (0.6% required; 0.46% determined). This was due to the prominence of paper (50% vol.) in the original mixture that was supplied, and also due to the low P content in apple pomace. However, this is acceptable for the use of vermicompost as fertilizer.

3.2.3. Number and biomass of earthworms

The earthworm number varied widely in each vermicomposter (Table 8). In vermicomposters I and II the earthworm number grew slowly during the observation. In vermicomposter III (the variant with horse manure) the earthworm number grew to the third month and subsequently dropped sharply, which was a sign of the lack of earthworm feed, and hence complete vermicomposting. In the third month in vermicomposter III, the earthworm number reached 625 pieces in 1 kg of material, the greatest in any of the treatments during the experimental period. By statistical testing, there was no statistically significant difference in the earthworm number between the vermicomposters in the first month. As early as the second month, vermicomposter I differed significantly from II and III. Vermicomposter II and III did not differ significantly from each other. There were statistically significant differences across all vermicomposters in the third month. For the fourth month, a statistically significant difference was found in vermicomposter II, which differed from I and III. From the second to the fourth month, the prerequisites for testing were met, both in data normality and homogeneity of variance. Tukey's test was used to evaluate significant differences. For the first month, the Kruskal-Wallis test was used because of the lack of data normality. Using a non-parametric test, it is possible to explain the reduced predictive ability for results in the first observation month, although large differences in mean values for individual vermicomposters were noted.

According to Table 9, earthworm biomass (in g earthworms/kg of vermicomposted material) almost copied their numbers. Only in vermicomposter III was the biomass decline not as sharp as the decrease in the number of individuals. Throughout most of the experi-

Table 6
Content of risk elements in vermicomposters at the process end.

mg/kg of dry matter								
	Cd	Pb	Hg	As	Cr	Cu	Ni	Zn
Vermic. I	<0.05	0.2 ± 0.07	< 0.01	<1.5	1.5 ± 0.58	3.1 ± 0.48	0.4 ± 0.21	5.2 ± 1.45
Vermic. II	<0.05	0.5 ± 0.08	< 0.01	<1.5	<0.05	12.7 ± 0.43	0.8 ± 0.45	18.8 ± 1.08
Vermic. III	<0.05	6.9 ± 0.12	< 0.01	<1.5	14.5 ± 1.88	28.4 ± 2.12	7.1 ± 0.35	123.1 ± 1.45

Values are means, ±standard deviation (n = 3).

Table 7
Qualitative properties after four months of vermicomposting (vermicomposter I, II, III).

	Czech State Standard 46 5736	Vermicomposter	Value
Humidity in %	50–70	I (PAP)	71.8
		II (AP)	79
		III (HM)	75.9
Total nitrogen as N recalculated on dry sample in %	Min. 1	I (PAP)	1.2
		II (AP)	1.6
		III (HM)	2
C:N ratio	Max. 30	I (PAP)	35.4:1
		II (AP)	26.6:1
		III (HM)	13.2:1
pH value	6.0–9.0	I (PAP)	7.4
		II (AP)	8.4
		III (HM)	8.8
P content in dry matter in mg/kg		I (PAP)	567
		II (AP)	1996
		III (HM)	5266
Content of P_2O_5 in dry matter in mg/kg	Min. 6000	I (PAP)	1299
		II (AP)	4571
		III (HM)	12,061
Content of K in dry matter in mg/kg		I (PAP)	4297
		II (AP)	13,322
		III (HM)	16,922
Content of K_2O in dry matter in mg/kg	Min. 10,000	I (PAP)	5178
		II (AP)	16,054
		III (HM)	20,393

Values are means (n = 3).

Table 8
Earthworm number in all vermicomposter variants within four months.

Vermicomposter/Number of earthworms (pieces)	Vermicomposter I	Vermicomposter II	Vermicomposter III
1st month	93.3 ± 16.07^{a}	247 ± 23.3^{a}	238 ± 15.3^{a}
2nd month	137 ± 25.2^{a}	302 ± 45.0^{b}	353 ± 33.3^{b}
3rd month	158 ± 15.3^{a}	342 ± 22.9^{b}	625 ± 12.7^{c}
4th month	217 ± 8.2^{a}	443 ± 91.8^{b}	231 ± 35.0^{a}

Values are means, ±standard deviation (n = 3). The indices show statistically significant differences according to the Kruskal-Wallis test in the 1st month and Tukey's test in the 2nd to 4th month ($P \leq 0{,}05$).

Table 9
Earthworm biomass in all vermicomposter variants within four months.

Vermicomposter/Biomass (g of earthworms in kg of material)	Vermicomposter I	Vermicomposter II	Vermicomposter III
1st month	10.5 ± 0.87^{a}	18.6 ± 1.50^{b}	24.3 ± 0.29^{c}
2nd month	13.5 ± 1.80^{a}	23.6 ± 3.86^{b}	35.2 ± 1.04^{c}
3rd month	15.2 ± 0.76^{a}	25 ± 2.2^{b}	51.1 ± 1.35^{c}
4th month	16.1 ± 0.35^{a}	31.5 ± 8.26^{a}	27.5 ± 1.36^{a}

Values are means, ±standard deviation (n = 3). The indices show statistically significant differences according to the Kruskal-Wallis test at month four, and Tukey's test at month one to month three ($P \leq 0{,}05$).

ment, the greatest biomass was in vermicomposter III. For earthworm biomass, ANOVA was performed for the first three months concerning assumptions. Subsequent Tukey's test revealed a statistically significant difference between vermicomposters in all three periods. For the fourth month, the Kruskal-Wallis test was performed due to a lack of data homogeneity, and there was no statistically significant difference between groups ($P = 0.65$). The null hypothesis, which argued that there is no statistically significant difference between vermicomposters was not rejected. Sharma and Garg (2018) vermicomposted cow dung together with rice straw and paper waste. Proportion of paper waste was 5, 10, and 20%. The increase in earthworm biomass was directly proportional to the proportion of paper. In the variant with the highest paper proportion the biomass increased from 316 to 1413 mg (4.5-fold) with a peak at day 75. In variant with horse manure of this experiment, there was also an increase in earthworm biomass up to the 3rd month.

3.2.4. Phytotoxicity test

Germination index (GI) is a significant biological indicator for assessing compost maturity and phytotoxicity (Zhang and Sun, 2019). The compost is considered mature when the GI reaches 80-90% (Gabhane et al., 2012). All nine samples in this experiment were tested in ten replications. A control was also performed in ten repetitions and then recalculated to the average by which the germination index was calculated. The average root length for controls was over 7 mm, the germination rate was 97.2% and the germination index was 100.2.

The results for vermicomposter I show that the material was only partially mature (Table 10). The germination index was 65.3%, and the average root length was only 5.2 mm. The material was therefore unusable according to the germination index and its application would be uneconomical, which is understandable because it was not vermicompost.

Vermicomposter II where apple pomace was vermicomposted achieved the best germination index at 94% and the average root length was 6.6 mm, which is also the best of all variants. This germination index points to well-mature vermicompost.

Vermicomposter III where paper with horse manure was vermicomposted exhibited a germination index of 92.2% and an average root length of 6.5 mm. These results confirm well-mature vermicompost.

In studies of Guo et al. (2012) focused on composting of pig feces and corn stalks with different C:N ratios (15; 18; 21), the compost with the lowest initial C:N ratio was significantly different from the other treatments and had the lowest and thus the worst germination index (53–66%). These results are not consistent with our study due to the very great C:N ratio in the paper itself and its difficult degradability without the addition of another bulking agent.

3.2.5. Disintegration of the vermicomposted material

In vermicomposter I, where only paper was vermicomposted, little decomposition of the material occurred within four months. Thus, the material could hardly be sieved, and almost nothing passed through the sieve (Table 11). Only the wet sample was sieved after three and four months on a 9 mm mesh screen. At most 10% of the material passed through the sieve, and therefore in no case could this control variant satisfy the disintegration requirement of more than 90%.

For vermicomposter II where paper and apple pomace were vermicomposted, according to the statistical test, the requirement for disintegration was met by dry and wet samples after three months of vermicomposting (in the case of sieving on a 9 mm mesh screen). Furthermore, after three months, the disintegration requirement was satisfied when the wet sample was sieved on a 5 mm mesh screen. The disintegration of the dry sample was met after four months according to the statistical test when measured on a 5 mm mesh screen. More than 90% of the material also passed through the smallest mesh screen after four months.

In vermicomposter III decomposition was faster than in the previous vermicomposters. Wet samples were sieved more easily than dry samples. According to the statistical test, the wet samples fulfilled the requirement for disintegration after only two months of vermicomposting. More than 90% of the dry material passed through the 5 and 9 mm mesh screens after three months, and a 2 mm mesh screen after four months.

In a previous experiment with kitchen waste (50% vol.) + paper (50% vol.) the proportions of three particle size fractions (>12, 12-5, and <5 mm) were assessed in the composts and vermicomposts after five months of the composting and vermicomposting processes. Composts and vermicomposts exhibited clear differences. Particles smaller than 5 mm represented almost 100% of the resulting fresh vermicomposts produced. The influence of earthworms on the efficiency of biological waste treatment was significant (Hanc and Dreslova 2016). The physical, mechanical, and agronomical attributes of produced vermicompost could be engineered to reduce their storage, handling, and utilization costs and environmental impacts. Pelletizing and drying are promising techniques to achieve these goals (Sarlaki et al., 2021). This study focused on the composting and vermicomposting of greaseproof wrapping paper together with apple pomace and horse manure. If other additives were used, different agrochemical and other properties of the resulting products would be achieved. These properties would also be affected by the use of another composting technology (e. g. in windrows) or large-scale vermicomposting in outdoor conditions.

Table 10
Phytotoxicity test results in vermicomposters.

	vermicomposter I (PAP)	
Replication	Average root length (mm)	Germination index (%)
1st	5.2	65.7
2nd	5	67.2
3rd	4.8	63.1
Average	5.00	65.3 ± 17.75
	vermicomposter II (AP)	
Replication	Average root length (mm)	Germination index (%)
1st	6.8	98.58
2nd	6.5	93.01
3rd	6.4	90.69
Average	6.6	94 ± 10.5
	vermicomposter III (HM)	
Replication	Average root length (mm)	Germination index (%)
1st	6.8	95
2nd	6.4	91
3rd	6.3	90.4
Average	6.5	92.2 ± 10.72

Table 11
Disintegration % during vermicomposting (variant I, II, and III in wet and dry samples).

Vermicomposter I (PAP)				
Wet sample	1st month	2nd month	3rd month	4th month
mesh 9 mm	0^{a}	0^{a}	6.7 ± 1.53^{a}	10 ± 1.0^{a}
mesh 5 mm	0^{a}	0^{a}	0^{a}	0^{a}
mesh 2 mm	0^{a}	0^{a} 0^{a} 0^{a}		
Dry sample				
mesh 9 mm	0^{a}	0^{a} 0^{a} 0^{a}		
mesh 5 mm	0^{a}	0^{a}	0^{a} 0^{a}	
mesh 2 mm	0^{a}	0^{a}	0^{a} 0^{a}	
Vermicomposter II (AP)				
Wet sample	1st month	2nd month	3rd month	4th month
mesh 9 mm	43 ± 1.0^{a}	46.3 ± 1.53^{a}	91.7 ± 3.51^{b}	97.3 ± 0.58^{b}
mesh 5 mm	29.3 ± 1.53^{a}	40.7 ± 0.58^{a}	84.7 ± 1.53^{b}	94.3 ± 0.58^{b}
mesh 2 mm	11.3 ± 3.06^{a}	24.7 ± 5.51^{a}	80 ± 1.0^{a}	91.7 ± 1.53^{b}
Dry sample				
mesh 9 mm	39.7 ± 0.58^{a}	62.3 ± 1.53^{a}	89 ± 1.0^{b}	97.7 ± 2.53^{b}
mesh 5 mm	34 ± 2.6^{a}	53.3 ± 1.53^{a}	83.7 ± 3.21^{a}	94.7 ± 2.53^{b}
mesh 2 mm	26.3 ± 1.53^{a}	41.3 ± 1.53^{a}	74 ± 2.6^{a}	90.3 ± 0.58^{b}
Vermicomposter III (HM)				
Wet sample	1st month	2nd month	3rd month	4th month
mesh 9 mm	77 ± 2.6^{a}	100 ± 0^{b} 100 ± 0^{b}	100 ± 0^{b}	
mesh 5 mm	65.3 ± 2.52^{a}	100 ± 0^{b}	100 ± 0^{b}	100 ± 0^{b}
mesh 2 mm	51.3 ± 1.53^{a}	85 ± 1.0^{b}	94.7 ± 2.52^{b}	95.3 ± 0.58^{b}
Dry sample				
mesh 9 mm	72.3 ± 0.58^{a}	75 ± 2.6^{a}	100 ± 0.58^{b}	100 ± 0^{b}
mesh 5 mm	41.3 ± 1.53^{a}	49 ± 1.0^{a}	93 ± 2.0^{b}	100 ± 0^{b}
mesh 2 mm	21 ± 1.0^{a}	26.7 ± 1.53^{a}	73 ± 4.4^{a}	97 ± 1.0^{b}

Values are means, ±standard deviation ($n = 3$). The indices show statistically significant differences according to the relative frequency test ($u \geq u\alpha$).

4. Conclusions

In terms of faster waste paper reduction, composting in the electric composter with the addition of organic waste was more efficient than vermicomposting. However, the material produced in this manner was not suitable as a soil amendment, unlike vermicomposts based on paper with apple pomace or manure. This was mainly due to the acidic pH and the extremely great electrical conductivity, which were caused by the input substrate, which was prepared based on food residues. The addition of input substrate to the tested material imitated the conditions of composting in an electric composter in restaurants. It was concluded that product from the electric composter was immature and phytotoxic. Therefore, it would be appropriate to continue with composting the material in the usual way, for example in turned piles or windrows. Vermicomposting took much longer than composting with a GreenGood, but the resulting variant with paper and manure appeared the most suitable as a soil amendment. The agrochemical properties of this variant were basically optimal. The greatest contents of total and available elements reached comparable values with vermicompost based on paper and apple pomace. According to the germination index, vermicomposts II and III containing apple pomace and horse manure were well-mature. The paper disintegration was the fastest with the addition of horse manure. Greaseproof wrapping paper does not need to end up in a landfill or an incinerator but can be composted or vermicomposted, and the products of these processes are used as organic fertilizer.

In next research on this topic, advanced sustainability tools, including techno-economic and life cycle assessment could be introduced. Integration of these tools can provide more reliable and accurate results than single approaches (Aghbashlo et al., 2022).

Author contributions

Conceptualization, methodology, investigation resources, writing and original draft preparation, project administration, funding acquisition - A.H. Data curation, visualization, sample and data collection – T.H. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Abbasi, S.A., Hussain, N., Tauseef, S.M., Abbasi, T., 2018. A novel FLippable Units Vermireactor Train System e FLUVTS e for rapidly vermicomposting paper waste to an organic fertilizer. J. Clean. Prod. 198, 917–930. https://doi.org/10.1016/j.jclepro.2018.07.040.

Acumen Research and Consulting, 2019. (Cit. 2022-10-25). https://www.globenewswire.com/news-release/2019/01/21/1702828/0/en/Greaseproof-Paper-Market-Worth-US-1-1-Billion-By-2025-Acumen-research-and-Consulting.html.

Aghbashlo, M., Hosseinzadeh-Bandbafha, H., Shahbeik, H., Tabatabaei, M., 2022. The role of sustainability assessment tools in realizing bioenergy and bioproduct systems. Biofuel Res. J. 9, 1697–1706. https://doi.org/10.18331/BRJ2022.9.3.5.

Badhwar, V.K., Singh, S., Singh, B., 2020. Biotransformation of paper mill sludge and tea waste with cow dung using vermicomposting. Bioresour. Technol. 318, 124097. https://doi.org/10.1016/j.biortech.2020.124097.

Barthod, J., Rumpel, C., Calabi-Floody, M., Mora, M.L., Bolan, N.S., Dignac, M.F., 2018. Adding worms during composting of organic waste with red mud and fly ash reduces CO_2 emissions and increases plant available nutrient contents. J. Environ. Manag. 222, 207–215. https://doi.org/10.1016/j.jenvman.2018.05.079.

Bernal, M.P., Paredes, C., Sánchez-Monedero, M.A., Cegarra, J., 1998. Maturity and stability parameters of composts prepared with a wide range of organic wastes. Bioresour. Technol. 63, 91–99. https://doi.org/10.1016/S0960-8524(97)00084-9.

Brennan, N.M., Evans, A.T., Fritz, M.K., Peak, S.A., von Holst, H.E., 2021. Trends in the regulation of per- and polyfluoroalkyl substances (PFAS): a scoping review. Int. J. Environ. Res. Publ. Health 18, 10900. https://doi: 10.3390/ijerph182010900.

BSI EN 13651, 2001. Soil Improvers and Growing Media - Extraction of Calcium Chloride/DTPA (CAT) Soluble Nutrients.

Czech State Standard 46 5736, 2018. "Vermicomposts", Czech Office for Standards, Metrology, and Testing. Prague, Czech Republic.

Eggen, T., Vethe, O., 2013. Stability indices for different composts. Compost Sci. Util. 9, 19–26. https://doi.org/10.1080/1065657X.2001.10702013.

European Standard EN 13432 Packaging – Requirements for Packaging Recoverable through Composting and Biodegradation – Test Scheme and Evaluation Criteria for the Final Acceptance of Packaging, 2000.

Gabhane, J., William, S.P.M.P., Bidyadhar, R., Bhilawe, P., Anand, D., Vaidya, A.N., Wate, S.R., 2012. Additives aided composting of green waste: effects on organic matter degradation, compost maturity, and quality of the finished compost. Bioresour. Technol. 114, 382–388. https://doi.org/10.1016/j.biortech.2012.02.040.

Ganguly, R.K., Chakraborty, S.K., 2021. Valorisation of toxic paper mill waste through vermicomposting: an insight towards cleaner engineering through alleviation of wastes. Clean. Eng. Technol. 2, 100070. https://doi.org/10.1016/j.clet.2021.100070.

Guo, R., Li, G., Jiang, T., Schuchardt, F., Chen, T., Zhao, Y., Shen, Y., 2012. Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. Bioresour. Technol. 112, 171–178. https://doi.org/10.1016/j.biortech.2012.02.099.

Hanc, A., Chadimova, Z., 2014. Nutrient recovery from apple pomace waste by vermicomposting technology. Bioresour. Technol. 168, 240–244. https://doi.org/10.1016/j.biortech.2014.02.031.

Hanc, A., Dreslova, M., 2016. Effect of composting and vermicomposting on properties of particle size fractions. Bioresour. Technol. 217, 186–189. https://doi.org/10.1016/j.biortech.2016.02.058.

Hanc, A., Pliva, P., 2013. Vermicomposting technology as a tool for nutrient recovery from kitchen bio-waste. J. Mater. Cycles Waste Manag. 15, 431–439. https://doi.org/10.1007/s10163-013-0127-8.

Hubbe, M.A., Pruszynski, P., 2020. Greaseproof paper products: a review emphasizing ecofriendly approaches. Bioresources 15, 1978–2004.

Hue, N.V., Liu, J., 1995. Predicting compost stability. Compost Sci. Util. 3, 8–15.

Karak, T., Bhattacharyya, P., Paul, R.K., Das, T., Saha, S.K., 2013. Evaluation of composts from agricultural wastes with fish pond sediment as bulking agent to improve compost quality. Clean: Soil, Air, Water 41, 711–723. https://doi.org/10.1002/clen.201200142.

Kliopova, I., Staniškiš, J.K., Stunženas, E., Jurovickaja, E., 2019. Bio-nutrient recycling with a novel integrated biodegradable waste management system for catering companies. J. Clean. Prod. 209, 116–125. https://doi.org/10.1016/j.jclepro.2018.10.185.

Kucbel, M., Raclavská, H., Růžičková, J., Švédová, B., Sassmanová, V., Drozdová, J., Raclavský, K., Juchelková, D., 2019. Properties of composts from household food waste produced in automatic composters. J. Environ. Manag. 236, 657–666. https://doi.org/10.1016/j.jenvman.2019.02.018.

Lazcano, C., Gómez-Brandón, M., Domínguez, J., 2008. Comparison of the effectiveness of composting for the biological stabilization of cattle manure. Chemosphere 72, 1013–1019. https://doi.org/10.1016/j.chemosphere.2008.04.016.

Meena, A.L., Karwal, M., Dutta, D., Mishra, R., 2021. Composting: phases and factors responsible for efficient and improved composting. Agric Food: e-Newsletter 3, 85–90. https://doi.org/10.13140/RG.2.2.21424.69125.

Meng, X., Liu, B., Zhang, H., Wu, J., Yuan, X., Cui, Z., 2019. Co-composting of the biogas residues and spent mushroom substrate: physicochemical properties and maturity assessment. Bioresour. Technol. 276, 281–287. https://doi.org/10.1016/j.biortech.2018.12.097.

Decree of the Ministry of Agriculture Czech Republic No. 474/2000 Coll., on Setting Requirements for Fertilizers, 2000.

Mu, D., Horowitz, N., Casey, M., Jones, K., 2017. Environmental and economic analysis of an in-vessel food waste composting system at Kean University in the. U.S. Waste Manage. 59, 476–486. https://doi.org/10.1016/j.wasman.2016.10.026.

Pandey, P.K., Cao, W., Biswas, S., Vaddella, V., 2016. A new closed loop heating system for composting of green and food wastes. J. Clean. Prod. 133, 1252–1259. https://doi.org/10.1016/j.jclepro.2016.05.114.

Paulapuro, H., 2000. Paper and Board Grades. Fapet Oy, Jyvaskyla.

Ravindram, B., Mnkeni, P.N.S., 2016. Bio-optimization of the carbon-to-nitrogen ratio for efficient vermicomposting of chicken manure and waste paper using *Eisenia fetida*. Environ. Sci. Pollut. Res. 23, 16965–16976. https://doi.org/10.1007/s11356-016-6873-0.

Ravindran, B., Wong, J.W.C., Selvam, A., Sekaran, G., 2016. Influence of microbial diversity and plant growth hormones in compost and vermicompost from fermented tannery waste. Bioresour. Technol. 217, 200–204. https://doi.org/10.1016/j.biortech.2016.03.032.

Sangamithirai, K., Jayapriya, J., Hema, J., Manoj, R., 2015. Evaluation of in-vessel co-composting of yard waste and development of kinetic models for co-composting. Int. J. Recycl. Org. Waste Agric. 4, 157–165. https://doi.org/10.1007/s40093-015-0095-1.

Sarlaki, E., Kermani, A.M., Kianmehr, M.H., Vakilian, K.A., Hosseinzadeh-Bandbafha, H., Ma, N.L., Aghbashlo, M., Tabatabaei, M., Lam, S.S., 2021. Improving sustainability and mitigating environmental impacts of agro-biowaste compost fertilizer by pelletizing-drying. Environ. Pollut. 285, 117412. https://doi.org/10.1016/j.envpol.2021.117412.

Sharma, K., Garg, V.K., 2018. Comparative analysis of vermicompost quality produced from rice straw and paper waste employing earthworm Eisenia fetida (Sav.). Bioresour. Technol. 250, 708–715. https://doi.org/10.1016/j.biortech.2017.11.101.

Sharma, K., Garg, V.K., 2022. Vermicomposting technology for organic waste management. In: Awasthi, M.K., Zhang, Z., Pandey, A. (Eds.), Current Developments in

Biotechnology and Bioengineering, Advances in Composting and Vermicomposting Technology. first ed., Elsevier, Netherlands, pp. 29–55.
Tan, E.C.D., Lamers, P., 2021. Circular bioeconomy concepts—a Perspective. Front.Sustain. 2, 701509. https://doi.org/10.3389/frsus.2021.701509.
Zhang, L., Sun, X., 2019. Improving green waste composting by addition of sugarcane bagasse and exhausted grape marc. Bioresour. Technol. 218, 335–343. https://doi.org/10.1016/j.biortech.2016.06.097.
Zmora-Nahum, S., Markovitch, O., Tarchitzky, J., Chen, Y., 2005. Dissolved organic carbon (DOC) as a parameter of compost maturity. Soil Biol. Biochem. 37, 2109–2116. https://doi.org/10.1016/j.soilbio.2005.03.013.
Zucconi, F., Pera, A., Forte, M., De Bertoldi, M., 1981. Evaluating toxicity of immature compost. Biocycle 2, 54–57.