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Wood ash admixture to organic wastes improves compost and its performance

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A B S T R A C T

Throughout Europe, increasing amounts of wood ash are produced from biomass incineration plants. Most of these ashes are currently landfilled, despite their nutrient and micronutrient contents. The aim of this research was to find a way to return wood ash from biomass incineration plants into the natural cycle of matter.

Three composts from source separated organic waste were produced with 0%, 8% and 16% ash admixture. The composting process was monitored by in situ measurements of temperature and CO_2 concentration in the windrows. Maturation of the composts was observed through the parameters basal respiration, microbial biomass, metabolic quotient, C_{org}, N_{tot}, C/N-ratio and plant growth tests with cress. Mature composts were further analysed for potential pH, electrical conductivity as well as for nutrient (Mg, K, P) and heavy metal contents. The process indicators showed that ash admixture had no adverse effects and all legal standards were met. All produced composts met the requirements of the Austrian Compost Ordinance (Compost Quality A or even A+).

In a field experiment – a recultivation trial on an alpine ski-run – we compared the effects of the three composts with an organic fertilizer and a mineral fertilizer. Best plant growth was found on the compost amended plots, followed by the organic fertilizer. Soil respiration measurements indicated a better performance of composts amended with 8% or 16% ash as compared to compost that did not contain ash.

Concluding it may be stated that up to 16% ash admixture to organic wastes does not impair the composting process but is even able to improve the product quality. However, it has to be made sure that only bottom ashes of low heavy metal contents are being used and strict quality control is implemented.

1. Introduction

According to the EU-Commission White Paper (KOM/97/0599) one of the goals of the EU is to raise the proportion of renewable energy to 12% of the total energy consumption. Among other measures, the construction of biomass combustion plants has been encouraged, and therefore increasing amounts of wood ash are starting to accumulate. Alone in Austria, around 100,000 t of ash are being produced each year. Most of this ash is landfilled at high cost, and alternatives are demanded.

Major nutrients found in ashes are K, Mg and Ca. P and microelements are present in smaller and variable amounts (Table 1). Nitrogen, which is essential for plant growth, is lacking. Beside the nutrients, pollutants are also found in the ashes; the concentration of heavy metals may vary greatly, depending on type of incineration, type of ash (bottom or cyclone ash), and source of fuel wood. However, bottom (or grate) ashes in many cases have low heavy metals and xenobiotic contaminations as has been shown in a review by Stockinger et al. (2006). Another problem for the use of ashes is the high pH (ranging from 12 to 13) and the salinity that may harm plant growth if ashes are not stabilized (Lundborg, 1998).

The nutrient and micronutrient contents suggest a use of ash as fertilizer, either pure, pelleted or in combination with other materials (in particular, nitrogen containing compounds). One option is to mix it with organic wastes and produce compost. As background information, maximum permissible values according to the Austrian Compost Ordinance – that currently allows a maximum of 2% admixture – are given in Table 3. The present investigation aims at challenging this limit value.

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Table 1
Average composition of wood ashes (mixtures of bottom and cyclon-fly ashes) produced in Austria (Obernberger, 1994, 1997)

	Bark ash (n = 12)	Ash from wood chips (n = 12)
pH	12.7	12.8
Electrical conductivity (mS cm^{-1})	9.2	9.8
C_{org} (% d.m.)	0.8	1.3
P (% d.m.)	0.74	1.57
K (% d.m.)	4.23	5.56
Ca (% d.m.)	30.2	32.0
Mg (% d.m.)	3.92	2.89
Na (% d.m.)	0.59	0.45
Al (% d.m.)	3.76	2.43
Fe (% d.m.)	2.45	1.61
Mn (% d.m.)	1.16	1.32
Cu (mg kg^{-1})	87.8	127
Zn (mg kg^{-1})	619	376
Co (mg kg^{-1})	23.9	15.3
Mo (mg kg^{-1})	4.8	1.7
As (mg kg^{-1})	11.4	8.2
Ni (mg kg^{-1})	94.1	61.5
Cr (mg kg^{-1})	133	54.1
Pb (mg kg^{-1})	25.3	25.4
Cd (mg kg^{-1})	3.9	4.8
V (mg kg^{-1})	58.4	42

Finnish authors found that fertilization with ashes caused a long-term elevation of pH (Perkiömäki and Fritze, 2002; Saarsalmi et al., 2004), with a major role of carbonates, oxides and hydroxides of Ca, Mg and K (Vance, 1996; Perkiömäki and Fritze, 2002). However, due to the mobility of these basic ions, in particular of K (Khana et al., 1994), pH and cation concentration declined several years after application. Saarsalmi et al. (2006) found that 23 years after fertilization with ash, a significantly elevated pH was found only for the highest dose (5 t ha^{-1}). Ca, Mg, as well as P, B, Cr, Cu, Mn and Zn were also elevated. Another effect of fertilization with ash is the reduced solubility of Al (Perkiömäki and Fritze, 2002), Mn, Zn, Fe and Cu (Clapham and Zibilske, 1992).

Jokinen et al. (2006) found not only an increase in microbial activity (thymidine incorporation) due to ash amendment, but also a change in the microbial community composition (PCR-denaturing gradient gel electrophoresis). Wood ash increased the amount of hydrophilic neutrals, while the amount of hydrophilic and hydrophobic acids decreased. Perkiömäki et al. (2002) demonstrated that the effect of ashes on microorganisms is persistent and depends to a high degree on the dose and pre-treatment of the ashes. Hardening of ashes reduced the effects on microorganisms. Besides the stimulation of microorganisms, ashes are also known to promote plant growth (Voundi Nkana et al., 1997; Moilanen et al., 2002). Experiments have shown that ashes act in a similar way as mineral fertilizers (Holzner, 1999). On the other hand, Demeyer et al. (2001) report negligible or negative effects of ashes in case of N-limitations in soils, therefore suggesting to balance ash amendments with N fertilization. This is also supported by Saarsalmi et al. (2006), who found a long-term effect only for combination treatments with N fertilizer.

According to Narodoslawsky and Obernberger (1994), the admixture of ash to organic wastes improves the composting process. The combination of ash with bio-organic residues from agricultural or domestic sources reduces the nitrogen losses and accelerates the degradation of organic compounds. Ash further enhances K, Ca and Mg in the market-ready compost. Conversely, N, P and humic matter contents are reduced due to dilution with the ashes. Koivula et al. (2004) found an improved oxygenation during the composting process, a reduced emission of odors and an increased mineralisation and humification by admixing ash. Electrical conductivity and pH were not altered.

Compost as fertilizer or soil conditioner may contribute to soil quality by improving aeration, water status, and aggregate stability and as a consequence erosion stability. Macro- and micronutrients improve plant growth, and the cation exchange capacity is improved (Amlinger et al., 2007). In addition, the soil microbiota is activated and its biomass is enhanced, the extent of the effects much depending on the quality and dose of the organic matter (Insam, 1990; Leita et al., 1999). Concerning the risk of nitrate leaching, composted organic wastes can be considered uncritical (Insam and Merschak, 1997).

The aim of this paper was to investigate the suitability of using ashes as a compost additive by studying both the composting process itself, as well as the suitability of the products to reclaim disturbed soils. For comparative purposes, we also used a commercial organic fertilizer, Agrobiosol, and a mineral fertilizer.

2. Material and methods

2.1. Compost preparation

Three different windrows of composts were set up in the composting plant Weer (Tyrol, Austria) on the 31st of January 2006. In all three cases a mixture of communal biowaste and tree-bush-cuttings in the ratio of 53:47 (w/w) served as the organic source. The variants differed in the amount of wood ash added, 0% ($K0$), 8% ($K8$) and 16% ($K16$) (w/w). The wood ash was provided from the incineration plant Kufstein (Tyrol, Austria) where bark, sawdust and wood chips are used as input materials. The ash was mixed with the compost substrates with a caterpillar. The pH and electrical conductivity of the ash were 12.3 and 6.7 mS cm^{-1}, respectively; the heavy metal contents are shown in Table 3. The composts were force-aerated for 4 weeks and turned two times a week during the 2nd month, and then sieved with a 1-cm sieve and left in an open pile until the 21st of June (21 weeks).

Temperature and CO_2 evolution were measured weekly for the whole composting period. The maturation was observed through C/N, basal respiration and microbial biomass measurements as well as a cress test for samples taken in April–June. Mature composts were analysed for pH and electrical conductivity, heavy metal (Pb, Cd, Cr, Cu, Ni, Hg, Zn) and nutrient contents (P, Ca, Mg, N). Compost analyses were done in triplicate, where each sample was a pooled sample out of 10 sub-samples taken from different sides of the composting pile (surface material excluded).

2.2. Field trial

The experimental field, a reclamation trial on a ski-slope in the Austrian Alps, was situated 1700 m above sea level, exposed to the NE and having a slope of 27%. The soil type was an Andosol of disturbed rendzina on a silica-based material, the soil texture was a silty clay. The pH of the soil was 5.5 (1:2.5 in 0.1 mol KCl), and the total contents of K, P and Mg (Aqua regia, Kompostverordnung 2001) were <50, <22 and 78 mg kg^{-1} d.m., respectively. Total carbon and nitrogen were 2.65% and 1.37% of soil d.m. The trial was set up in a randomized block with four replicates. The treatments were

- AB: organic fertilizer (AgroBiosol®, a product containing fungal mycelium, N content 7%, P 1%, K 1%) (1143 kg d.m. ha^{-1}).
- MD: mineral fertilizer (Nitrophoska spezial, 12% N, 12% P_2O_5, 17% K_2O) (333 kg d.m. ha^{-1}).
- $K0$: compost without ash (23.7 t d.m. ha^{-1}).
- $K8$: compost with 8% wood ash (25.6 t d.m. ha^{-1}).
- $K16$: compost with 16% wood ash (29.3 t d.m. ha^{-1}).

The composts and fertilizers were applied at N-equivalent rates of 40 kg ha^{-1} available N (according to Amlinger, 2003, 10% of the

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total N) per year on 28 June 2006. After the application of the fertilizers a seed mixture containing *Festuca nigrescens*, *Poa alpina*, *Phleum rhaeticum*, *Phleum hirsutum*, *Trifolium pratense* spp. *nivale*, *Anthyllis vulneraria* spp. alpestris was sowed at a rate of 100 kg ha^{-1} (HBLFA Raumberg-Gumpenstein, Austria).

Soil sampling and evaluation of plant growth were done on 26 September, 3 months after setup of the trial. Overall impression and green aspect were assessed on a scale from 1 (very good) to 9 (very bad). Total plant cover as well as soil cover by grasses, leguminous plants, herbs and mosses were estimated as a percentage of the total covered area. Soil samples were taken from the top 10 cm with a Pürkhauer auger (6 cm diameter). For each plot a pooled sample was created out of 15 sub-samples. The soil was sieved with a 2-mm sieve and stored at room temperature until analysis. Biological parameters were measured within 5 days.

2.3. Laboratory analyses

Nutrient contents in the mature composts were determined according to the Austrian Compost Ordinance (2001) with *Aqua regia* digestion. Electrical conductivity (EC) and pH of composts were measured in 1:6.25 (w/v) compost/0.01 mol KCl solution slurries, whereas EC and pH of soils were determined in mixtures of 10 g soil with 25 ml solution (deionized water/KCl). Carbon and total N were measured from soil samples dried at 45 °C for 48 h (Leco TruSpec Macro CHN). One gram soil was muffled in a furnace (Carbolite, CWF 1000) for 5 h at 550 °C to eliminate the organic carbon, and then again analysed for C as above with a CHN analyser.

Soil basal respiration was measured as CO_2 evolution from moist (60% WHC) soil samples at 22 °C, using a continuous flow infrared gas analysis (IRGA) (Heinemeyer et al., 1989). Microbial biomass carbon (C_{mic}) was determined by substrate-induced respiration (SIR) after the addition of 1% glucose (Anderson and Domsch, 1978), using the IRGA as above. From basal respiration and C_{mic} the metabolic quotient (qCO_2, μg CO_2-C g^{-1}C_{mic} h^{-1}) was calculated.

A plant growth test was done according to the Austrian Compost Ordinance. Glass dishes (diameter 12 cm, 6 cm high) were filled with 100 ml glass sand, and on top of it 200 g of a mixture composed of tennis sand, standard soil and 0%, 15% and 30% (w/w) of compost. The surface was seeded with 0.4 g of cress seeds that were again covered with another 50 g of glass sand. Substrates were water saturated and covered with a black foil until germination. We determined the lag time of germination, as the total number of germinated seeds after 9 days. The aboveground dry weight of the cress was also determined after 9 days.

2.4. Statistical evaluation

Compost samples were taken in triplicates. The field experiment was set up in randomized block design with four replicates. Data sets were compared by ANOVA followed by a Tukey *B*-test.

3. Results

3.1. Compost production and quality

The temperature dynamics was similar in all three windrows, and showed the typical peak about 2 weeks after the start of the forced aeration (Fig. 1). In all three composts the legal hygiene requirement of a minimum of 6 days above 65 °C were met. The maximum temperatures reached were 73.4, 69.3 and 73.4 °C for *K*0, *K*8 and *K*16, respectively. In the unaerated period after sieving, the ash composts exhibited a slightly higher temperature than the unamended compost. After 17 weeks, all windrows had reached ambient temperature.

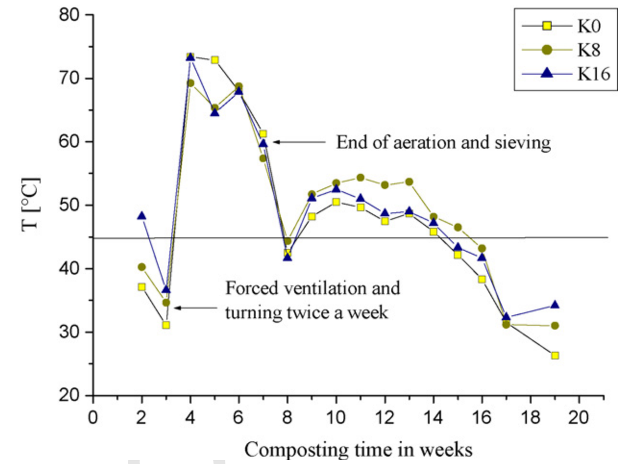

Fig. 1. Temperature during the composting of organic wastes without, and with 8% and 16% wood ash (mean coefficient of variance = 17.3%).

During the forced aeration phase in the macropores a mean CO_2 concentration of about 10% was measured. After sieving, the compost piles remained unaerated, and we found up to 20% CO_2 1 week after sieving, decreasing to approximately 8% at the end of the process. No significant differences among the three composts were found in the later stages of the composting process, while the CO_2 content was significantly lower for the compost with the highest ash dose in the first weeks of composting (data not shown).

Organic C contents decreased during the rotting process; in the mature composts we found 217, 192 and 169 mg g dm^{-1} for the *K*0, *K*8 and *K*16 samples, respectively. Total N remained constant, for *K*16 we found slightly lower values than for *K*0 and *K*8 (Table 2). The C/N ratios were similar in all three composts. Phosphate contents were lower in the ash composts than in the control, while K and Mg contents were enhanced.

All biological process parameters like basal respiration, microbial biomass, metabolic quotient, C_{org}, N_{tot}, C/N-ratio and plant growth tests with cress indicators showed that ash admixture had no adverse effects on process performance and all legal standards were met. At the end of the composting process, microbial biomass and basal respiration (data not shown) were slightly lower in the ash composts than in the control. Increasing ash doses increased the pH significantly from 6.9 to 7.7. Electrical conductivity decreased from 1.6 to 1.1 mS cm^{-1}.

Heavy metals contents in the ash are limiting admixture in composting; the ashes we used were below the limits according to Austrian Compost Ordinance. Table 3 shows the heavy metal contents in the mature composts and, for comparison, the limit values according to the compost ordinance. In the case of Cr, Ni and Zn we found higher contents in the ash composts, while for Pb, Cd,

Table 2
Organic C and nutrient contents (± standard deviation) in the three produced composts

	C_{org} (% d.m.) (n = 3)	N (% d.m.) (n = 3)	C/N (n = 3)	P (% d.m.) (n = 3)	K (% d.m.) (n = 3)	Mg (% d.m.) (n = 3)
*K*0	21.7 (±4.6) a	1.69 (±0.45) a	13.1 (±1.1) a	0.42 (±0.00) a	1.18 (±0.02) a	1.2 (±0.01) a
*K*8	19.2 (±1.0) a	1.56 (±0.1) a	12.4 (±1.2) a	0.39 (±0.00) b	1.33 (±0.01) b	1.57 (±0.02) b
*K*16	16.9 (±0.2) a	1.37 (±0.02) a	12.3 (±0.1) a	0.36 (±0.00) c	1.28 (±0.01) b	1.58 (±0.01) b

Dissimilar letters in a column indicate statistically significant differences among the composts (n = 3; Tukey *B*-test).

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Table 3
Heavy metal contents of different ashes from the Kufstein biomass incineration plant and of composts produced without, and with 8% and 16% ash (mean ± S.D.) and the limit values for quality composts A+, A and B according to the Austrian Compost Ordinance (2002)

	Heavy metal contents in ashes (n = 3)			Heavy metal contents in mature compost (mg kg^{-1} d.m.)			Limits for different compost qualities		
	Min	Mean	Max	*K*0%	*K*8%	*K*16%	A+	A	B
Pb	2.5	12	31	58.0 (±2.9) a	39.3 (±2.4) b	34.6 (±4.2) c	45	120	200
Cd	0.1	1.4	4.4	0.8 (±0.1) a	0.6 (±0.1) b	0.7 (±0.1) b	0.7	1	3
Cr	25	112	250	25.2 (±13.7) a	27.1 (±2.8) a	27.9 (±0.2) a	70	170	250
Cu	40	92	320	67.3 (±6.7) a	66.6 (±11.3) a	55.4 (±1.9) b	70	150	500
Ni	9	46	56	16.4 (±1.4) a	22.1 (±10.7) b	20.6 (±2.0) ab	25	60	100
Hg	0.05	0.07	0.5	0.4 (±0.1) a	0.2 (±0.1) b	0.2 (±0.1) b	0.4	0.7	3
Zn	25	344	1100	181 (±19) a	183 (±24) a	189 (±7) a	200	500	1800

Quality A+ may be used in organic (biological) agriculture, quality A conforms for general use in agriculture, quality B composts may only be used for landscaping. For *K*0, *K*8 and *K*16 dissimilar letters in a row indicate statistically significant differences among the variants (Tukey *B*-test).

Cu and Hg the values were lower when ash was added. Heavy metal contents did not exceed the limits for quality A+ in any of the ash-amended composts.

3.2. Field trial

3.2.1. Soil chemical and microbiological analysis

Fertilizers, and in particular organic fertilizers and composts are known to enhance the availability of organic matter for microbial degradation either indirectly (through stimulating plant growth) or directly (through carbon input), a phenomenon also termed priming effect. In this case, we found a pronounced stimulation of microbial basal respiration by all organic amendments; compared to the mineral fertilization treatment was, however, this effect was statistically significant only for the 8% ash-amended compost (Table 4).

Microbial biomass was highest on the plots that had received compost with 8% ash. The effects of all other treatment were, compared to the mineral fertilizer and organic fertilizer, not statistically significant.

3.2.2. Classification of plant growth

Already 3 months after setup of the trial, soil plant cover was significantly different among the treatments (Table 5). Total soil cover was 65% for *K*16 and exceeded 70% for *K*0 and *K*8; for AB and mineral fertilizer, 53% and 38%, were estimated, respectively. Composts enhanced coverage of both grasses and leguminous plants to a similar degree. No difference was found between the three different kinds of composts (0, 8 and 16% ash).

The lushest green was obtained with mineral fertilizer, pointing towards luxurious supply with nitrogen. The best overall impression was achieved with *K*8 (mark 2.3), followed by *K*0 and *K*16 with marks 2.4 and 2.9, respectively (Table 5).

4. Discussion

4.1. Composting process

In general, the observed temperature dynamics is typical for composting processes with sequential mesophilic, thermophilic and cooling phases (Insam and de Bertoldi, 2007). The sudden temperature changes between week 3 and 4, and week 7 and 8, may be explained by the onset of forced aeration in week 3 and the sieving event at week 7, respectively (Fig. 1). Our results confirm earlier observations (Koivula et al., 2004; Narodoslawsky and Obernberger, 1994) that ash admixture to organic wastes may enhance heat production and may thus indicate accelerated microbial activity. However, when wood ash is being composted, the onset of an exothermic carbonisation process of the oxidic compounds is to be expected (Narodoslawsky and Obernberger,

Table 4
Soil organic C, total nitrogen, C/N ratio, pH, electrical conductivity (EC) and biological properties (basal respiration R_{mic}, microbial biomass C_{mic} and metabolic quotient qCO_2) on revegetation plots on the Mutterer Alm skiing-area near Innsbruck, Austria, fertilized with composts without (*K*0), with an admixture of 8 (*K*8) and 16% (*K*16) wood ash, AgroBiosol (AB) and a mineral fertilizer (MD) (mean ± standard deviation)

	C_{org} (% d.m.)	N (% d.m.)	C/N	pH	EC (μS cm^{-1})	R_{mic} (μg C $g^{-1}C_{org}$ h^{-1})	C_{mic} (μg CO_2-C g^{-1} d.m.)	qCO_2 (mg CO_2-C g^{-1} h^{-1})
*K*0	3.1 (±0.6) ab	0.19 (±0.04) a	16.5 (±1.0) a	6.4 (±0.1) a	130 (±21) ab	5.74 (±1.57) abc	370 (±136) ab	14.0 (±0.7) a
*K*8	3.3 (±0.5) a	0.20 (±0.04) a	16.9 (±1.3) a	6.6 (±0.1) a	196 (±54) a	8.48 (±2.29) a	597 (±183) a	14.5 (±0.9) a
*K*16	2.6 (±0.5) abc	0.15 (±0.04) ab	17.1 (±0.4) a	6.6 (±0.1) a	186 (±50) a	6.61 (±3.2) ab	425 (±67) ab	14.2 (±1.6) a
AB	1.8 (±0.4) c	0.09 (±0.03) b	21.6 (±4.3) a	6.6 (±0.1) a	98 (±23) b	4.59 (±0.81) bc	297 (±23) ab	15.6 (±3.2) a
MD	2.0 (±0.2) bc	0.11 (±0.02) b	18.9 (±18.9) a	5.6 (±0.3) b	80 (±22) b	3.20 (±0.71) c	255 (±43) b	12.5 (±1.3) a

Dissimilar letters in a column indicate statistically significant differences among the treatments (Tukey *B*-test).

Table 5
Comparison of plant growth in the field experiment

	*K*0	*K*8	*K*16	AB	MD
Total plant cover (%)	70.5(±4.2) a	71.5(±5.0) a	65.0(±3.1) a	52.5(±9.5) b	38.0(±2.7) c
Grass cover (%)	39.0(±2.6) a	40.0(±5.1) a	37.0(±2.0) a	31.8(±7.2) b	26.0(±2.6) b
Leguminous plant cover (%)	29.0(±2.3) a	30(±2.9) a	26.8(±2.1) a	19.3(±2.6) b	10.5(±5.0) c
Forb cover (%)	2(±1.7) a	1.5(±0.5) a	1.3(±1.4) a	1.5(±0.5) a	1.5(±0.5) a
Moss cover (%)	1.1(±0.5) a	0.9(±0.2) a	1.3(±0.4) a	1.5(±0.5) a	1.5(±0.9) a
Green aspect (1–9)	4.9(±0.2) a	4.8(±0.3) a	5.0(±0.4) a	4.6(±0.8) a	3.4(±1.1) a
Overall impression (1–9)	2.4(±0.7) a	2.3(±0.9) a	2.9(±0.6) a	5.1(±1.4) b	7.1(±0.41) c

Mean (±S.D.) of total soil cover (% of the area), and coverage by grasses, leguminous plants, forbs and mosses, as well as green aspect and overall impression (1–9, 1 = very good, 9 = very poor). Dissimilar letters in a row indicate statistically significant differences among the treatments (Tukey *B*-test).

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1994). This might result in abiotic heat production, obscuring the effects of microbial activity. Koivula et al. (2004) argue that prolonged high temperatures (as were also found in this study) might result from a higher heat capacity of the material due to its ash contents. The lower microbial biomass of ash composts in the end of the composting process may be due to exhaustion of substrates, or to a lower availability of nutrients.

The low temperature of the material at the end of the process indicates that the compost has achieved a state of considerable maturity. It is also important to note that with all three composts the current legal requirements concerning hygiene were met with at least 6 days at a temperature exceeding 65° (Kompostverordnung, 2002).

Alike heat production, CO_2 production is an indicator of microbial activity in composts (Itavaara et al., 2002); however, the above-mentioned carbonisation reactions result in the uptake of produced CO_2 and may thus obscure activity measurements based on CO_2 (Narodoslawsky and Obernberger, 1994). Thus we cannot tell with certainty to which degree ash admixture influenced the biological activity. The in situ measurements of CO_2 indicate clearly the effect of the forced aeration (during this period, however, the data variability was quite high), as well as the decreasing microbial activity towards the end of the process.

The lower organic C content in the ash composts may be explained by the dilution through ash admixture, and by an enhanced mineralisation. Carbon contents of our composts are well within the range that is usually demanded for mature composts (Pfundtner, 1998).

Nitrogen may be lost during composting by ammonia evaporation which is particularly high during the thermophilic phase and when the pH is high. High microbial biomass, on the other hand, ensures proper binding of the nitrogen. According to de Bertoldi et al. (1983) even microbial N fixation is possible. The addition of ash resulted in a dilution of N, however, N contents were still in the usual range (0.7–1.7% d.m.).

To make sure that enough N is available to the plants, a C/N ratio <20 is required (Hue and Sobiesczyk, 1999) which is met by all our composts. *K*0 and *K*8 have reached values <15 already after 2 months, and *K*16 after 3 months; however, temperature, CO_2 concentrations and cress tests indicated that at that time the maturation had not been finished (data not shown). This supports the studies by Zmora-Nahum et al. (2005) and Jimenez and Garcia (1991) who do not regard the C/N ratios in solid phase as a reliable parameter to indicate maturity. Similar to our study, also Narodoslawsky and Obernberger (1994) found C/N ratios between 12 and 13 for ash composts. On the other hand, if the C/N ratio is narrow (<12) there is a certain risk of N leaching which could cause groundwater problems. This was tested in a mini-lysimeter experiment (as in Insam and Merschak, 1997; data not shown) where we did not find nitrate concentrations in the leachate exceeding 35 mg ml^{-1}. The observations corresponded with the study of Insam and Merschak (1997). The total sum of nitrate that was leached from the compost amended plots was lower when the composts had received ash, an observation that has also been made by Plank (2007) who studied combination effects of ash with anaerobic sludges.

Heavy metals may harm the environment, and therefore the Austrian compost ordinance sets limits not only for the product, but also for the input materials (Kompostverordnung, 2002). Since heavy metal contents of wood ashes often exceed those of organic wastes, the admixture of ash might decrease the quality of the end product compost (Koivula et al., 2004; Narodoslawsky and Obernberger, 1994). With the exception of Ni, Cr and Zn this was not the case here since in most cases the heavy metal contents in the ash-amended composts were lower than in the unamended one (Table 3). In terms of end product quality, the ash composts qualified for A+ while the unamended compost did not. This may be attributed to the very low heavy metal contents in the ash, which was in the lower range of the ashes usually found. In addition, it is possible that the extractability of heavy metals from ash-amended composts with Aqua regia is lower than that of unamended composts. However, calculations showed that if ash of the poorest quality ever found in the Kufstein biomass incineration plant (see Table 3) would have been used, a downgrading to compost class B might have occurred with 16% ash amendment (data not shown). It is thus indispensable that ashes are being analysed before admixture. Magnesium and potassium contents in the composts were increased by ash which increased their nutritional value; P contents, on the other hand, were decreased which may be attributed to a dilution effect (Narodoslawsky and Obernberger, 1994) or to a less efficient extraction when ash is container in the matrix. In summary, in all cases Mg, K and P contents were in the typical range of composts produced in Austria (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, 1998).

Through carbonates, oxides and hydroxides of its Mg, Ca and K, ash increases the pH of acid soils (Vance, 1996). While Koivula (2004) – probably due to the high buffering capacity of the organic matter – did not find any pH effect of ash, we found that ash addition increased the pH in the early stages of composting. The final pH of both the control and ash composts was in the range usually found in composts (pH 7–8) (Jimenez and Garcia, 1991).

The electrical conductivity is a measure of salinity; while wood ash is characterized by high salinity, carbonatisation reduces solubility, and thus a large increase in conductivity is not to be anticipated (Obernberger, 1997). We even found a reduction of conductivity compared to the control. For reasons of plant health the conductivity should not exceed < 2 mS cm^{-1}, a limit that was never reached. From this point of view, all the composts may be regarded harmless for plants.

Immature compost may contain phytotoxic compounds (Zucconi et al., 1983), which may explain that our 2- and 3-months-old composts showed a decreased cress biomass production (data not shown). The final product, however, did not show any difference to the control. Ash amendment had no adverse effect, but also did not enhance germination and cress biomass production.

4.2. Field trial

4.2.1. Organic C (C_{org}), nitrogen (N_{tot}) and C_{org}/N_{tot} ratio

Organic matter has many beneficial properties for the reclamation of unvegetated slopes ranging from improved soil aeration, supply of nutrients and erosion stability (Amlinger et al., 2007). Increased soil organic matter contents due to compost application were also found here; besides C_{org}, also the soil N contents of the compost variants were higher than those of the Agrobiosol and mineral fertilizer variants. The lower C/N ration in the ash composts indicates a more advanced maturation.

4.2.2. Other nutrients and heavy metals

Plant available (acetate extraction) K (50 mg kg^{-1} d.m.) and P (22 mg kg^{-1} d.m.) contents on the trial site were low while Mg contents (130 mg kg^{-1} d.m.) were considerable. An amelioration measure that brings additional K and P would thus be desirable to support long-term establishment of a vegetation cover. It may be assumed that the compost fertilization will cover nutrient demands for a few years, while the other fertilizers will have to be applied repeatedly.

4.2.3. Potential pH and electrical conductivity (EC)

Compost fertilization may increase the pH of acid grassland soils (Amlinger et al., 2007); this was also fond here, but no additional effect was found by the admixture of ash. This may be

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attributed to the fact that the ash had already been neutralized to a large degree during the composting process. The high application rate resulted in an increased EC. This is in contrast to the observations with the composts themselves where a lower EC was found for the ash-amended products. In any case, negative effects for plant health are only expected at an EC $>1.5\ \mathrm{mS\,cm^{-1}}$ (Pfundtner, 1998).

4.2.4. Basal respiration (R_{mic}), microbial biomass (C_{mic}) and metabolic quotient (qCO_2)

It is commonly known that composts and organic fertilizers are able to enhance microbial activity and biomass (Insam, 1990). These parameters were slightly enhanced in the field trial (and were also significant in a mini-lysimeter experiment—data not shown). Similar results were obtained with the application of pure ash (Plank, 2007; Perkiömäki and Fritze, 2002; Jokinen et al., 2006). Calculating the results on basis of C_{org} rather than on soil dry matter suggests that the ash improves accessibility (availability??) of organic matter (Jokinen et al., 2006). This may be regarded as a positive side effect, since more nutrients are released this way for the vegetation.

The metabolic quotient (qCO_2) is often used as a stress indicator (Liao and Xie, 2007; Moreno and Hernandez, 1999). None of the treatments resulted in a significant change of the qCO_2; adverse effects of the ash on the microbial metabolic efficiency may thus be excluded.

4.2.5. Classification of plant growth

Ultimate aim of any high-alpine reclamation effort is to obtain a plant cover of 70% (which is considered a threshold for effective erosion prevention) as soon as possible, which was best obtained with the composts, supporting earlier findings by Insam (1990) and Amlinger, personal communication. The success is related to slow but sufficient nutrient release, in combination with improved aggregate formation (de Bertoldi et al., 1983). For pure ash fertilization it is known that plant growth is improved as long as N is not a limiting factor (Holzner, 1999; Voundi Nkana et al., 1997; Moilanen et al., 2002) which was also supported by the present data.

Concerning the green aspect the best score was obtained with the mineral fertilizer. This may be attributed to the high amount of plant available N. The composition of the plant community was changed by the composts in favour of grasses and leguminous plants (Table 5); a similar effect was found on the Gamlitz Alm, another alpine pasture (Amlinger, personal communication). In particular the enhancement is desirable, since this way biological nitrogen fixation is anticipated to contribute to a considerable extent to the long-term N supply.

5. Conclusion

This study demonstrated that wood ash may safely be added to organic wastes up to an amount of 16% before the composting process starts. Ash does neither negatively affect the composting process (temperature dynamics, microbial activity) nor the product (no increased heavy metal contents, improved nutrient balance). Trials on re-vegetated ski-slopes demonstrated that all the investigated composts, and in particular the ash-amended composts, showed a better performance than mineral and organic fertilizers in terms of plant cover and soil microbiological properties. Great potential is seen in the utilization of high-quality ashes when it comes to the development of site- and crop-specific composts and fertilizers. Prerequisite, however, is the development of a quality standard for ashes, and regular tests.

Q3 Uncited references

Insam (1989) and Trinkwasserverordnung (2001).

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