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Innovative reuse of drinking water sludge in geo-environmental applications

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ABSTRACT

In recent years, the replacement of natural raw materials with new alternative materials, which acquire an economic, energetic and environmental value, has gained increasing importance. The considerable consumption of water has favoured the increase in the number of drinking water treatment plants and, consequently, the production of drinking water sludge. This paper proposes a protocol of analyses capable of evaluating chemical characteristics of drinking water sludge from surface water treatment plants. Thereby we are able to assess their possible beneficial use for geo-environmental applications, such as the construction of barrier layers for landfill and for the formation of "bio-soils", when mixed with the stabilized organic fraction of municipal solid waste. This paper reports the results of a study aimed at evaluating the quality and environmental aspects of reconstructed soils ("bio-soil"), which are used in much greater quantities than the usual standard, for "massive" applications in environmental actions such as the final cover of landfills. The granulometric, chemical and physical analyses of the sludge and the leaching test on the stabilized organic fraction showed the suitability of the proposed materials for reuse.

The study proved that the reuse of drinking water sludge for the construction of barrier layers and the formation of "bio-soils" reduces the consumption of natural materials, the demand for landfill volumes, and offers numerous technological advantages.

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1. Introduction

The most important drinking water system in Southern Italy is the Acquedotto Pugliese, whose water network, 15,000 km long, is the longest in Europe. Its six purification plants (Sinni, Pertusillo, Fortore, Locone, Camastra and Metapontino) treat 11,000 l/s of surface water, generating around 70 ton/day of sludge, and creating a total amount of around 25,200 ton/year.

If we hypothesize the purification of about 70% of the water volumes needed for meeting the needs of the Italian population and a moisture content of the sludge produced equal to 70%, we obtain a yearly production of sludge equal to 270,000 ton/year which could be compared to the yearly production of the urban solid waste of the whole Italian region of Basilicata (600,000 inhabitants). The daily drinking water sludge production on a world scale is increasing more and more: at present, it exceeds 10,000 ton/day.

In 2009, the production of municipal solid waste (MSW) in Italy was 32.1 million tons. More than 20% of the MSW production is composed of an organic undersieve fraction, which undergoes an aerobic stabilization, in order to reduce its hazard for the environment. This organic fraction is converted into a stabilized organic fraction, SOF, and afterwards is dumped in landfills. Considering the increasing and renewed environmental awareness, the identification of suitable application fields of these new materials is extremely important in order to prevent their disposal.

In 1998, in a landfill area located near Valencia, Ingelmo et al. carried out an experiment to verify the possibility of making vegetation take root by replacing the usual top layer which was made up of fertile vegetable soil with a thin layer of inert soil covered with a much thinner surface layer of organic waste materials. In order to assess the best characteristics of this latter layer, they carried out trials on parcels treated with dry sludge or with SOF, or characterised by an absence of organic matter (Ingelmo et al., 1998).

Studies carried out in a quarry near Gerona (Spain) verified the evolution of organic chemical compounds in soils treated with drinking water sludge (Molina et al., 2000).

From July 2002 to November 2004, the Italian region of Piedmont, together with the Italian Institute for Wood, Plants and the Environment (I.P.L.A.), carried out a set of trials on land parcels which were constituted by using SOF and soil in different proportions and methods (mixing or stratification), or containing pure soil and soil added with a compost from the treatment of sludge and green fraction. In order to assess the best mixing ratios for the mixtures of sludge and SOF, some studies were carried out by analysing the sludge from a wastewater treatment plant. Mixtures of sludge, SOF and Clinoptilotite were analyzed to produce compost. Clinoptilotite was added due to its ability to store up heavy metals (Zorpas et al., 2000). Further hypotheses of mixing sludge and SOF were studied (Delgado et al., 2004). Stability

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analyses were carried out on mixtures of sludge and SOF and on the separated materials (Delgado et al., 2004).

Moreover, several biological assays have been combined with standard chemical analyses. Multiple studies showed that the chemical approach does not provide satisfactory tools to define the environmental risk associated to a mixture of pollutants (Pasini et al., 2000). Information about phytotoxicity is necessary for the evaluation of the environmental risk of pollution (Wang et al., 2001). The presence of toxicological agents can be detected by analysing the changes caused on a test organism. These tests are reliable, convenient, fast and simple (Valerio et al., 2007). Laboratory tests can be divided into acute and chronic (or sublethal) tests. An acute test uses increasing doses for short periods, from 15 min to 96 h. Chronic tests have a duration variable from days to months and are conducted typically using low concentrations for long periods. The use of plants offers an advantage if compared to other organisms, because they may be more sensitive to environmental stress (Valerio et al., 2007). Furthermore, the use of ecotoxicological assays allows us to evaluate, on one side, the bioavailable fraction of the pollutants, and, on the other hand, any synergy and/or antagonism phenomena of different substances (Pasini et al., 2000).

The *Spartium junceum* (or Spanish Broom) is a test organism used for structuring chronic bioassays. In fact, it is suitable for carrying out revegetation activities on closed landfills and it is capable of adapting itself to difficult soils, such as dry or clayey soils. A Spanish Broom plantation brings a considerable increase in cohesion in the surface layers of the soil (Preti and Giadrossich, 2009). In literature, there are different experiences of using biological assays to evaluate the effects of heavy metals on living organisms. In 2007, Valerio et al. attested the potentialities of the use of bioassays on lettuce for the determination of phytotoxicity of elements with high solubility in soils.

In this research paper, an analytical protocol is designed to test the suitability of drinking water sludge mixed with municipal solid waste stabilized organic fraction, SOF, in order to create innovative "bio-soils" to be used for daily and final covering in controlled landfills. We applied environmental bioassays, in order to test the proposed reuse scenario. Vegetation tests were used to evaluate the toxicity of some heavy metals on vegetable species by varying the growth substrate, and an innovative test with *Spartium junctium* was applied. The objective of this research was to assess the chemical–physical characteristics of such waste materials in order to meet the specific needs for reuse in the fields they are meant for. The subjects of the study were the sludge produced by the drinking water treatment plant of "Masseria Romaniello" (Potenza, Southern Italy), which is fed by the Camastra artificial lake, and the SOF coming from the plant of bio-mechanical treatment of Venosa (Potenza).

2. Materials and methods

The analysis protocol proposed in this study assesses: the main physical and chemical characteristics of the materials to be tested when they are mixed with different substrates, the possible percolation of pollutants in groundwater, the variation in the dry matter production of the epigeal biomass, the Germination Index and the Inhibition of the Growth Radical Index. Therefore, the analysis protocol is able to describe the influence of the analyzed materials on soil receptors, vegetation material and groundwater resources.

2.1. The materials used for the experiments

The drinking water sludge (Fig. 1d) comes from the surface water purification plant of "Masseria Romaniello", which treats the water collected in the Camastra dam and is located in the town of Potenza (Southern Italy). This purification plant has a capacity of 1050 l/s and produces about 3 tons of sludge a day, creating a yearly quantity of around 1095 tons. It is worth underlining how its reuse in industrial productions is characterised by some technological and economic limitations. Drinking water sludge, in fact, is characterised by a high moisture content that is on average between 70% and 80%. Such a characteristic makes transportation to places far from the production sites inconvenient, thus limiting the practical possibilities of reuse. The sludge treatment plant includes gravity thickeners, filterpress and beltpress. The reagents used in the different stages of water treatment of the "Masseria Romaniello" drinking water treatment plant are: chlorine dioxide, carbon dioxide, aluminum and polyvinyl organic flocculent – anion only at the stage of the sludge dehydration. The treatment outline involves an enrichment of aluminum sludge as a result of the use of polyvinyl aluminum as a coagulant reagent. The SOF used for the experimental work comes from a bio-mechanical plant for the treatment of MSW coming from small urban settlements in the northern province of Potenza (Basilicata Region, Sothern Italy). The cycle of treatment is articulated into two phases: opening of the plastic bags and dry–wet separation with a slowly rotating cylindrical sieve. These treatments provide a very small tearing of plastic fractions and a low breakage of glass components.

Only the fraction characterized by a dimension less than 80 mm (undersieve) undergoes a stabilization process in aerated bioreactors (biocells) of 25 m^3. The cycle of treatment involves the permanence in the biocell for a time sufficient to ensure an adequate degree of stabilization of the treated material. The process determines the development of bio-oxidative processes in thermophilous times ranging from 8 to 14 days. The processing time depends on the biological stability level desired. The plant in question operates on a cycle of 14 days to obtain a potentiality equal to 16–20 ton/day.

The material extracted from the biocells underwent a first stage of refining aimed at eliminating the inert matter and coarse fractions. The operation was conducted in a drum sieve with a mesh of 20 mm. The screening resulted in 41% decrease in the weight of the material. For the experimental tests, the material exiting from biocells was further refined with a rotating screen at 10 mm. Afterwards, the material was sampled and subjected, for further 60 days, to a maturation phase without forced ventilation. At the end, we proceeded to form the test samples by mixing the obtained SOF with inert structuring fractions and drinking water sludge, which was used as a corrector of granulometry.

2.2. Granulometric analysis of drinking water sludge

Sludge is characterised by a high water content, marked hydrophilia, and scarce or absent biological activity. In the sludge, we noticed the presence of hydroxides, which originate from coagulating agents, colloids, organic matter and inorganic precipitates. The sludge underwent a granulometric analysis, performed at the Geotechnical Laboratory of the Department of Structures, Geotechnics, and Geology, at the University of Basilicata.

2.3. Preliminary laboratory analyses: determination of heavy metals and leaching tests

The operation for separating solid and liquid phases was carried out according to the method codified by the Italian Agency for Environmental Protection and Technical Services (APAT, 2003). The analytical determination of contaminants in the mixture was based on the methods of the Italian Water Research Institute (IRSA, 2006). The metal content in SOF and sludge was analyzed according to the methods set down by the Italian Environmental

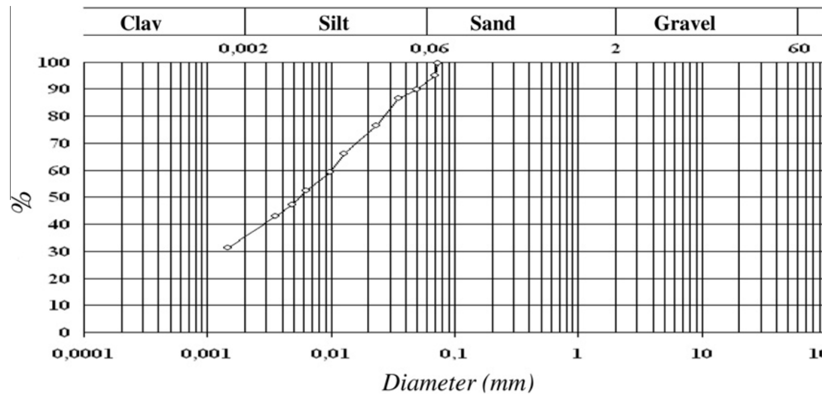

Fig. 1. Granulometric curve.

Protection Agency (ANPA, 2001). The analytical measures of metals were carried out by an inductively coupled plasma spectrometer (ICP), Variant 710.

The mixture of SOF and sludge were submitted to a leaching test with molar 0.5 acetic acid. The test simulates the erosion of materials made by atmospheric agents and the percolates from mixed landfill, in order to assess whether the liquid phase obtained shows noticeable traces of pollutants.

2.4. Merceological analysis

The different merceological categories were identified and recognized in the sample and manually separated.

2.5. Determination of SOF biological stability

It is necessary to evaluate the biological stability of an organic material in order to programme a further phase of processing and recovery. It is useful to notice that the concept of stability is strictly related to the slowdown in the activity of oxidation of the organic matter.

The biological stability was determined according to the Di.Pro.Ve. method, developed by the Department of Plant Production at the Agriculture Faculty (University of Milan) and described in "Methods of microbiological analysis of compost" (Italian Environmental Protection Agency, 2003). The method consists of the determination of the oxygen consumption under controlled conditions in an adiabatic aerobic system. The parameter thus obtained is called Potential Dynamic Respiration Index (PDRI) and is representative of the biological stability of the analyzed sample. We used a Respirometer 3022, produced by Costech International, interfaced with an acquisition unit of continuous process parameters (temperature, oxygen, air flow).

2.6. Tests on the mixtures of SOF and drinking water sludge

2.6.1. Vegetation tests with Lactuca sativa

Chemical analyses of SOF and sludge, even if indispensable, are not comprehensive for the aim of this research. It is very important to assess the presence of some substances or properties which cannot be detected with chemical analyses such as: synthetic organic matter (which cannot be foreseen even if the origin of biomass is known), mobility of the different chemical forms of metals under different environmental conditions, additive and synergistic effects due to the contemporaneous presence of several contaminants, bio-availability and transfer rate of organic and inorganic contaminants to vegetable tissues. Biochemical characteristics of materials can be evaluated through acute and chronic tests, carried out on vegetable species used as indicators.

The developed acute test is an assay of agronomic compatibility, i.e. the vegetation test with *L. sativa*. This method, proposed by the Department of Physiology of Cultivated Plants and Agrarian Chemistry at the University of Milan (Italian Environmental Protection Agency, 2003), is based on the assessment of the production of the epigeal biomass realized by lettuce plants in the presence of increasing doses of the material to be tested. The test can assess, globally, the phytotoxicity and the agronomic attitude of a wide range of by-products, liquid, solid and sludge, whose agricultural recovery is hypothesized.

A total number of 28 samples were prepared (six dosages repeated 4 times and four control vases containing standard substratum – "Control") for the phytotoxicity test. Dosages were selected in function of the type of by-product to test (sludge and compost):

- for sludge, doses must include between 0 and 3.33 g ss/kg of substratum;
- for compost, between 0 and 15 g of ss/kg of substratum.

For the preparation of 10 kg of standard substratum (for 40 vessels of 250 g), 400 ml of deionized water and 150 g of peat were poured in a container of about 30 l. The suspension was covered with a layer of 8750 g of sand; we waited about 10 min so that peat and sand were soaked and then we proceeded to stir the mixture. Therefore, we added 900 g of clay and 200 g of agricultural soil and we mixed again until we obtained a homogeneous mixture. In order to turn the expressed dosage into t/ha of substratum, we multiplied the dosage by a coefficient equal to 4.53, referred to a hectare of land made up of a standard substratum (apparent density 1.51 g/cm^3) at a depth of 30 cm. We carried out the transplant of lettuce seedlings (three for each vase) taken from the germination tray. 21 days after the transplant, we carried out the harvest, through cutting the aerial part of the plants at the plant neck. We measured the fresh weight and the dry weight (weight/vase) after drying at 105 °C.

2.6.2. Germination and radical elongation test with S. junceum

The germination and radical elongation test was performed on *S. junceum* (Spanish Broom). This test allowed us to obtain the effects of the trial materials on a species actually used in interventions of reclamation and renaturation. In fact, the broom is especially suitable for the recolonization of areas (i.e. final cover of landfills) and is naturally spread in different environments, from coasts to dry high grounds, from uncultivated lands to waysides. It is a pioneer species, with a high ecological value, which also plays a role in the mechanic defence of soil. It is a broom, an erected shrub

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Table 1
Hypothesis of mixture dosages in soil.

	Unit of measure	Dose 1	Dose 2	Dose 3	Dose 4	Dose 5	Dose 6	Dose 7
Dosage	t ss/ha	200	750	1000	1500	2000	3000	4000
Content of the tested material in "bio-soil"	g ss/kg	44.2	165.6	220.8	331.1	441.5	662.3	883.0

from the Leguminosae family which grows to 3–4 m. The Spanish Broom is widespread all over the Italian territory on slopes and difficult lands (dry, sandy or rocky lands) and it is extremely beautiful during flowering.

The germination and radical development trials on the *S. junceum* were carried out in the greenhouses of CODRA Mediterranea spa (Operational Centre for Defence and Environmental Restoration) in Pignola (PZ). After the determination of the non-phytotoxicity of the suggested mixture, as showed in Section 2.6.1, we carried out the assessment of the maximum dosages admissible under the conditions actually proposed for the hypothesized reuse. We simulated the mixture additions on soil shown in Table 1.

We prepared a total number of 91 samples organized as follows:

- in seven groups of 10 vases, with increasing dosages of the mixture of SOF and sludge (200, 750, 1000, 1500, 2000, 3000, 4000 t s.s./ha), mixed with a inert substratum made up of sand;
- a control, made up of 22 vases containing a mixture of peat and loam, optimal for the germination and development of the selected vegetable specie.

The prepared vases are the following:

- in seedling (made up of 6 × 10 cells), seven groups (corresponding to seven doses) of six repetitions each (A, B, C, D, E, F), plus 18 control cells with the mixture of peat and loam. In such a seedling, we added, for each cell, seven seeds of *S. junceum*;
- eight groups of three repetitions of cylindrical vases (height 20 cm, diameter 15 cm), three of which were controls;
- seven cylindrical vases (height 40 cm, diameter 30 cm), each filled with sand mixed with a different dose of the mixture of grey compost and drinking water sludge.

30 days after germination, we carried out the explant of bedders and the measurement of their radical apparatus.

After the acquisition of measurements, we calculated the Germination Index, GI (%) with the following equation:

$$GI\ (\%) = \frac{G_1 \cdot L_1}{G_c \cdot L_c} \cdot 100 \quad (1)$$

where G_1 is the number of seeds germinated in the sample; G_c that of the seeds germinated in the control; L_1 is the radical length of the sample; L_c that of the control.

The Inhibition Index, Inib (%), was calculated with the following equation:

$$Inib\ (\%) = \frac{L_c - L_1}{L_c} \cdot 100 \quad (2)$$

where L_1 is the radical length of the sample and L_c is the radical length of the control.

2.6.3. Transfer tests

For the transfer test on the amended soils, we used seven samples of amended soil (each corresponding to the different seven dosages of the mixture of grey compost and drinking water sludge), on which we carried out distilled water transfer tests taking into consideration the following parameters:

- elution ratio 1:10 (namely 50 g of sample on 500 g of water);
- contact time: 24 h with continuous moderate agitation;
- analysis on the solution after filtration at 0.45 μm.

Table 2
Results of the determination of metals in the samples of drinking water sludge and SOF.

Parameter	Drinking water sludge (mg/kg)	SOF (mg/kg)
Al_237	101,525.40	8115.84
Cd	–	<1
Ni	–	36.94
Cr	–	58.70
Cu	–	71.17
Zn	19.81	336.72
Pb	–	86.50

Table 3
Leaching test results.

Parameter	Drinking water sludge results (mg/l)	SOF results (mg/l)
Al	10.03	0.21
Cd	0.02	0.02
Ni	–	–
Cr	<0.20	<0.20
Cu	<0.10	<0.10
Zn	–	1.16
Pb	<0.20	0.06

Table 4
Merceological analysis results on the undersieve and the oversieve.

Merceological category	Oversieve (%)	Undersieve (%)
Organic	35	95
Paper	23	1
Inert matter (metals or glass)	21	3
Plastic	16	1
Textiles	5	–

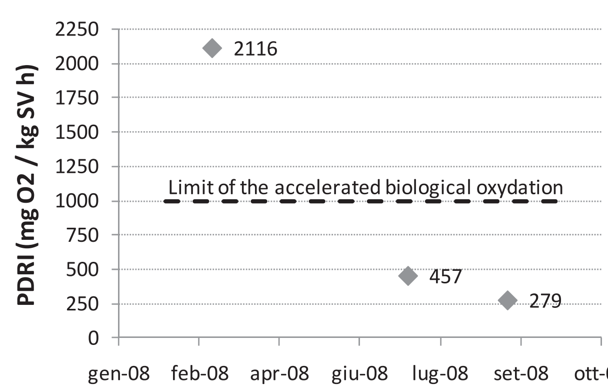

Fig. 2. Variation of the Potential Dynamic Respiration Index in MSW organic fraction.

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Table 5
Results of the vegetation test with *Lactuca sativa*.

	Standard substrate (g)	Sludge (g)	SOF (g)	Epigeal biomass weight (g)	Epigeal biomass dry weight (g)
Dose 0 (control)					
Vase A	277.69	0	0	0.044	0.004
Vase B	277.69	0	0	0.061	0.002
Vase C	277.69	0	0	0.031	0.004
Vase D	277.69	0	0	0.077	0.004
Equivalent dose in ton/ha		Mean		0.05325	0.0035
0.0		St. deviation		0.02004	0.001
Dose 1					
Vase A	277.69	0.3885	1.75	0.031	0.005
Vase B	277.69	0.3885	1.75	0.031	0.002
Vase C	277.69	0.3885	1.75	0.051	0.004
Vase D	277.69	0.3885	1.75	0.119	0.008
Equivalent dose in ton/ha		Mean		0.058	0.00475
38.7		St. deviation		0.041745	0.0025
Dose 2					
Vase A	277.69	0.4773	2.15	0.047	0.003
Vase B	277.69	0.4773	2.15	0.051	0.004
Vase C	277.69	0.4773	2.15	0.096	0.005
Vase D	277.69	0.4773	2.15	0.113	0.005
Equivalent dose in ton/ha		Mean		0.07675	0.00425
47.6		St. deviation		0.032827	0.000957
Dose 3					
Vase A	277.69	0.5661	2.55	0.115	0.008
Vase B	277.69	0.5661	2.55	0.082	0.004
Vase C	277.69	0.5661	2.55	0.11	0.009
Vase D	277.69	0.5661	2.55	0.065	0.003
Equivalent dose in ton/ha		Mean		0.093	0.006
56.5		St. deviation		0.02365	0.002944
Dose 4					
Vase A	277.69	0.6549	2.95	0.045	0.003
Vase B	277.69	0.6549	2.95	0.082	0.004
Vase C	277.69	0.6549	2.95	0.061	0.004
Vase D	277.69	0.6549	2.95	0.086	0.004
Equivalent dose in ton/ha		Mean		0.0685	0.00375
65.3		St. deviation		0.019122	0.0005
Dose 5					
Vase A	277.69	0.7437	3.35	0.091	0.003
Vase B	277.69	0.7437	3.35	0.084	0.004
Vase C	277.69	0.7437	3.35	0.068	0.007
Vase D	277.69	0.7437	3.35	0.068	0.005
Equivalent dose in ton/ha		Mean		0.07775	0.00475
74.2		St. deviation		0.011615	0.001708
Dose 6					
Vase A	277.69	0.8325	3.75	0.072	0.003
Vase B	277.69	0.8325	3.75	0.062	0.005
Vase C	277.69	0.8325	3.75	0.076	0.004
Vase D	277.69	0.8325	3.75	0.075	0.004
Equivalent dose in ton/ha		Mean		0.07125	0.004
83.0		St. deviation		0.006397	0.000816

3. Results and discussion

3.1. Characterization of materials

3.1.1. Granulometric analysis of drinking water sludge

The granulometric analysis allowed us the classification of the material as a weakly sandy clay-silt, as can be seen in the curve reported in Fig. 1.

Sludge has a permeability coefficient between $k = 10^{-8}/10^{-6}$ m/s, and a variation interval close to the one characterizing clay ($k = 10^{-9}/10^{-4}$ m/s). Such information suggests the possible use of drinking water sludge to replace clay in the technical top layer of landfills.

3.1.2. Chemical analysis of sludge and SOF: determination of heavy metals and leaching tests

The results obtained from the analytical determinations of metals on drinking water sludge and SOF samples are reported in Table 2. There was a significant difference of the concentration between drinking water sludge, which does not present any contamination except for aluminium (polyvinyl aluminum is added as a coagulant reagent during the drinking water treatment), and SOF. Concentrations of metals in SOF are low if compared with values

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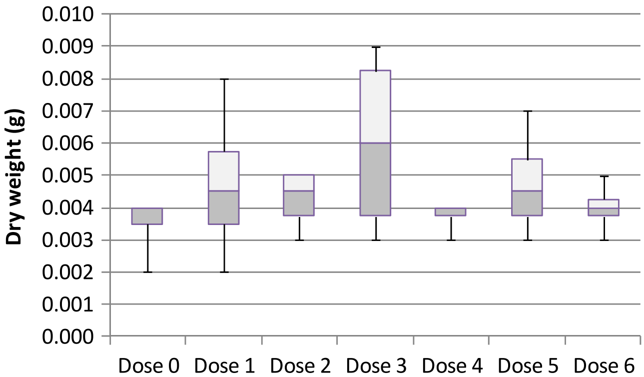

Fig. 3. Box plots of the epigeal biomass dry weights for the seven dosages.

found in literature (Prechthai et al., 2008). Moreover, if we assimilate drinking water sludge and SOF to sewer sludge, the obtained concentrations are lower than the limits prescribed by the US EPA for land application of sewer sludge (US EPA, 1995).

Table 3 reports the results of the ICP measurement in the liquid phase from the leaching test, for drinking water sludge and SOF respectively. The concentration values of the metals present in the samples analyzed are very low. Consequently, in a landfill, the mixture "sludge – SOF – natural soil" used as a superficial top layer do not release high concentrations of metals if it is exposed to atmospheric agents.

3.1.3. Merceological analysis of SOF

At the Venosa platform, the waste underwent a screening at 80 mm and the undersieve was submitted to an aerobic biological stabilization in biocells. From these biocells, the material was submitted to a 20 mm screen which when collected gave the following results:

- 41% oversieve;
- 59% undersieve.

The merceological analysis gave the percent composition of the oversieve and the undersieve fractions shown in Table 4.

The undersieve, after previous aeration at the Codra Mediterranea plant, produced the SOF sample.

Its product analysis highlighted that it possesses the agronomic characteristics of the compost; consequently it is suitable for the formation of "bio-soils".

Table 6
Results of the germination and radical elongation tests with *Spartium junceum*.

Dose	Repetition	Equivalent dose (ton/ha)	Number of germinated seeds	Average number of germinated seeds	Radical length (mm)	GI (%)	Inib (%)
1	A	200	4	4.83	106.5	55	18
	B		6		92.8	71	29
	C		6		81.2	62	38
	D		4		110.5	57	15
	E		5		85.8	55	34
	F		4		109.8	56	16
2	A	750	6	5.17	93.7	72	28
	B		5		101.6	65	22
	C		5		104.2	67	20
	D		5		93.0	60	28
	E		6		99.5	77	23
	F		4		126.3	65	3
3	A	1000	6	5.00	80.5	62	38
	B		4		94.3	48	28
	C		6		71.2	55	45
	D		4		90.8	47	30
	E		5		79.6	51	39
	F		5		63.8	41	51
4	A	1500	5	3.83	98.0	63	25
	B		2		26.0	7	80
	C		3		115.7	45	11
	D		4		121.5	62	7
	E		4		90.5	46	30
	F		5		70.4	45	46
5	A	2000	5	4.83	95.6	61	26
	B		6		80.5	62	38
	C		5		89.0	57	32
	D		4		111.0	57	15
	E		5		91.4	59	30
	F		4		103.8	53	20
6	A	3000	5	4.67	100.8	65	22
	B		4		128.3	66	1
	C		5		115.8	74	11
	D		4		139.5	72	−7
	E		5		119.2	76	8
	F		5		116.0	74	11
7	A	4000	5	4.83	111.6	72	14
	B		4		146.8	75	−13
	C		6		97.0	75	25
	D		4		128.5	66	1
	E		5		105.4	68	19
	F		5		109.2	70	16

3.2. Determination of the SOF biological stability

We have reported the results obtained from the respirometric analysis of the material which underwent treatment in biocells for 20 days and a subsequent aeration for seven.

The values obtained for the Potential Dynamic Respiration Index, PDRI, were equal to 2116 mgO_2/kgSSV h. Considered the high value obtained for the PDRI, we decided that the material required a further period of stabilization. Therefore, the SOF was subjected to an additional stage of refining by using a 10 mm sieve, and further maturation without forced ventilation, combined with mechanical handling at weekly intervals, for 60 days.

After 60 days of ripening, the material tested reached PDRI values compatible with an extremely safe delivery to the landfill. After a further 60 days, in fact, the level of biological activity of the material was virtually identical to the ligno-peaty soils of undergrowth, as shown in Fig. 2.

3.3. Tests on the mixtures of SOF and drinking water sludge

3.3.1. Results of vegetation test with L. sativa

The results of the vegetation test with *L. sativa* are reported in Table 5. The judgment of suitability to vegetation growth is mainly based on the interpretation of the results of the statistical comparison referring to the average dry weight. We assessed whether the seven levels of concentration of the mixture of grey compost and sludge are statistically differentiated at the level of significance $\alpha = 0.05$ through an ANOVA test. The result of the ANOVA test affirms that the major variability of data is due to the diversity of the values in each series rather than to the diversity of the seven series of measurements. The value of probability obtained is equal to 0.45, which is greater than the significance $\alpha = 0.05$. This means that the seven series of measurements can be considered statistically equal.

The reading of the box plots in Fig. 3 demonstrates that the distribution of the samples obtained does not show a great variance. This means that the increasing dosage does not influence the growth of *L. sativa*. Therefore, we can infer that the analyzed product does not negatively affect the growth of plants and that it can be considered suitable for agricultural use.

3.3.2. Results of the germination and radical elongation test with S. junceum

Through the germination and radical development trials, we tried to identify a dose/effect relation able to allow us the assessment of which concentration of the mixture under study gives the best results at the earliest phases of the development of a vegetable species commonly used in interventions of environmental restoration. Table 6 shows the results obtained from the germination and radical elongation test with *S. junceum*. The control had an average radical length of 130 mm and six germinated seeds.

The judgment of suitability to vegetation growth is mainly based on the interpretation of the results of the statistical comparison referring to the number of germinated plants and to the radical length. We assessed whether the seven tested doses are statistically differentiated at the level of significance $\alpha = 0.05$ through two ANOVA tests. The results of the ANOVA test on the number of germinated plants affirms that the major variability of data is due to the diversity of the values in each series rather than to the diversity of the seven series of measurements. The value of probability obtained is equal to 0.20, which is greater than the significance $\alpha = 0.05$. This means that the seven series of measurements can be considered statistically equal. The results are confirmed by observing the box plots in Fig. 4a and b. The graph in Fig. 4c shows a very low variation of the average Germination Index at the analyzed mixture doses. This means that the analyzed product does not negatively affect the growth of plants and that it can be considered suitable for interventions of environmental restoration. We observed, moreover (graphs in Fig. 4c and d) that the dose more favorable to the development of the broom is equal to 750 t/ha ss and that the increasing of this dose causes firstly a decline of the Germination Index, GI (with a corresponding increase of the Inhibition Index) and then its growth, but only for higher doses to which, however, excessive concentrations of copper and nickel in the eluate correspond, as we showed in paragraph 3.2.3.

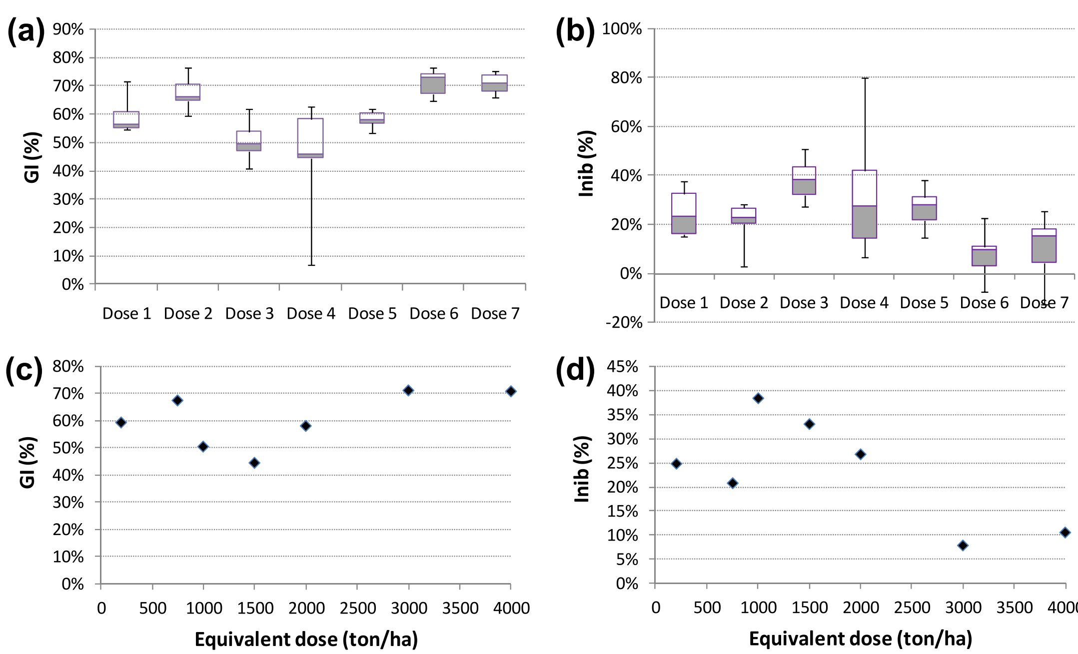

Fig. 4. (a) Box plots of the Germination Index (%), GI, for the seven dosages. (b) Box plots of the Inhibition Index (%), Inib, for the seven dosages. (c) Trend of the average Germination Index at the various mixture doses. (d) Trend of the average Inhibition Index at the various mixture doses.

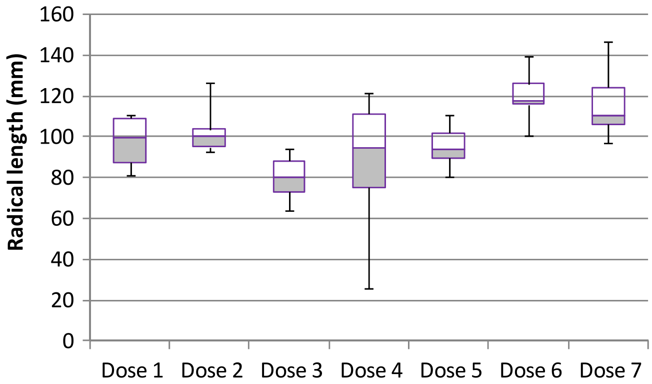

Fig. 5. Box plots of the radical length for the seven dosages.

The results of the ANOVA test on the radical length affirms that around 60% of the variability of data is due to the diversity of the values in each series, meanwhile 40% of the variability of data is due to the diversity of the seven series of measurements. The value of probability obtained is equal to 0.0045, which is lower than the significance $\alpha = 0.05$. This is an indication that the series of measurements from the different doses are not the same. This means that the seven series can be considered statistically dissimilar. We can get some graphical assurance that the means are different by looking at the box plots in Fig. 5. Therefore, we can infer that the analyzed product does not negatively affect the growth of plants and that it can be considered suitable for agricultural use.

4. Conclusions

The analyses carried out showed that the chemical composition of the drinking water sludge does not show substances that could be dangerous for the environment, as we noticed a low risk of contamination for human beings and low concentrations of transfer pollutants to soil and groundwater.

Taking into account the results obtained from the experiments, we can ascertain that the use of low-concentration SOF (values between 200 and 750 t ss/ha), allows us to obtain good results in the case of the creation of ''bio-soils'' for the top covering layer of closed landfills. The effects of such values are of little significance, with a release of eutrophicating elements in percolation waters only in the initial phases, since the removal of fertilizing elements, especially nitrogen, is maximized by vegetation. On the contrary, the use of higher quantities of SOF (1500/2000 t ss/ha) gives, mainly during the initial phases, a limited drainage with subsequent phenomena of hydromorphia of the substratum and release of eutrophicating elements and heavy metals in percolating water. It is also important to bio-stabilize the SOF in order to obtain a greater biological stability.

The use of SOF and drinking water sludge to build ''bio-soils'' and technical layers for covering waste disposal plants allows us the extension of their operation period, the compacting of stocked materials, the saving of inert material and environmental recovery. The ''bio-soil'' obtained from the sieving, stabilisation and maturation of the SOF from MSW, mixed with drinking water sludge, is suitable to have an amending action for the daily covering of landfills or final covering of closed landfills. There are no significant environmental risks even with doses higher than 2000 ton ss/ha in single applications. SOF recovery is made easier in plants which use low intensity cycles of mechanical treatments and with aeration static systems. Under such conditions, SOF and drinking water sludge recovery can be a concrete measure to reduce the quantities of materials conveyed to landfills until there is the full development of the system of sorted collection at the source of the biodegradable organic fractions.

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