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Quarry rehabilitation employing treated residual sludge from dimension stone working plant

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Abstract	<p>Waste from stone and aggregate quarrying industry represents a serious environmental and economic problem in view of the difficulties related to its disposal, especially of the finest fraction. Although some attempts have been made to investigate possible reuse of these materials, little is known about their potential as components of a cultivation substrate. Their low physical and chemical fertility require the mixing with other materials to improve the general properties. The aim of this study was to evaluate if such a prospect product can be employed within the quarry for its environmental rehabilitation. Samples from gangue saw with abrasive shot (GSS), from diamond frame saw (DSS), and mixed sludge (MS)—from gangue and DSS—were collected and mixed with compost, green manure, and soil material. The resulting mixtures were further composted, distributed on parcels within the quarry area and sowed. The original materials and the mixtures were analyzed for metals and hydrocarbons (TPH) and for their phytotoxicity.</p>	

The parcels were sampled and analyzed after 8 years. The results show that mixing with foreign materials can improve the overall quality and fertility of the sludge and that the mixture is not phytotoxic. Most metals concentrations decreased on mixing and further diminished after 8 years. TPH content was drastically reduced and fertility parameters tend toward equilibrium. This indicates that the residual sludge can be employed for quarrying rehabilitation after improvement of its fertility and of its environmental quality.

Keywords (separated by '-') Residual sludge - Stone industry - Quarry remediation - Cultivation substrate - Italy

Footnote Information

2 **Quarry rehabilitation employing treated residual sludge**
3 **from dimension stone working plant**

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Keywords Residual sludge · Stone industry · Quarry 38
remediation · Cultivation substrate · Italy 39

Introduction 40

Quarrying is a very important industry in Italy especially 41
for dimension stones and aggregates. The overall turnover 42
of the production chain (quarries, working plants, labora- 43
tories, shops, etc) was nearly 40 billion € in 2011, almost 44
2 % of the Italian Gross Domestic Product (Ceruti 2013). 45
In addition, Italian dimension stone exploitation during 46
2012 shows an export increment of 9.8 % from 2011 and 47
an import decrement of -6 % (from 2011 to 2012). These 48
values show the importance of quarrying industry which is, 49
at present, characterized by an incertitude due to global 50
crisis in the stone sector (Anonymous 2013). 51

Exploitation activities require an obligatory phase of 52
environmental rehabilitation of both dumps and quarrying 53
areas: the soil stripped during exploitation phases has to be 54
separated from the waste rocks, and it should be saved for 55
the subsequent vegetation re-establishment in the quarry 56
area (Neri and Sanchez 2010). Topsoil from external 57
sources is often employed for the purpose, however, due to 58
the lengthy duration of the quarrying activities or whenever 59
old abandoned quarries have to be remediated (Brodckom 60
2001; Milgrom 2008) and this results in an additional cost. 61
On the other hand, quarries and working plants produce 62
huge amounts of waste that has a potential for recovery 63
(Luodes et al. 2012). The most difficult to recover is the 64
residual sludge (EWC code 01 04 13—waste from stone 65
cutting and sawing), a very fine material that can be used 66

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67 either as a filler for land rehabilitation or as a feeding
68 material for different industrial uses, or dumped (Ministero
69 dell’Ambiente 2006; Dino et al. 2013). The current cost
70 connected to sludge landfilling may represent more than
71 3 % of the operating costs of dimensional stone working
72 plants so there is an increasing interest into its recovery for
73 environmental restoration.

74 The possibility of employing waste materials in quarry
75 rehabilitation has been investigated by several authors.
76 Bending et al. (1999) offered an overview of the possibility
77 of using various materials for the rehabilitation of quarries.
78 Sort and Alcañiz (1996) had studied the effects of sewage
79 sludge additions to control erosion in limestone quarries.
80 They reported a positive effect on soil physical properties
81 in general and on soil loss in the plots treated with the
82 sludge. More recently, the effects of applying urban wastes
83 to quarries in arid environments were investigated by
84 Castillejo and Castelló (2010). On the contrary, Bonoli and
85 Dall’Ara (2012) observed negative effects in the environ-
86 mental restoration of a former quarry by paper sludge with
87 production of unwanted biogas.

88 Burrigato et al. (1999) investigated the possibility of
89 employing a mud from siliceous sand treatment for envi-
90 ronmental rehabilitation. They observed that the size of
91 mud particles and the lack of pores were conducive to
92 progressive compaction and rendered the sludge virtually
93 impermeable. This may represent a threat for the soil sur-
94 face erosion and its permeability, and ultimately may
95 increase the risk of landslides. Therefore, the physical and
96 chemical structure of the sludge matrix should be properly
97 adjusted. To this aim, Barrientos et al. (2010) advocate the
98 use of granite sawdust as a soil surface sealant in view of
99 its physical properties. Similarly, a recent paper by Sivri-
100 kaya et al. (2014) illustrated the effectiveness of stone
101 waste in improving the physical quality of clayey soils. A
102 direct agricultural application of such materials is seem-
103 ingly hindered by their low chemical and physical fertility
104 but they could be treated and recovered to obtain a culti-
105 vation substrate. If used in quarry rehabilitation the *cradle-*
106 *to-cradle* principle would be respected as all the exploited
107 material would be sold as products and the waste could be
108 employed for the environmental rehabilitation of the *cradle*
109 quarry site. Little is known, however, about the possible
110 success of the field application of these materials.

111 The paper outlines the results obtained from a remedi-
112 ation treatment of residual sludge coming from dimension
113 stone working plants to obtain an artificial cultivation
114 substrate. The tested bioremediation treatment consists in
115 the composting of a mixture of waste materials (mineral
116 and organic), added with specific activators (Dino et al.
117 2006, 2012). The aim of the research is to evaluate if this
118 prospect product, the artificial substrate, can be employed
119 in quarry rehabilitation.

Materials and methods

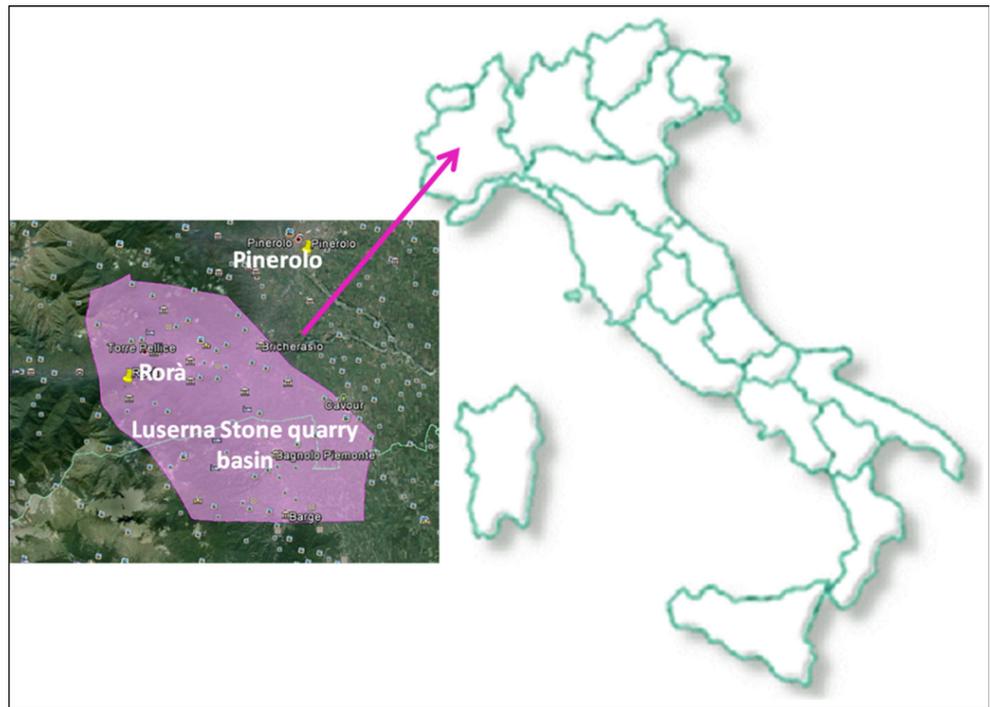
Geographic and geological setting

The materials employed come from local plants which
work *Luserna Stone* blocks, exploited in the area between
Luserna San Giovanni and Bagnolo Piemonte (SW Pied-
mont region, Italy, Fig. 1). *Luserna Stone* is the commer-
cial name of a gray-greenish gneiss, which locally changes
the color to light blue. Petrographically, it is a leucogranitic
orthogneiss characterized by a micro-“Augen” texture
(Sandrone et al. 2000). It pertains geologically to the Dora-
Maira Massif (Sandrone et al. 1993) and it outcrops in quite
a wide area (approximately 50 km²) in the Cottian Alps
(Fig. 2); it shows a sub-horizontal attitude, with a marked
foliation that is mostly associated to a visible lineation. The
layers rich in mica give the flat schistous aspect to the rock;
the average distance between the layers is 7–8 cm (range
2–40 cm). The principal components of the rock are quartz,
mica, and feldspar (Table 1) and its chemical composition
is shown in Table 2.

Sludge from the working plant

The products which reach the stone market are mostly slabs,
squared blocks, often sold to other companies, *mosaico* (split
face pieces for “crazy” paving), belgian blocks, and kerb-
stones. The transformation from block to slab is carried out
by means of gangue saw with abrasive shot (GSS), or dia-
mond frame saw or by manual wedging. Samples from GSS,
sludge from diamond frame saw (DSS), and mixed sludge
(MS)—from gangue and diamond frame saw in the case of a
single productive line—were collected in accordance with
the method ISO/DIS 10381-1-2. Samples were air-dried,
gently crushed and sieved to <2 mm with plastic sieves to
reduce metal contamination. Grain-size analysis was per-
formed by sieving according to ASTM standards (D421-85;
D422-63). A portion of the sample was further ground to
<0.15 mm for *aqua regia* (HCl/HNO₃, 3:1 solution)
digestion. Metal content (As, Cd, Co, Cr, Fe, Hg, Mn, Ni, Pb,
and Zn) was determined by ICP–OES (TJA IRIS Advantage/
1000 radial plasma spectrometer) in the *aqua regia* extracts.
The analyses were performed by following the standard
methods of the Italian Ministry of Agriculture (Mipaf 1999).
Triplicates were made for all samples and results accepted
when the coefficient of variation was within 5 %. A blank
and soil CRM BCR 141 R reference material (Joint Research
Centre—Institute for Reference Materials and Measure-
ments, Geel, Belgium) were included in each batch of
analyses for quality control. Results were considered satis-
factory when within a range of ±10 % from the certified
value. Furthermore, total petroleum hydrocarbons (TPH)
were determined by ISO 16703:2004 method.

Fig. 1 Geographical setting: in the enlargement on the left the quarry in Rorà (TO): Cava del Tiglio–Pra del Torno (44°47'36"N 7°11'07"E) is indicated



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169 **Mixing materials**

170 The materials employed for the experimentation were
 171 compost, shredded pruning material (green manure), and a
 172 soil material taken from a grassland near the quarry area.
 173 The compost from municipal organic waste and the green
 174 manure (clippings from gardening operations) were
 175 obtained from the ACEA Pinerolese company which
 176 operates in Pinerolo (Turin, Italy). These materials were
 177 characterized by following the same methodology
 178 employed for sludge characterization. Organic C and total
 179 N were measured by dry combustion (Methods ISO 10694;
 180 13878). Approximately 35 m³ (60 t) of each sludge type
 181 (humidity around 30 %) and 60 m³ (40 t) of mixing
 182 material were used to obtain the mixtures. Previous
 183 experiments had demonstrated that these proportions gen-
 184 erated the optimal conditions for the physical and biolog-
 185 ical functioning of the mixture. In particular, another
 186 research (Dino et al. 2003a, b) on the recovery of diamond
 187 frame saw sludge (gneiss material from Canton Ticino,
 188 Switzerland) was conducted; the products obtained from
 189 sludge bioremediation treatment were employed for envi-
 190 ronmental rehabilitation.

191 **Composting process**

192 The composting of the four mixtures (Fig. 3) was started in
 193 the spring and was carried on for 12 weeks. The mix-
 194 tures were arranged in triangular-shaped heaps (70 m³:

2.5 × 1.6 × 35 m) placed under a shed. Completion of the
 composting process was ensured by regular suction filtra-
 tion and air regulation, wetting, and mechanical mixing and
 homogenization of the material. These operations were
 programmed on the basis of the results obtained by peri-
 odical physical and biological parameter tests. Process
 operating conditions (temperatures, colony forming units-
 CFU/g, pH, and moisture) were monitored and occasion-
 ally reassessed during the fermentation (4 weeks), as well
 as during the maturing phase (8 weeks) (Dino et al. 2006).
 The mixtures were chemically and physically characterized
 following the same methodology employed for their start-
 ing materials.

Phytotoxicity of the composted mixtures

Phytotoxicity was tested in greenhouse bioassays, in order
 to evaluate their effects on the germination and growth of
 crops. Corn, winter wheat, and lentils were planted
 (10 seeds/pot) in each of the mixture in a random block
 scheme (five replicates). After 4 and 17 weeks, total
 number of plants, plants height (in cm), and dry matter
 production were determined. The compost and the soil used
 for the mixtures were used as controls.

The total (150 m³) of the four mixes was employed for
 quarry rehabilitation in *Luserna Stone Basin*: it was dis-
 tributed in plots of 10 m in width and length (thickness
 8–10 cm) on a hill side in “Cava del Tiglio” Loc. Pra del
 Torno (Fig. 4), in Rorà village (Turin) and sown with a

Fig. 2 Structural sketch map of the Western Alps (Dino et al. 2003a, b). 1 Delphinois-Helvetic domain (dashed line external crystalline massifs). Penninic Domain—2 Prealps, 3 Subbriançonnais Zone, 4 Briançonnais Zone, 5 Simplon-Tessin Nappes (A Antigorio, ML Monte Leone) and Camughera-Orselina-Moncucco Zone (CM), 6 Internal crystalline massifs (MR Monte Rosa, GP Gran Paradiso, DM Dora Maira), 7 Piedmontese Zone; North-Penninic Calcschists; Triassic-Neocomian succession of Versoyen, Montenotte and Sestri-Voltaggio Units, 8 Alpine Helminthoid Flysch of Ubaye-Embrunais and Liguria, 9 Sesia-Lanzo Zone (SL) and Dent Blanche Nappe (DBL), 10 Southern Alps, 11 Post-Alpine intrusives of Traversella and Valle del Cervo, 12 Appennines and Tertiary sediments of the Turin Hill, 13 Quaternary and Tertiary sediments of the Ligurian-Piedmontese Basin, 14 Main tectonic lines (CL Canavese Line, SVL Sestri-Voltaggio line), 15 Granite, 16 Serizzo, 17 Beola, 18 Luserna Stone

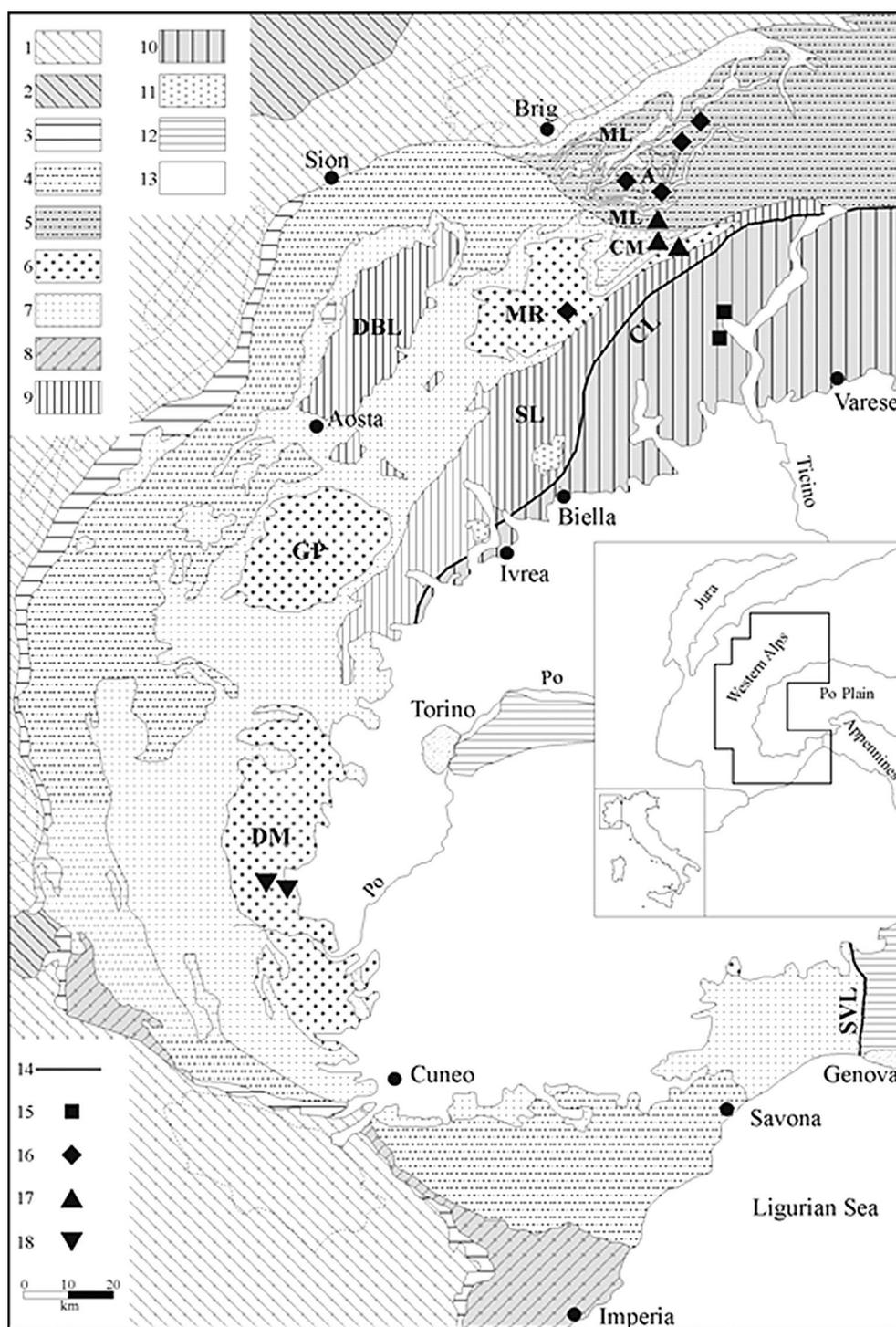


Table 1 Modal composition (% w/v) range of Luserna Stone

Quartz	K-feldspar	Plagioclase (% anorthite)	Biotite and/or chlorite	Phengite	Others
30–45	10–25	15–25 (2–5)	4–8	10–20	≤3

Data from Vialon (1966) and Barisone et al. (1979)

mixture of *Lolium perenne* L., *Festuca rubra* L., and *Poa pratensis* L. (Dino et al. 2006). A geotextile was placed over the plots to protect them from erosion.

In October 2013, all the plots were sampled, and all the sampled materials were characterized following the same methodology employed for the starting materials.

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Table 2 Chemical composition (% weight of oxides) of Luserna Stone (Sandrone et al. 1982)

SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	CaO	MgO	K ₂ O	Na ₂ O	P ₂ O ₃
71.6–75.8	0.1–0.2	13.1–15.6	0.4–1.0	0.3–0.7	0.8–1.2	0.4–1.1	3.7–5.2	2.9–4.7	0.1–0.4

Fig. 3 Treatment flow sheet

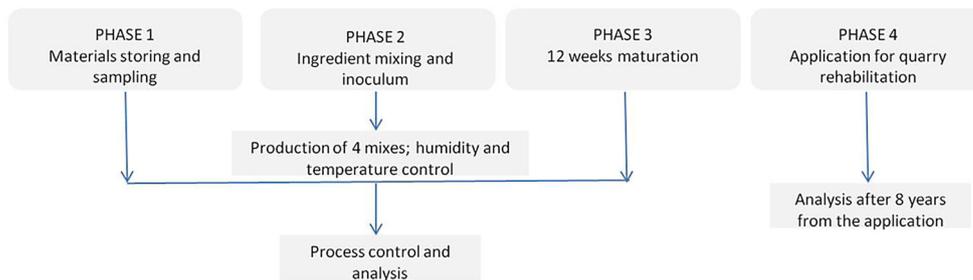


Fig. 4 Scheme of plots present on the hill side of “Cava del Tiglio” Loc. Pra del Tomo—Rorà, Turin (44°47’36”N 7°11’07”E). **a** 1st step of quarry rehabilitation; **b** plant growth 3 months after seeding; **c** quarry rehabilitation after 8 years

228 **Results and discussion**

229 The characteristics of the residual sludge depend on the
 230 nature of the mother rock and on the working activities
 231 they undergo. In all cases, the sludge material was char-
 232 acterized by an alkaline pH, due to the use of lime as an
 233 antioxidant in the sawing operation. The average pH was
 234 **AQ1** 10.7 for GSS, 9.2 for DSS, and 11.2 for MS. The size
 235 distribution is fine (more than 40 % is <25 μm average
 236 diameter) all samples being clayey silt weakly sandy. The
 237 solid fraction of the sludge constitutes, for its physical
 238 characteristics, an impermeable massive material which
 239 would not be usable, as such, for plant growing. The sludge
 240 contains variable amounts of metals and hydrocarbons
 241 (TPH) coming from working activities (Table 3). GSS
 242 contains notable amounts of metals coming from abrasive
 243 shot, in particular Cr and Cu, and Zn; DSS contains metals
 244 from the binder material of diamond cutting tools—Co,
 245 Cu—and has also the highest Zn concentration. The MS
 246 samples are heavily enriched in Cr, Cu, and Ni. Compared
 247 to the Italian legislative thresholds for soils (Ministero
 248 dell’Ambiente 2006), Cd, Co, Cr, Cu, and Ni and TPH in
 249 all materials result to be above the limits for residential

250 areas reinforcing the notion that sludge cannot be used as
 251 such (Dino 2004). Magnetic separation of the metals from
 252 the GSS sludge was tested in a specific project (PIC
 253 Interreg III A “Residual sludge exploitation”). The metal
 254 concentration was decreased, but the technical feasibility
 255 of the method is still debated (Dino et al. 2003a, b).

256 The sludge was mixed with organic materials and a soil
 257 in view of improving its fertility and environmental qual-
 258 ity. The organic materials (Table 4) have a high pH and,
 259 while the compost has an equilibrated C/N, in the green
 260 manure carbon material prevails; the soil has a circum-
 261 neutral pH and an average content of C and N. The con-
 262 tents of contaminants (Table 4) are relatively high for some
 263 metals in the compost: Cr, Cu, and Zn are above the Italian
 264 legislative limits. This was taken into account in the
 265 composition of the mixtures (Table 5). The mixtures have
 266 properties that reflect their composition (Table 6). While
 267 the pH remains above neutrality, the C/N ratio increases in
 268 consideration of the inclusion of green manure. The general
 269 biological quality, as illustrated by the CFU count (Fig. 5),
 270 shows a definite improvement at the end of the process,
 271 fostering the use of the mixes for cultivation. The mixing
 272 and composting of the materials had some effects on the

273 contaminant contents. While TPH decreased sharply, the
 274 metals showed somewhat erratic results as a consequence
 275 of their relatively high concentration in the compost. Co,
 276 Cr, and Cu are still above the legislative limits for soils of
 277 green and residential areas in some of the mixes. The
 278 performance of the mixtures was tested in terms of ger-
 279 mination (Fig. 6) and yield (Fig. 7) of lentil (*Lens culin-*
 280 *aris*, Medik.), corn (*Zea mays*, L.), and winter wheat
 281 **AQ2** (*Triticum aestivum*, L.). Although in general the results
 282 were below the performance of a standard compost used as
 283 a benchmark, neither the mixes, nor the sludge itself

284 appeared to be harmful to the plants tested. It should be
 285 noted, in addition, that the mixes in some cases produced a
 286 better results than those of the soil.

287 Eight years after the implementation, the substrate was
 288 again sampled and analyzed (Table 7). The plots had never
 289 been irrigated nor the plants were removed. The results
 290 show that while the pH has remained above 7 in all cases,
 291 the content of organic C and N tends toward equilibrium
 292 with a decrease of the amount of C and a consequent
 293 decrease of the C/N ratio. The metal content, as well as the
 294 TPH concentration all are reduced after 8 year with the
 295 notable exception of Pb. No sources of Pb contamination
 296 are present in the area. It is then possible that the inorganic
 297 forms of Pb have become more labile through the years and
 298 the *aqua regia* extraction—which does not extract part of
 299 the residual, more stable forms (Rauret et al. 1999)—was
 300 more complete at the end of the experiment. The increase
 301 in mobility of metals has been observed, e.g., in experi-
 302 ments of repeated soil reduction–oxidation cycles (Balint

Table 3 Contaminants in the sludge

		GSS	DSS	MS	Italian legislative threshold values for soils according to their use	
					Green, residential	Commercial, industrial
As	µg/kg	9.8	14.2	12.9	20	50
Hg	µg/kg	0.9	0.1	0.4	1	5
Cd	mg/kg	1.8	0.6	3.1	2	15
Co	mg/kg	14.4	89.4	18.7	20	250
Cr	mg/kg	166	24.5	189	150	800
Cu	mg/kg	188	49.9	219	120	600
Ni	mg/kg	95.3	10.1	132	120	500
Pb	mg/kg	12.6	8.2	14.9	100	1,000
Zn	mg/kg	75.7	98.8	38.8	150	1,500
TPH	mg/kg	746	411	165	50	750

Italic values exceed the threshold values of the Italian legislations

Table 4 Characteristics and contaminants of organic materials and the soil (values are on dry weight—d.w.)

		Compost	Green manure	Soil
pH		8.6	7.5	6.4
Total organic C	%	24	32	1.9
Total N	%	2.3	0.51	0.18
C/N ratio		10.3	63.3	10.6
As	µg/kg	3.9	2.0	12.9
Hg	µg/kg	0.5	0.1	0.1
Cd	mg/kg	<0.5	<0.5	0.6
Co	mg/kg	bdl*	4	19
Cr	mg/kg	154	76	94
Cu	mg/kg	142	34	45
Ni	mg/kg	98	47	84
Pb	mg/kg	82	19	37
Zn	mg/kg	330	104	80
TPH	mg/kg	bdl*	889	319

* Below detection limit

Italic values exceed the threshold values of the Italian legislations

Table 5 Composition of the four mixes (% d.w.)

	Mix A	Mix B	Mix C	Mix D
GSS	–	–	62	–
DSS	59	59	–	–
MS	–	–	–	61
Compost	18	14	8	8
Green manure	23	17	20	20
Soil	–	10	10	11
Total	100	100	100	100

Table 6 Properties and contaminants of Mix A, B, C, and D after the composting process

		Mix A	Mix B	Mix C	Mix D
pH		7.6	7.6	7.6	8.0
Total organic C	%	7.7	4.9	7.6	6.9
Total N	%	0.26	0.18	0.23	0.28
C/N ratio		29	27	33	25
As	µg/kg	11.2	13.5	10.8	9.7
Hg	µg/kg	<1	<1	<1	<1
Cd	mg/kg	0.5	0.5	0.5	0.5
Co	mg/kg	49	62	13	14
Cr	mg/kg	41	36	190	122
Cu	mg/kg	72	63	207	168
Ni	mg/kg	31	30	116	90
Pb	mg/kg	22	14	26	23
Zn	mg/kg	116	91	99	93
TPH	mg/kg	10	10	10	10

Italic values exceed the threshold values of the Italian legislations as reported in Table 3 (values are on dry weight—d.w.)

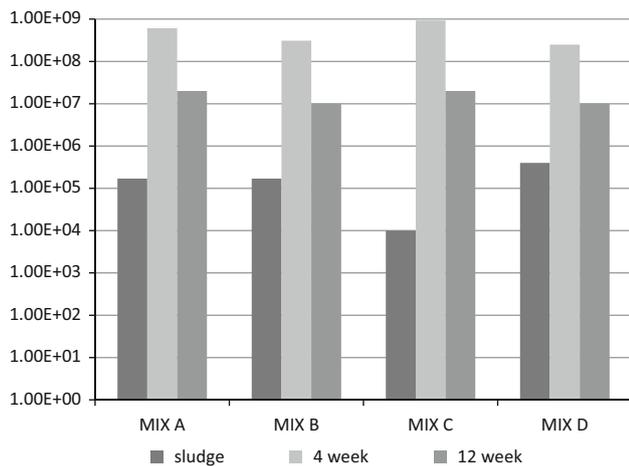


Fig. 5 Colony-Forming Unit (CFU) changes from t0 (start of composting) to t4 (4th week after start) and to t12 (12th week after composting start)

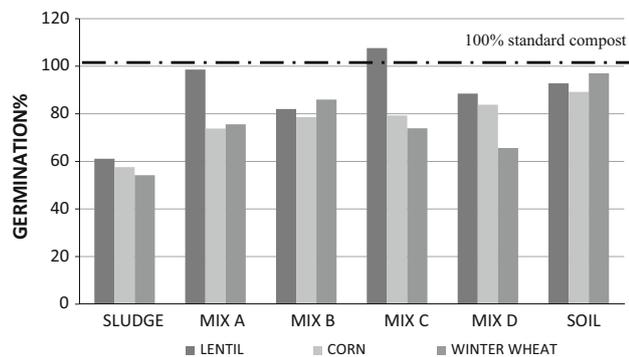


Fig. 6 Germination ratio versus standard compost (100 % = standard compost)

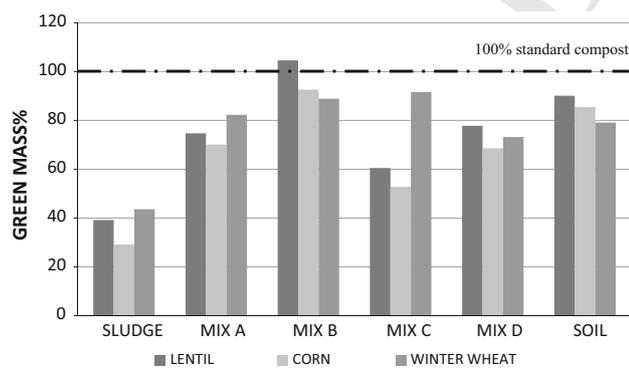


Fig. 7 Green mass development versus standard compost (100 % = standard compost)

et al. 2014) and the effect of the vegetation itself should be taken into account. In a comprehensive study of Pb in the area of Oslo (Norway) Reimann and coworkers

Table 7 Characterization and contaminant contents of the four mixes after 8 years

	Mix A	Mix B	Mix C	Mix D
pH	7.5	7.4	8.1	8.1
Total organic C %	3.2	3.0	4.0	2.9
Total N %	0.22	0.25	0.29	0.19
C/N ratio	14	12	14	15
As µg/kg	11.2	12.1	10.8	9.7
Hg µg/kg	<1	<1	<1	<1
Cd mg/kg	0.5	0.5	0.8	0.7
Co mg/kg	32	54	24	16
Cr mg/kg	40	32	130	84
Cu mg/kg	65	59	174	91
Ni mg/kg	32	29	103	63
Pb mg/kg	30	20	39	31
Zn mg/kg	83	78	99	79
TPH mg/kg	10	10	10	10

Italic values exceed the threshold values of the Italian legislations as reported in Table 3 (values are on dry weight—d.w.)

demonstrated a distinct effect of the components of the biosphere on the cycling of Pb in the environment.

Conclusions

A pilot experiment was conducted for the remediation of a quarry site using dimension stone sludge, soil, and/or organic waste materials such as composted municipal waste and green manure. Despite the presence of numerous inorganic and organic contaminants, the mixtures gave positive results both in terms of abatement of contaminants and improvement of mid-term fertility. After eight years from the implementation, and without external intervention—irrigation, fertilization or cropping—the mixtures host a composite vegetation and show no sign of surface erosion. The environmental quality of the substrate, in terms of concentration of contaminants, could be improved. A more scrupulous consideration of the proportion of the components in terms of environmental quality would easily improve the response of the method. The employment of such waste materials appears to be promising in view of the general adoption of the *cradle-to-cradle* principle.

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