



Waste washing pre-treatment of municipal and special waste

Raffaello Cossu^a, Tiziana Lai^{a,*}, Kostyantyn Pivnenko^b

^a Department of Hydraulic, Maritime, Environmental and Geotechnical Engineering, University of Padua, Lungargine Rovetta, 8 – 35127, Padova, Italy

^b Department of Environmental Engineering, Technical University of Crete, Politechniopolis, 73100 Chania, Greece

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ABSTRACT

Long-term pollution potential in landfills is mainly related to the quality of leachate. Waste can be conveniently treated prior to landfilling with an aim to minimizing future emissions. Washing of waste represents a feasible pre-treatment method focused on controlling the leachable fraction of residues and relevant impact. In this study, non-recyclable plastics originating from source segregation, mechanical–biological treated municipal solid waste (MSW), bottom ash from MSW incineration and automotive shredder residues (ASR) were treated and the removal efficiency of washing pre-treatment prior to landfilling was evaluated. Column tests were performed to simulate the behaviour of waste in landfill under aerobic and anaerobic conditions. The findings obtained revealed how waste washing treatment (WWT) allowed the leachability of contaminants from waste to be reduced. Removal rates exceeding 65% were obtained for dissolved organic carbon (DOC), chemical oxygen demand (COD) and Total Kjeldahl Nitrogen (TKN). A percentage decrease of approximately 60% was reached for the leachable fraction of chlorides, sulphates, fluoride and metals, as proved by a reduction in electric conductivity values (70%).

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1. Introduction

Modern landfill design should aim to adopt the most effective, environmentally sustainable strategy to deal with the leachable fraction of waste that poses a potential threat to the environment in the short and long term. The objective is to achieve an equilibrium with the environment, a final storage quality (FSQ), within the span of one generation [1]. The pre-treatment of waste prior to landfilling plays a fundamental role in achieving this goal [2].

Selected biodegradable waste fractions can be conveniently treated mechanically and biologically before landfilling to minimize future emissions [i.a. 3]. Further to this option and to thermal treatment, other methods of waste pre-treatment may be applied to reduce the leachability of contaminants from waste prior to landfilling. In particular, the washing of waste represents an innovative method.

Several studies have demonstrated the efficacy of the washing of incineration residues in reducing the leachable fraction of metals [4–7]. A recent study on washing of automotive shredder residues (ASR) has demonstrated an efficiency rate of more than 60% in the removal of dissolved organic carbon (DOC), metals, chlorides, sulphates, fluorides [8].

Waste washing treatment (WWT) could likewise be applied prior to landfilling to residues of different waste management processes: non-recyclable plastics originated from source segregation, mechanical–biological treated municipal solid waste (MSW) and ASR [9].

In order to assess the potential of WWT for full scale application, technical washing tests were carried out at the Sanitary Engineering Laboratory of the University of Padua (LISA) and the removal efficiency was evaluated.

Following evaluation of the removal efficiency, column tests were conducted under both aerobic and anaerobic conditions with the aim of assessing the emission potential of washed waste in landfill.

2. Experimental set-up

The general scheme for the research programme is illustrated graphically in Fig. 1.

Samples of different waste were washed on a technical scale. Raw waste samples and washed waste samples were compared to assess landfill acceptability by carrying out standard batch leaching tests. Subsequently, landfill simulation of washed waste was carried out in small lysimeter columns.

2.1. Sample composition and characterization

Technical scale washing tests were performed on five types of waste:

* Corresponding author. Tel.: +39 049 827 8990; fax: +39 049 827 8984.

E-mail addresses: raffaello.cossu@unipd.it (R. Cossu), tiziana.lai@unipd.it, la.tiziana@gmail.com (T. Lai), kpivnenko@isc.tuc.gr (K. Pivnenko).

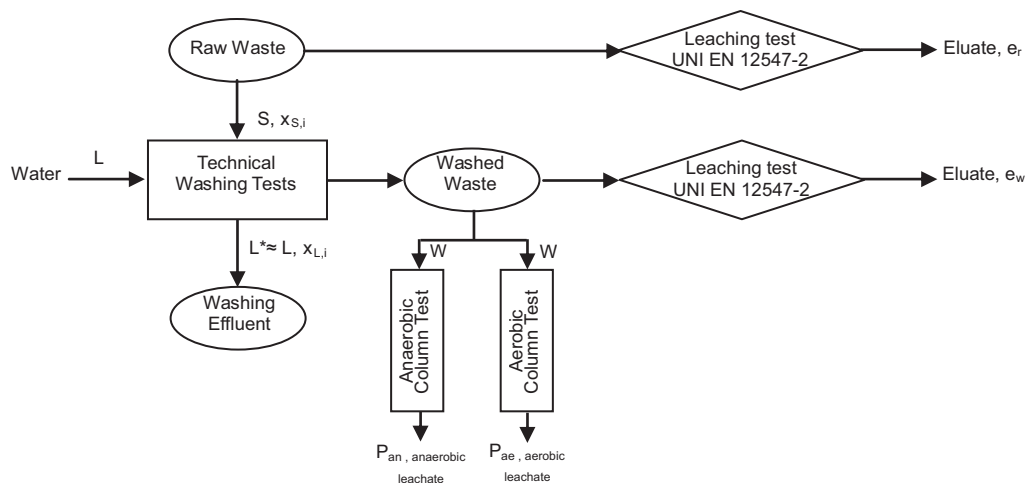


Fig. 1. Scheme of the experimental methodology (L : amount of washing water; S : amount of washed waste; $x_{S,i}$: concentration of i -substance in the raw waste; L^* : amount of washing effluent; $x_{L,i}$: concentration of i -substance in the washing effluent; W : amount of washed waste in column; $e_{r,i}$: concentration of the i -substance in the eluate of batch leaching test for the raw waste samples; and $e_{w,i}$: concentration of the i -substance in the eluate of batch leaching test for the washed waste samples).

- USP: under-sieve residues from plastics sorting process;
- ESP: end residues from plastics sorting process;
- MBT: mechanical–biological treated waste;
- BA: bottom ash from MSW incineration; and
- ASR: automotive shredder residues.

The first two residues were sampled in a sorting plant for source segregated plastics (Fig. 2).

The USP residue is generated from the ballistic sorting unit and is mainly made up of non-recyclable fine fraction, representing 20% of total input material. The ESP residue is constituted by the non-recyclable portion of the heavy fraction, representing 15% of total input material.

All samples from MSW management were collected in treatment plants located in the Veneto Region, Italy. The production of waste in the area is 1.3 kg/cap/d. The average composition is reported in Table 1. Source segregation rates are among the highest in Italy, reaching mean values of 43% [10].

The ASR sample was collected at a plant for the mechanical treatment (shredding and sorting) of end-of-life vehicles (ELV). Whilst metals and other components are forwarded to recover the residual light fraction (ASR), representing approximately 30% of total weight of ELV, is landfilled. The plant, located in Northern Italy, produces approximately 6000 tons of ASR per year (2008).

All residues were sampled according to the Italian reference method UNI 10802 [11], collecting a minimum quantity of 50 kg for each material.

Table 1

Average composition of municipal solid waste in the Veneto Region, Italy [10].

| | |
|---|-------|
| Putrescible fraction | 20.0% |
| Garden waste | 15.0% |
| Paper and paperboard | 20.6% |
| Plastics | 11.7% |
| Glass | 7.0% |
| Textiles | 2.5% |
| Aluminium, ferrous and non-ferrous materials | 2.3% |
| Wood | 0.9% |
| Other (fine fraction, tetra pak, inert materials, napkins, hazardous waste ...) | 20.0% |

First all samples were classified in terms of fine fraction (<20 mm and <10 mm for the bottom ash) and other material fractions that differed according to each individual type of waste. The samples were then ground to a size <4 mm using a laboratory cutting mill (model Retsch SM 2000) and analysed.

Analyses were carried out on both the solid and the leachable fraction using the equipment and methods reported in Table 2.

The solid fractions were analysed for the following parameters: total solids (TS), volatile solids (VS), respirometric index (RI₇), Total Kjeldahl Nitrogen (TKN), total organic carbon (TOC) and metals (Ba, Cd, Cr, Cu, Mo, Ni, Pb, Zn). Analyses were performed in triplicate.

Batch leaching tests were performed as established by UNI EN 12547-2. Eluates, filtered at 0.45 μm, were analysed for the following parameters: chemical oxygen demand (COD), DOC, TKN, metals (Ba, Cd, Cr, Cu, Mo, Ni, Pb, Zn), electric conductivity (EC), chlorides,

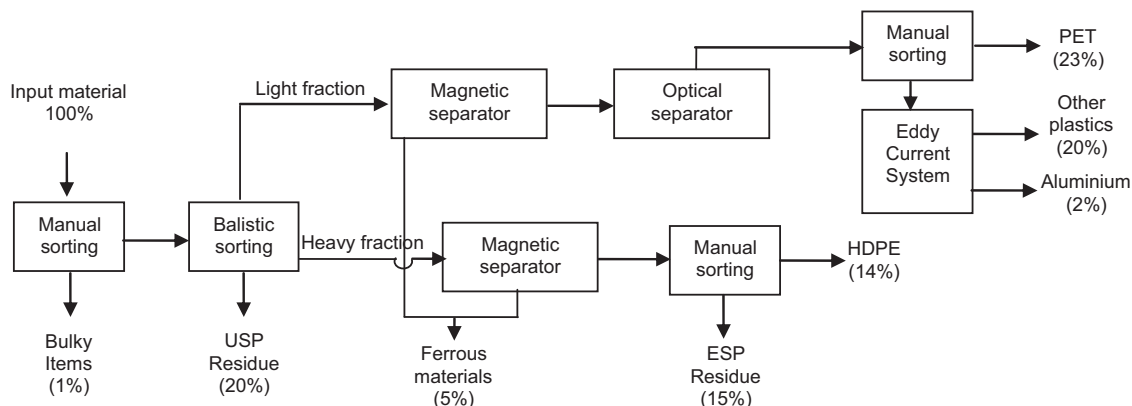


Fig. 2. Scheme of the sorting plant for source segregated plastics where USP and ESP residues were sampled [9].

Table 2
Reference analytical methods and equipment used in testing of liquid and solid samples.

| Parameter | Sample | Reference method/equipment | Description |
|--------------------------------|--------|-------------------------------------|--|
| TS | Solid | IRSA CNR Q.64/85 vol. 2 n° 2 | Gravimetric methods after drying at 105 °C for 12 h |
| | Liquid | IRSA CNR 29/03 vol. 1 n° 2090 A | |
| VS | Solid | IRSA CNR Q.64/85 vol. 2 n° 2 | Gravimetric methods after drying at 550 °C for 4 h |
| | Solid | Sapromat and VoithSulzer Respiromat | |
| TKN | Solid | IRSA CNR Q.64/85 vol. 3 n° 6 | Determination of ammonia by titration with a standard mineral acid, after conversion of amino nitrogen and free ammonia into ammonium by acid digestion followed by distillation |
| | Liquid | IRSA CNR 29/03 vol. 2 n° 5030 A | |
| TOC | Solid | Shimadzu TOC-VCSN analyser | Infrared detection of CO ₂ during dry combustion |
| | Liquid | Shimadzu TOC-VCSN analyser | |
| DOC | Liquid | IRSA CNR 29/03 vol. 2 n° 5040 | Infrared detection of CO ₂ during dry combustion |
| COD | Liquid | IRSA CNR 29/03 vol. 2 n° 5130 | Acid digestion with potassium dichromate followed by titration with Mohr's salt |
| Ba, Cd, Cr, Cu, Mo, Ni, Pb, Zn | Solid | EPA 1996 n° 6010 | Analysis of aqua regia extracts by inductively coupled plasma atomic emission spectroscopy |
| | Liquid | IRSA CNR 29/03 vol.1 n° 3010+3020 | |
| Cl ⁻ | Liquid | IRSA CNR 29/03 vol. 2 n° 4090 | Direct titration with silver nitrate |
| F ⁻ | Liquid | IRSA CNR 29/03 vol. 2 n° 4100B | Potentiometric method |
| SO ₄ ²⁻ | Liquid | IRSA CNR 29/03 vol. 2 n° 4140A | Turbidimetric method: precipitation of barium sulphate in HCl medium |
| pH | Liquid | IRSA CNR 29/03 vol. 1 n° 2060 | Potentiometric method |
| EC | Liquid | IRSA CNR 29/03 vol. 1 n° 2030 | Measure of electrical resistance using a conductivity cell |

fluorides, and sulphates. Parameters were determined by standard methods [12,13].

2.2. Washing tests

Washing tests were carried out by introducing 5 kg of material (ground to <4 mm) into a mixing device (a commercial mixer for concrete preparation) and adding water to reach a liquid/solid ratio L/S=5. This value together with test duration (6 h) was chosen on the basis of optimal conditions observed in a previous study carried out by the authors [9].

After washing, the solid and liquid fractions were separated and the solid fraction used for the second part of the research (column tests).

2.3. Landfill condition simulation

Following washing and separation from liquid fraction, the material was packed into PMMA (polymethylmethacrylate) columns with an internal diameter of 10 cm and a height of 104 cm (Fig. 3). The upper end of each column is equipped with valves providing for the introduction of water and sampling of gas, the lower end is equipped with a valve for leachate extraction.

For each waste sample two separate columns were set up, one simulating aerobic (AE) and the other anaerobic conditions (AN). Aerobic conditions were achieved by injection of air by means of an air pump (maximum delivery capacity 4 Nl/h).

Water was added on a daily basis and leachate samples were collected for different L/S ratios: 1, 2, 3, 5, 10, 15. In order to ensure a good flow distribution, and avoid clogging of the leachate collection valve, a gravel layer (gravel size 20–40 mm; height 100 mm) was placed both at the bottom of the column and above the waste layer. The observation period lasted 3 months.

3. Results and discussion

3.1. Waste composition

Composition of waste samples expressed as percentage by weight of total mass is shown in Table 3.

As expected, plastic was prevalent in USP and ESP samples. USP was also characterized by a high presence of putrescible (7.4%)

and fine fractions (37%). Metals in USP (5.5%) were mostly represented by cables and crushed electronic equipment, whereas ESP (1%) contained mainly aluminium particles.

MBT was characterized by more than 70% of fine fractions, whilst plastic content (13%) was largely made up of non-biodegradable plastic bags used for waste collection. BA was represented almost entirely by the fine fraction (87%); non-combustible materials such as metals (2%) and inert materials (11%) were also present. ASR sample was represented mostly by the fine fraction (42%) as a consequence of shredding pre-treatment, in addition to textiles and foam stuffing fraction (33%). The metal fraction, accounting for more than 5% of the composition, consisted mainly in electric cables (2.8%).

3.2. Physical and chemical characterization of waste

The results of physical and chemical characterization of waste samples prior to testing are shown in Table 4.

The highest TOC content (75% TS) was observed in ESP sample whilst the lowest, as expected, in the BA sample (<0.02% TS).

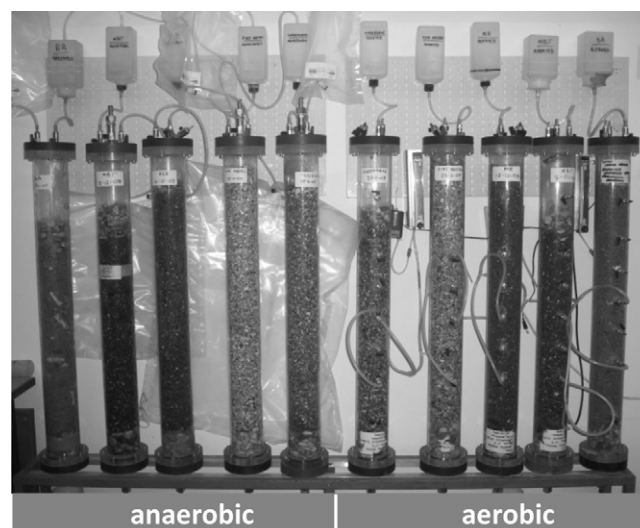


Fig. 3. Column test apparatus.

Table 3
Composition of waste samples.

| | USP | ESP | MBT | BA | ASR |
|---------------------------|-------|-------|-------|-------|-------|
| Composites | – | 1.0% | 0.5% | – | – |
| Glass and inert materials | 6.4% | 0.3% | 4.4% | 11.0% | – |
| Metals | 5.5% | 1.0% | 1.5% | 2.0% | 5.2% |
| Municipal hazardous waste | 1.2% | – | 0.2% | – | – |
| Plastics | 40.0% | 91.0% | 13.3% | – | 13.0% |
| Putrescible fraction | 7.4% | 0.5% | 1.9% | – | – |
| Wood and paper | 2.5% | 5.2% | 7.5% | – | 0.8% |
| Rubber | – | – | – | – | 6.1% |
| Textiles and sponge | – | – | – | – | 32.9% |
| Under-sieve 20 mm | 37.0% | 1.0% | 70.7% | – | 42.0% |
| Under-sieve 10 mm | – | – | – | 87.0% | – |

USP: under-sieve residues from plastic sorting process; ESP: end residues from plastic sorting process; MBT: mechanical–biological treated waste; BA: bottom ash from MSW incineration; and ASR: automotive shredder residues.

Table 4
Chemical–physical analysis of raw waste samples.

| | Unit | USP | ESP | MBT | BA | ASR |
|-----------------|--|------|------|------|-------|-------|
| TS | g _{TS} /g _{TSQ} | 0.89 | 0.98 | 0.75 | 0.74 | 0.87 |
| VS | g _{VS} /g _{TS} | 0.67 | 0.97 | 0.44 | 0.04 | 0.67 |
| TOC | g _C /g _{TS} | 0.60 | 0.75 | 0.32 | <0.02 | 0.59 |
| RI ₇ | mg _{O₂} /g _{TS} | 4.6 | 3 | 15.3 | 1 | 6.3 |
| TKN | g _N /kg _{TS} | 6.5 | 1.4 | 10.9 | 0.5 | 19.8 |
| Ba | mg/kg _{TS} | 25.7 | 23.6 | 130 | 1473 | 1363 |
| Cd | mg/kg _{TS} | 2.10 | 0.28 | 0.51 | 0.78 | 3.63 |
| Cr | mg/kg _{TS} | 9.35 | 4.60 | 177 | 413 | 88 |
| Cu | mg/kg _{TS} | 200 | 16.4 | 604 | 6029 | 10574 |
| Mo | mg/kg _{TS} | 0.85 | 3.03 | 7.84 | 50.5 | 15.9 |
| Ni | mg/kg _{TS} | 7.25 | 1.35 | 79.9 | 337 | 72.6 |
| Pb | mg/kg _{TS} | 14.2 | 7.92 | 281 | 1115 | 1332 |
| Zn | mg/kg _{TS} | 166 | 19.7 | 606 | 4516 | 3946 |

USP: under-sieve residues from plastic sorting process; ESP: end residues from plastic sorting process; MBT: mechanical–biological treated waste; BA: bottom ash from MSW incineration; and ASR: automotive shredder residues.

Seven-day respirometric index (RI₇) indicated low biological activity for all materials. The highest value (15 mg_{O₂}/g_{TS}) was observed for the MBT sample.

The highest TKN content was measured for ASR and MBT samples (approximately 2% and 1% TS, respectively). This is mainly due to the presence of polyurethane plastics and foam in ASR sample [14], and proteins and humic substances in MBT sample [15].

The modest content of TKN detected in BA sample was constituted by uncombusted organic matter [16].

The highest metal content was observed for copper and zinc in the ASR sample (10570 mg/kg_{TS} and 3950 mg/kg_{TS}, respectively,

corresponding to approximately 1% and 0.4%). Copper was present in electric cables whilst zinc is used in tyres and paint as pigment additive.

Copper and zinc concentrations exceeding 6000 and 4500 mg/kg_{TS} were also found in BA sample. Previous studies have shown that copper and zinc concentrations in bottom ashes vary considerably mainly due to waste composition differences [17,18].

MBT featured a significant content of lead (281 mg/kg_{TS}), copper and zinc (approximately 600 mg/kg_{TS}) to be connected to the street sweeping residues, characterized by a high heavy metal concentration [19,20].

Table 5
Values ($x_{L,i}$) of different parameters (*i*) analysed in the effluent from the technical washing tests.

| | Unit | USP | ESP | MBT | BA | ASR |
|-------------------------------|--------------------------------|--------|-------|--------|--------|--------|
| TOC | mg _C /l | 1073 | 506 | 838 | 96 | 191 |
| COD | mg _{O₂} /l | 4741 | 4573 | 4174 | 191 | 515 |
| TKN | mg _N /l | 288 | 118 | 231 | 12.0 | 11.8 |
| Ba | mg/l | 0.13 | 0.59 | 0.76 | 0.07 | 0.39 |
| Cd | mg/l | <0.003 | 0.007 | <0.003 | <0.003 | <0.003 |
| Cr | mg/l | 0.05 | 0.16 | 0.50 | 0.05 | <0.02 |
| Cu | mg/l | 0.37 | 0.65 | 1.16 | 0.80 | 0.19 |
| Mo | mg/l | 0.02 | 0.03 | 0.10 | 0.17 | 0.06 |
| Ni | mg/l | 0.28 | 0.08 | 0.48 | <0.02 | 0.15 |
| Pb | mg/l | 0.09 | 0.28 | 0.49 | 0.06 | 0.35 |
| Zn | mg/l | 9.06 | 3.04 | 1.83 | 0.18 | 4.08 |
| Cl [−] | mg/l | 301 | 266 | 1206 | 745 | 95 |
| F [−] | mg/l | 0.22 | 0.53 | 0.20 | <0.05 | 0.25 |
| SO ₄ ^{2−} | mg/l | 833 | 9 | 1190 | 19 | 112 |
| EC | mS/cm | 3.3 | 1.6 | 6.7 | 4.5 | 0.7 |
| pH | – | 5.9 | 6.2 | 7.5 | 11.7 | 6.9 |

USP: under-sieve residues from plastic sorting process; ESP: end residues from plastic sorting process; MBT: mechanical–biological treated waste; BA: bottom ash from MSW incineration; and ASR: automotive shredder residues.

Table 6
Efficiency of the waste washing treatment (η_w) in the removal of different substances.

| | USP | ESP | MBT | BA | ASR |
|-----|-------|-------|-------|-------|-------|
| TOC | 0.89% | 0.34% | 1.33% | 2.40% | 0.16% |
| TKN | 22.0% | 41.0% | 11.0% | 11.8% | 0.30% |
| Ba | 2.53% | 12.5% | 2.92% | 0.02% | 0.14% |
| Cd | 1.43% | 12.5% | 5.88% | 3.85% | 0.83% |
| Cr | 2.67% | 17.4% | 1.41% | 0.06% | 0.11% |
| Cu | 0.93% | 19.8% | 0.96% | 0.07% | 0.01% |
| Mo | 8.82% | 4.95% | 6.38% | 1.68% | 1.89% |
| Ni | 19.3% | 29.6% | 3.00% | 0.03% | 1.03% |
| Pb | 3.17% | 17.7% | 0.87% | 0.03% | 0.13% |
| Zn | 27.3% | 77.2% | 1.51% | 0.02% | 0.52% |

USP: under-sieve residues from plastic sorting process; ESP: end residues from plastic sorting process; MBT: mechanical–biological treated waste; BA: bottom ash from MSW incineration; and ASR: automotive shredder residues.

Table 7
Batch leaching performance for the different waste considered in this research, before (e_r) and after washing (e_w). Concentration in eluates are compared with the limits for waste acceptance in landfill, set by the Italian regulation (D.M. 27/09/2010), for different kind of waste (I: inert; NH: non-hazardous; SH: stable non-reactive hazardous in non-hazardous waste landfills; and H: hazardous).

| | Unit | USP | | ESP | | MBT | | BA | | ASR | | I | NH | SH | H |
|-------------------------------|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|------|------|------|
| | | e_r | e_w | e_r | e_w | e_r | e_w | e_r | e_w | e_r | e_w | | | | |
| DOC | mg _C /l | 578 | 114 | 261 | 22 | 623 | 215 | 30.6 | 24 | 94.6 | 35 | 50 | 100 | 80 | 100 |
| COD | mg _{O₂} /l | 977 | 139 | 480 | 58 | 1342 | 563 | 89 | 36 | 231 | 101 | – | – | – | – |
| TKN | mg _N /l | 50 | <5 | 25 | <5 | 105 | 27 | 7.8 | <5 | 8.4 | <5 | – | – | – | – |
| Ba | mg/l | 0.08 | 0.07 | 0.09 | 0.04 | 0.14 | 0.06 | 0.14 | 0.04 | 0.27 | 0.21 | 2 | 10 | 10 | 30 |
| Cd | mg/l | <0.003 | <0.003 | <0.003 | <0.003 | <0.003 | <0.003 | <0.003 | <0.003 | <0.003 | <0.003 | 0.004 | 0.1 | 0.1 | 0.5 |
| Cr | mg/l | 0.02 | 0.01 | 0.02 | <0.01 | 0.32 | 0.11 | 0.07 | 0.02 | <0.01 | <0.01 | 0.05 | 1 | 1 | 7 |
| Cu | mg/l | 0.17 | 0.03 | 0.18 | 0.01 | 0.34 | 0.15 | 0.46 | 0.22 | 0.19 | 0.04 | 0.2 | 5 | 5 | 10 |
| Mo | mg/l | <0.01 | <0.01 | 0.02 | <0.01 | 0.07 | 0.02 | 0.17 | 0.06 | 0.04 | 0.02 | 0.05 | 1 | 1 | 3 |
| Ni | mg/l | 0.20 | 0.04 | <0.02 | <0.02 | 0.36 | 0.14 | <0.02 | <0.02 | 0.10 | 0.02 | 0.04 | 1 | 1 | 4 |
| Pb | mg/l | <0.03 | <0.03 | <0.03 | <0.03 | 0.12 | 0.10 | <0.03 | <0.03 | <0.03 | <0.03 | 0.05 | 1 | 1 | 5 |
| Zn | mg/l | 1.51 | 0.14 | 0.51 | 0.06 | 1.46 | 0.84 | 0.38 | 0.04 | 2.28 | 0.43 | 0.4 | 5 | 5 | 20 |
| Cl ⁻ | mg/l | 195 | 78 | 124 | 71 | 674 | 301 | 443 | 121 | 94 | 47 | 80 | 2500 | 1500 | 2500 |
| F ⁻ | mg/l | 0.18 | 0.04 | 0.17 | 0.03 | 0.12 | 0.08 | 0.12 | 0.07 | 0.19 | 0.08 | 1 | 15 | 15 | 50 |
| SO ₄ ²⁻ | mg/l | 429 | 44.5 | 3 | 0.4 | 114 | 61.5 | 28 | 10.6 | 43 | 11.8 | 100 | 5000 | 2000 | 5000 |
| EC | mS/cm | 2 | 0.6 | 0.9 | 0.2 | 4.2 | 1.4 | 3.2 | 0.9 | 0.5 | 0.2 | – | – | – | – |
| pH | – | 7.6 | 8.2 | 7.5 | 7.5 | 7.6 | 8.2 | 11.4 | 11.7 | 7.8 | 7.5 | – | – | – | – |

USP: under-sieve residues from plastic sorting process; ESP: end residues from plastic sorting process; MBT: mechanical–biological treated waste; BA: bottom ash from MSW incineration; and ASR: automotive shredder residues.

3.3. Waste washing test

Table 5 illustrates the parameters analysed in effluent from washing tests.

USP displayed the highest emission of TOC (1070 mg_C/l), COD (4740 mg_{O₂}/l) and TKN (290 mg_N/l). MBT displayed largely similar levels of TOC, COD and TKN emissions (840 mg_C/l, 4170 mg_{O₂}/l and 230 mg_N/l).

With regard to heavy metals the highest values were measured in eluate from USP and ESP (zinc concentration of 9 mg/l and 3 mg/l, respectively) and MBT (zinc and copper concentration of 1.8 mg/l and 1.2 mg/l, respectively).

The characteristics of washing effluent imply the need for treatment prior to discharge into surface waters. Because of the low concentration of organic compound and the relatively high concentration of heavy metals, biological treatment does not seem to

Table 8
Efficiency of the acceptability increase ($\eta_{A,i}$) calculated for different substances, after washing treatment. e_r and e_w values from batch leaching test are reported in Table 7.

| | USP | ESP | MBT | BA | ASR |
|-------------------------------|------|------|------|------|------|
| DOC | 80% | >90% | 65% | 22% | 63% |
| COD | 86% | 88% | 57% | 60% | 56% |
| TKN | >90% | 80% | 74% | >36% | >40% |
| Ba | 13% | 56% | 57% | 71% | 22% |
| Cd | n.c. | n.c. | n.c. | n.c. | n.c. |
| Cr | 50% | >50% | 66% | 71% | n.c. |
| Cu | 82% | 94% | 56% | 52% | 79% |
| Mo | n.c. | >50% | 71% | 65% | 50% |
| Ni | 80% | n.c. | 61% | n.c. | 80% |
| Pb | n.c. | n.c. | 16% | n.c. | n.c. |
| Zn | 91% | 88% | 42% | 89% | 81% |
| Cl ⁻ | 60% | 43% | 55% | 73% | 50% |
| F ⁻ | 78% | 82% | 33% | 42% | 58% |
| SO ₄ ²⁻ | 90% | 87% | 46% | 62% | 73% |
| EC | 71% | 78% | 66% | 72% | 60% |

USP: under-sieve residues from plastic sorting process; ESP: end residues from plastic sorting process; MBT: mechanical–biological treated waste; BA: bottom ash from MSW incineration; and ASR: automotive shredder residues.
n.c. concentration in eluates of raw samples was under the detection limit of the instrument.

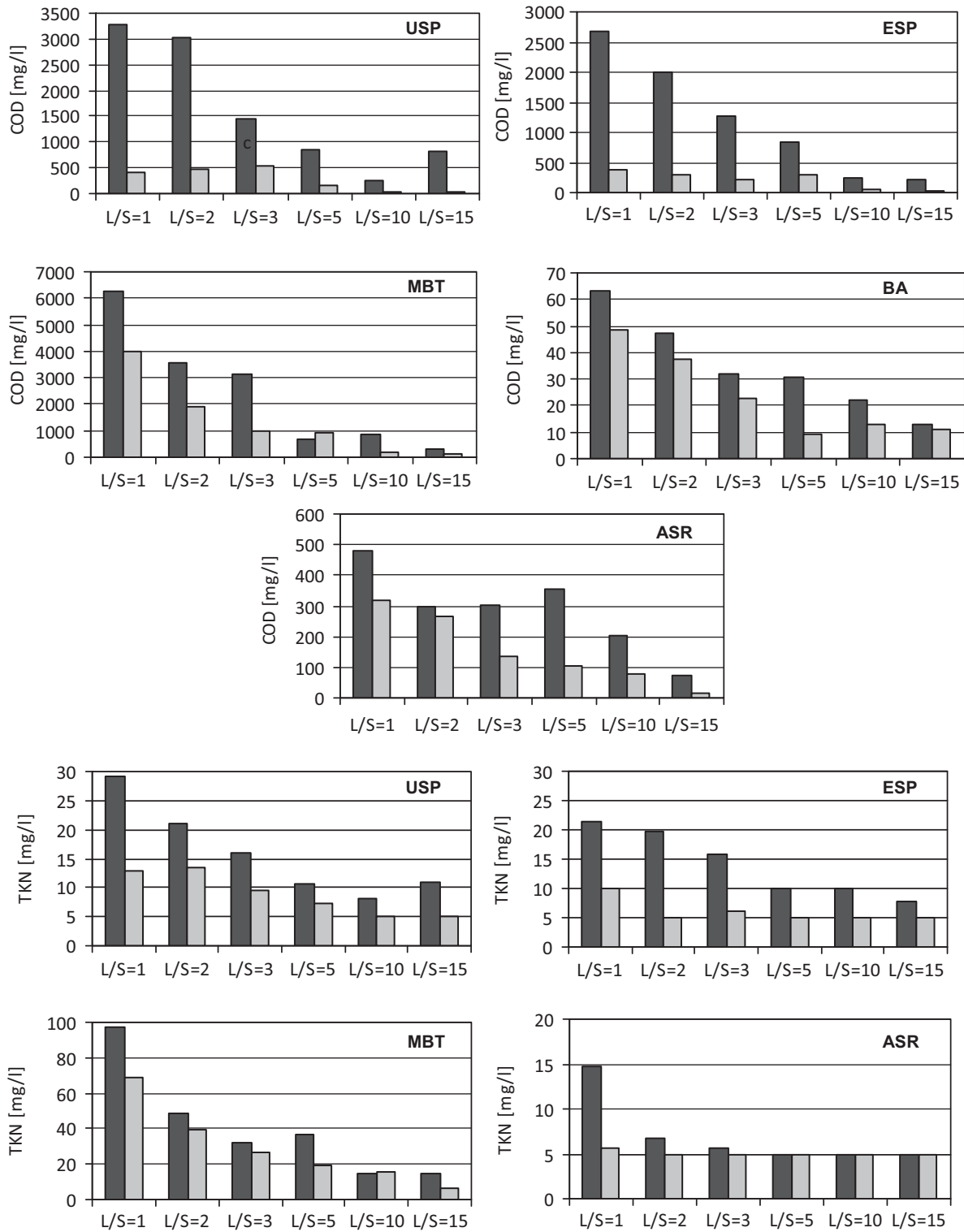


Fig. 4. COD and TKN in the leachate from the columns containing different waste, under anaerobic (■) and aerobic (□) conditions vs different L/S ratios (USP: under-sieve residues from plastic sorting process; ESP: end residues from plastic sorting process; MBT: mechanical-biological treated waste; BA: bottom ash from MSW incineration; and ASR: automotive shredder residues).

be effective [21,22]. Physical/chemical treatment, in a single step or a combination of multiple steps, including: nanofiltration [23], reverse osmosis [24,25], adsorption on different materials such as activated carbon or zeolite [26] could be considered to achieve high removal efficiency [27–29]. The latter in particular displays a high removal efficiency with relatively low capital and operating costs [22,30].

Removal efficiency (η_w) obtained by washing treatment was calculated as follows:

$$\eta_w = \frac{Lx_{L,i}}{Sx_{S,i}} \quad (1)$$

where L is the amount of washing water (l); S the amount of washed waste (kg); $x_{L,i}$ the concentration of i -substance in the washing

effluent; and $x_{S,i}$ the concentration of i -substance in the raw waste, before washing.

It was assumed that the amount of water used for washing (L) was roughly equal to the output of washing effluent (L^*) (see Fig. 1).

Table 6 illustrates the efficiency of waste washing treatment for TKN, TOC and metals.

The highest removal efficiency was measured for TKN and metals, particularly in USP and ESP sample. TKN removal efficiency of 22% and 41% was observed in USP and ESP samples, respectively. The highest removal of metals was measured for zinc (77% for ESP and 27% for USP) and nickel (30% and 19% for ESP and USP, respectively).

Additional pilot scale studies and a life cycle analysis and assessment should be undertaken to evaluate the cost of waste washing treatment and ascertain the environmental performance of waste washed prior to disposal in landfill compared to other alternative and traditional treatments such as direct disposal in landfill [31,32]. Accordingly, the advantages of the proposed technology could be discussed from a broader perspective.

3.4. Improvement of landfill acceptability

Parameters measured in batch leaching tests carried out on raw waste samples are reported in Table 7. The measured values were compared with limits established by Italian regulations (D.M. 27/09/2010) for waste acceptance in landfill.

With the exception of BA, DOC concentrations in eluates invariably exceeded limits established. However, USP, ESP and MBT are assimilated to municipal solid wastes which are not subjected to regulations on landfill acceptance criteria.

The highest COD values were observed in eluate from MBT (1350 mg_{O₂}/l) and USP (1000 mg_{O₂}/l) samples, whilst the lowest concentration of 90 mg_{O₂}/l was found in BA.

TKN concentration was higher in eluates from MBT (105 mg_N/l), whilst lower concentrations were measured in ASR and BA eluates, 8.4 mg_N/l and 7.8 mg_N/l, respectively.

The highest concentrations of metals were detected for zinc (2.3 mg/l in eluate from ASR and 1.5 mg/l in eluate from USP and MBT) and copper (0.46 mg/l in eluate from BA and 0.34 mg/l in eluate from MBT).

Highest EC values were measured for MBT and BA, 4.2 and 3.2 mS/cm, respectively. High values of EC may be correlated with high concentrations of chlorides, metal ions, and with presence of ionized suspended particles [33].

Metal and anion concentrations in eluates of all samples complied with regulation limits for acceptance in non-hazardous waste landfill.

The efficiency of the acceptability increase after waste washing treatment was calculated as follows [9]:

$$\eta_{A,i} = \frac{e_{r,i} - e_{w,i}}{e_{r,i}} \quad (2)$$

where $e_{r,i}$ is the concentration of the i -substance in the eluate of UNI EN 12547-2 batch leaching test for the raw waste samples; and $e_{w,i}$ the concentration of the i -substance in the eluate of UNI EN 12547-2 batch leaching test for the washed waste samples.

Removal percentages calculated for parameters analysed are illustrated in Table 8.

DOC removal efficiency ranged from more than 90% for ESP to 22% for BA. A marked removal of DOC leachable fraction was also observed for USP (80%).

In ASR DOC removal produced a decrease in concentration from batch leaching test eluates from 95 mg/l to 35 mg/l after washing (63%). A similar decrease would result in acceptable levels thus allowing disposal of ASR in a landfill for inert wastes.

Removal percentages calculated for COD are comparable to those calculated for DOC.

Removal efficacy for TKN was significant: concentrations present in eluates from batch leaching tests of USP and ESP decreased following treatment from 50 mg_N/l and 25 mg_N/l, respectively, to a value of <5 mg_N/l.

With regard to heavy metal content, copper and zinc concentrations in eluates obtained from batch leaching tests following washing were significantly lower; the decrease of leachable fraction was more than 80% in almost all samples examined. The electric conductivity decrease, included in a range from 60% to 78%, proved a considerable efficiency removal of metals and anions.

3.5. Landfill simulation

The long-term pollution potential of a landfill is determined by residual concentrations of specific substances present in leachate.

The quality of leachate in aerobic and anaerobic columns after washing pre-treatment was evaluated by comparing time trends obtained for macro parameters such as COD and TKN concentrations. COD showed significant reduction trends with marked differences between aerobic and anaerobic columns.

Fig. 4 illustrates the results obtained for samples analysed. For USP anaerobic columns showed a reduction of COD from values exceeding 3000 mg_{O₂}/l to less than 800 mg_{O₂}/l, whereas in aerobic columns initial COD values were much lower, displaying a decrease from 418 mg_{O₂}/l to 33 mg_{O₂}/l. Similar trend was observed for ESP and MBT samples.

TKN also displayed a reduction trend with slight differences between aerobic and anaerobic columns. The results obtained for TKN in BA columns are not illustrated as concentrations were below detection limits (<5 mg/l).

At the end of the observation period seven-day respirometric index (RI₇) indicated a reduction of biological activity, in particular for MBT (2.8 mg_{O₂}/g_{TS} and 4 mg_{O₂}/g_{TS} for samples from aerobic and anaerobic columns, respectively) and ASR (2.6 mg_{O₂}/g_{TS} and 2.8 mg_{O₂}/g_{TS} for samples from aerobic and anaerobic columns, respectively). USP samples displayed a RI₇ decrease from 4.6 mg_{O₂}/g_{TS} to 1.4 mg_{O₂}/g_{TS} in aerobic column and 2.6 mg_{O₂}/g_{TS} in anaerobic column; similar results for ESP samples (1.3 mg_{O₂}/g_{TS} and 2.7 mg_{O₂}/g_{TS} for samples from aerobic and anaerobic columns, respectively). For both BA samples RI₇ was lower than 1 mg_{O₂}/g_{TS}.

4. Conclusions

Waste washing treatment was applied to residues of different waste management processes in order to reduce the leachable fraction of contaminants prior to landfilling.

The efficacy of pre-treatment was assessed by calculating efficiency of the acceptability increase on the basis of results obtained in batch leaching tests; COD removal was more than 85% for USP and ESP, and approximately 60% for other wastes. After washing a similar removal rate was observed for DOC. In particular, DOC concentration decrease observed for ASR (63%) would be sufficient to allow disposal of this waste in a landfill for inert materials.

The metals released in largest quantities in batch leaching tests were copper and zinc. In particular, after washing the concentrations of these metals released in eluates of batch leaching tests were reduced by 80%. Electrical conductivity decreased subsequent to washing to values ranging from 60 to 78% for ASR and ESP, respectively.

It is feasible to maintain that washing treatment allows the environmental impacts of residues to be minimized prior to disposal in landfills.

The comparison of results for columns operated under anaerobic and aerobic conditions revealed a greater reduction of COD and TKN in particular in aerobic columns.

A combination of pre-treatment and specific landfill management techniques may therefore contribute towards achieving an equilibrium with the environment within a shorter time frame.

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