Automobile shredder residues in Italy: characterization and valorization opportunities

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Highlights

▶ ASR materials coming from two industrial shredding tests are characterized. ▶ The tests differ about the feed and the pre-shredding operations. ▶ Two post-shredding treatments are tested, aimed both at material and thermal recovery. ▶ The proposed treatments may be easily applied by existing shredding plants.

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Automobile Shredder Residues in Italy: Characterization and valorization opportunities

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ABSTRACT

At the moment Automobile Shredder Residue (ASR) is usually landfilled worldwide, but European draft Directive 2000/53/CE forces the development of alternative solutions, stating the 95%-wt recovery of an End of Life Vehicle (ELV) weight to be fulfilled by 2015.

This work describes two industrial tests, each involving 250–270 t of ELVs, in which different pre-shredding operations were performed. The produced ASR materials underwent an extended characterization and some post-shredding processes, consisting of dimensional, magnetic, electrostatic and densimetric separation phases, were tested on laboratory scale, having as main purpose the enhancement of ASR recovery/recycling and the minimization of the landfilled fraction.

The gathered results show that accurate depollution and dismantling operations are mandatory to obtain a high quality ASR material which may be recycled/recovered and partially landfilled according to the actual European Union regulations, with particular concern for Lower Heating Value (LHV), heavy metals content and Dissolved Organic Carbon (DOC) as critical parameters. Moreover post-shredding technical solutions foreseeing minimum economic and engineering efforts, therefore realizable in common European ELVs shredding plants, may lead to multi-purposed (material recovery and thermal valorization) opportunities for ASR reuse/recovery.

1. Introduction

The shortening of autovehicles average life (currently estimated equal to about 10–12 years in European Union, EU) (EU Parliament, 2007; Eurostat, 2009a) produced in the last 15 years an impressive enhancement of End of Life Vehicles (ELVs) amount. At present about 12 M of ELVs (the 75% coming from Germany, UK, France, Spain and Italy) are involved each year in the EU (EU Parliament, 2007; Eurostat, 2009a; Rossetti et al., 2006), 15 M in the United States (EPA, 2006), and more than 4 M in Japan and Korea (Kim and Joung, 2004; Sakai and Noma, 2007), leading to about 50 M/y of ELVs in the world (Jody and Daniels, 2006). Although it should be considered that the export of second-hand cars before they reach their end of life is an important feature of the international car market, resulting in a longer life of the circulating vehicles. Moreover in several EU Countries a relevant difference between deregistered vehicles and scrapped ELVs is observed, because a significant number of vehicles are garaged or abandoned or scrapped by unlicensed operators.

The shredding of an ELV, whose total weight changes from 1.1 to 1.4 t considering European, Japanese or US manufacturers (Ferrao and Amaral, 2006a), has the primary goal of ferrous metals recovery (65–70%-wt of a vehicle total weight, depending on ELV's age), usually sold to secondary fusion foundries. Pre-shredding operations, consisting in depollution (removal of hazardous components, i.e. battery, fluids, oil, LPG tanks, that account for about the 3%-wt of a ELV) and recyclable components dismantling (tires and alloy wheels are usually disconnected, sometimes also fuel tanks, bumpers and windscreens, making in total for the 8–10%-wt of a vehicle), leave behind an heterogeneous material defined Automobile Shredder Residue (ASR) or car fluff (Nourredine, 2007), which counts for about the 20–25% of a vehicle total weight. Actually EU-production of fluff is estimated to be in the order of 2.4 Mt/y, against a total amount of hazardous wastes of more than 97 Mt/y (Eurostat, 2009b). This trend is destined to dramatically increase, because vehicles composition changes affects both quality and quantity of ASR: in the last decades automotive manufacturers were inclined to deplete vehicles fuel consumption by enhancing the fraction of light components and materials (Ferrao and Amaral, 2006a; Passarini et al., 2012).

ASR is generally made of about 20–30%-wt of plastic (rigid, polyurethane foam – PUF, textiles), 15–20%-wt of rubber (simple, textile/metal reinforced), 20–40%-wt of paper and wood, and of about 10%-wt of not combustible materials (i.e. inerts, such as glass, paint, soil) and metals (magnetic, non-magnetic and PVC wrapped wires) (Kim and Joung, 2004; Lanoir et al., 1997; Mirabile et al., 2002; Forton et al., 2006).

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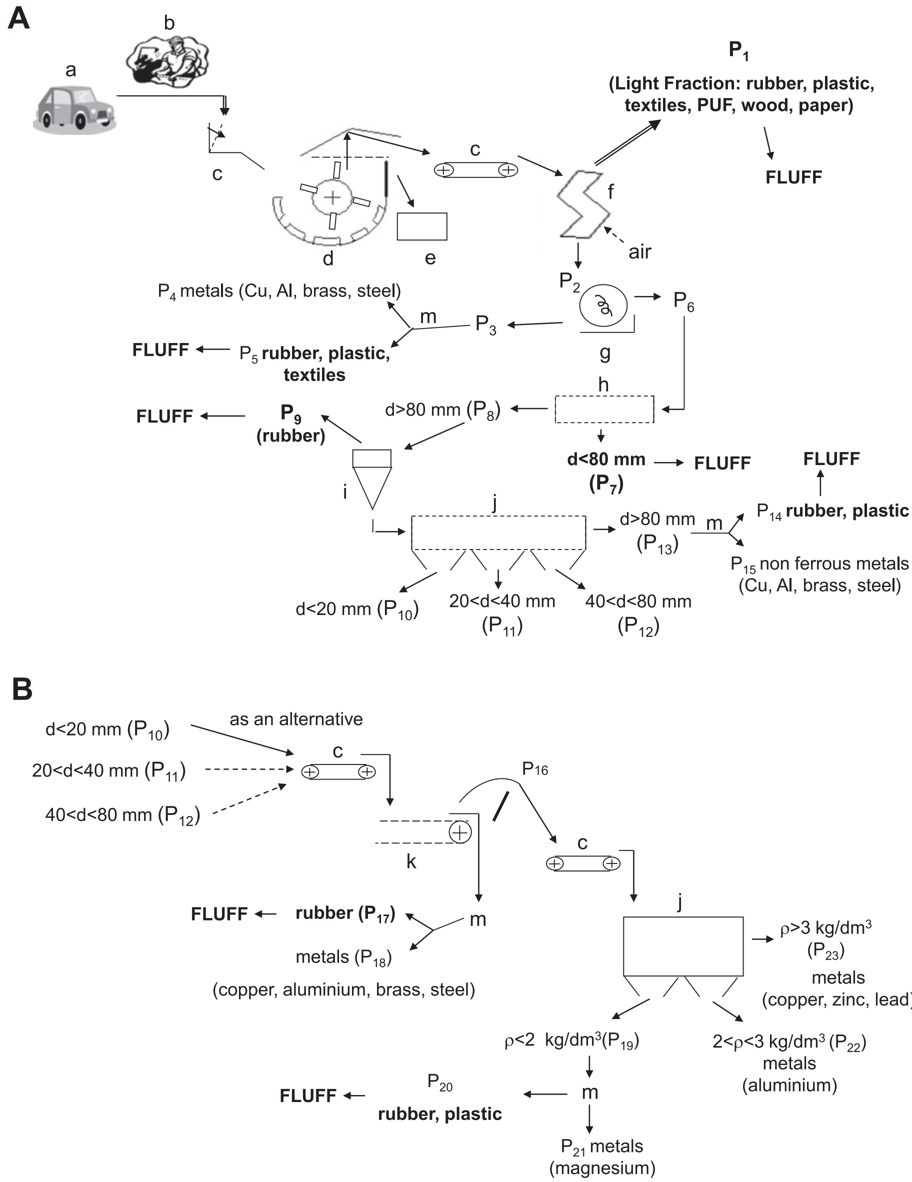

Fig. 1. Scheme of the Shredding plant 1: (A) shredding, magnetic and dimensional separation phases; (B) magnetic, densimetric and electrostatic separation phases (PUF: polyurethane foam). (a) Feed; (b) control cabin; (c) loading device/loading belt; (d) hammer mill; (e) not grindable pieces; (f) pneumatic classifier; (g) drum magnetic classifier; (m) manual selection; (h) trommel; (i) cyclone; (j) densimetric separation plant; (k) electrostatic classifier. P_1, light fraction (fluff); P_2, heavy fraction; P_3, magnetic fraction; P_4, proler; P_5, rubber, plastic, textiles (fluff); P_6, non ferrous metals; P_7, $d < 80$ mm fraction (fluff); P_8, $d > 80$ fraction; P_9, rubber (fluff); P_{10}, $d < 20$ mm fraction (fluff); P_{11}, $20 < d < 40$ mm fraction; P_{12}, $40 < d < 80$ mm fraction; P_{13}, $d > 80$ mm fraction; P_{14}, P_{20}, rubber, plastic (fluff); P_{15}, non ferrous metals; P_{16}, non magnetic fraction; P_{17}, rubber (fluff); P_{18}, metals; P_{19}, $\rho < 2$ kg/dm^3 fraction; P_{21}, metals (magnesium); P_{22}, $2 < \rho < 3$ kg/dm^3 fraction (metals: aluminum); P_{23}, $\rho > 3$ kg/dm^3 fraction (metals: copper, zinc, lead).

So far ASR has been mostly landfilled all over the world (EPA, 2006; Kim and Joung, 2004; Sakai and Noma, 2007; Nourredine, 2007; Forton et al., 2006), but European Directive 2000/53/CE stated that by 2015, when 17 Mt/y of ELVs are expected in EU (EPA, 2006), only the 5%-wt of a vehicle may be landfilled, and the 10%-wt may be incinerated, leading to a mandatory 95% of a ELV total weight recycled/recovered. Directive 2000/53/CE also stated for manufacturers the accomplishment of the 95%-wt recovery/recycling target for vehicles produced after 2008, with a 10%-wt target for thermal valorization. At the moment only Sweden and the Netherlands fulfilled the 85%-wt recycling target, taking advantage of a centralized system of take back-shredding-recovery/recycling financed by a fee applied to new vehicles registration (EU Parliament, 2007; ARN Sustainability Report, 2009), and most EU Countries are near to the 80%-wt (EU Parliament, 2007). Moreover, according to European Directive 1999/31/CE wastes having a LHV higher than 13,000 kJ/kg are not admittable in any landfill category, thus ASR, characterized by a LHV varying from about 19 MJ/kg (Lanoir et al., 1997) to about 23 MJ/kg (Kim and Joung, 2004), is not admittable in any landfill without a further treatment designed to lower combustible components, and also Dissolved Organic Carbon (DOC) and heavy metals contents may be critical parameters. At the moment, Italian landfills are accepting ASR in an exception regimen (DLgs 225/2010).

About the 70%-wt of ASR is made of combustible materials (rubber, plastic, textiles, PUF, wood and paper) and this fraction has a Lower Heating Value (LHV) of about 15–30 MJ/kg, depending on the relative abundance of the described components (EPA, 2006). Many efforts have been devoted to optimize energy recovery from ASR, evaluating incineration/co-incineration and pyrolisis/gasifica-

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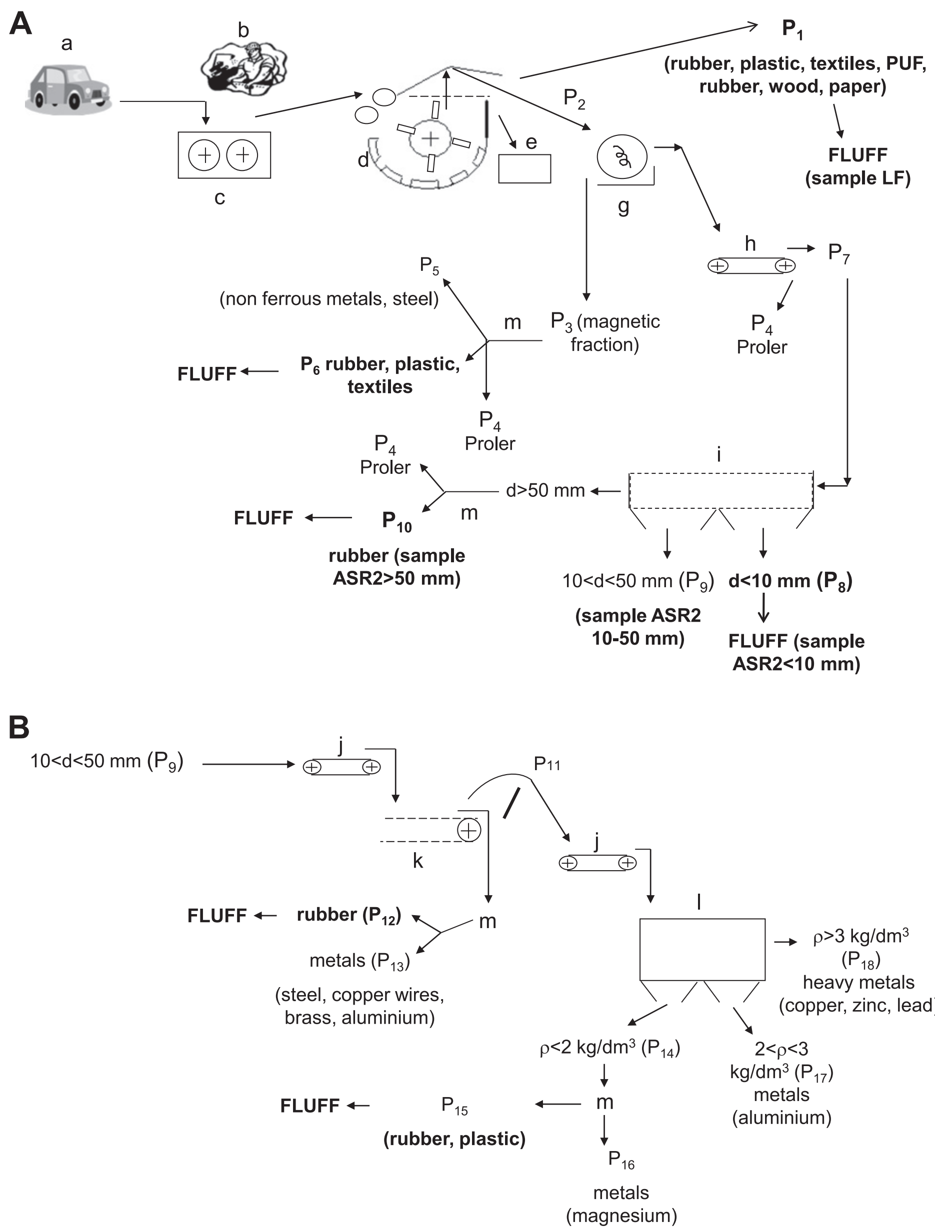

Fig. 2. Scheme of the Shredding plant 2: (A) shredding, magnetic and dimensional separation phases; (B) magnetic, densimetric and electrostatic separation phases (PUF: polyurethane foam). (a) feed; (b) control cabin; (c) pre-grinding phase; (d) hammer mill; (e) not grindable pieces; (f) pneumatic classifier; (g) drum magnetic classifier; (m) manual selection; (h) magnetic belt classifier; (i) trommel; (j) loading belt; (k) electrostatic classifier; (l) densimetric separation plant; P_1, light fraction (fluff); P_2, heavy fraction; P_3, magnetic fraction; P_4, proler; P_5, non-ferrous metals (copper, aluminum, brass) and steel; P_6, rubber, plastic, textiles (fluff); P_7, non-magnetic fraction; P_8, $d < 10$ mm fraction (fluff); P_9, $10 < d < 50$ mm fraction; P_{10}, $d > 50$ mm fraction (rubber, fluff); P_{11}, non-magnetized fraction; P_{12}, rubber (fluff); P_{13}, magnetized fraction (steel, copper wires, brass, aluminum); P_{14}, $\rho < 2$ kg/dm^3 fraction; P_{15}, rubber, plastic (fluff); P_{16}, non-ferrous metals (magnesium); P_{17}, $2 < \rho < 3$ kg/dm^3 fraction (metals: aluminum); P_{18}, $\rho > 3$ kg/dm^3 fraction (metals: copper, zinc, lead).

tion technologies (Nourredine, 2007; Mirabile et al., 2002; Mancini et al., 2010; Viganò et al., 2010; Vermeulen et al., 2011; Santini et al., 2011), and the environmental impact of these processes was also taken into account (Van Caneghem et al., 2010). Several other studies are dedicated to the recovery of ASR as a secondary raw material by means of mechanical and physical processes (Forton et al., 2006; Vermeulen et al., 2011; Kurose et al., 2006), mainly considering building materials such as concrete and asphalt mixtures (Rossetti et al., 2006; Péra et al., 2004) and some innovative possibilities, such as the encapsulation of ASR into thermoplastic materials (Robson and Goodhead, 2003) and the hydrometallurgical recovery of metals (Granata et al., 2011) have been studied. The environmental impacts of mechanical treatment and thermal valorization processes were compared and discussed (Ciacci et al., 2010).

ASR energy recovery technologies fail to meet the EU regulations recovery/recycling target if the ash generated is not recycled in any way. In fact considering that ASR is about 20–25%-wt of an ELV, even if all the combustible components of ASR were incinerated, a 8–10%-wt of inorganic ash would remain, thus still if everything apart from the ash was recycled, the recovery rate would be 90–92%-wt, with a landfilled fraction equal to 8–10%-wt. It is not enough to reach the EU 95%-wt recovery target, and also the incineration quote is exceeded, therefore some technical solutions focused on the recovery of ASR inorganic components are necessary. With these premises, ASR post-shredding physico-mechanical separation technologies may be considered definitely promising.

This work is aimed to give evidence to which phase of the global ELVs processing treatment, considering both pre- and post-shred-

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Table 1
Boundary conditions of the industrial tests and collected ASR samples.

Plant	Test A 1	Test B 2
Feed	306 ELVs (270 t) 90% M1[a], 10% N1[b] >15 years old Origin: 53% Italy, 15% France, 13% Germany, 19% other Numerous abandoned vehicles	241 ELVs (249 t) 95% M1[a], 3% N1[b], 2% motorbikes <10 years old Origin: 60% Italy, 5% France, 35% other 25% from crash tests
Depollution and dismantling	Standard (removal of fluids, filters, batteries and tires)	Enhanced (removal of fluids, filters, batteries, tires, fuel tanks, bumpers, alloy wheels)
ASR samples	Samples SR and ASR1	Samples ASR2, LF, ASR < 10 mm, ASR 10–50 mm, ASR > 50 mm

[a] M1: passenger vehicles with less than eight seats (Directive 2000/53/EC).
[b] N1: vans not exceeding 3.5 t (Directive 2000/53/EC).

ding operations, it is necessary to focus to fulfil the EU recovery/recycling targets. The authors performed two industrial tests, each involving 250–300 t of ELVs, to evaluate how the ASR quality changes according to pre-shredding operations. The significance of post-shredding operations was then subsequently evaluated by means of some treatment processes, carried out on the ASR material obtained from one of the industrial tests. The obtained sub-samples underwent leaching tests according to the EN 12457/2 procedure to evaluate their recovery and disposal possibilities.

2. Experimental

2.1. The industrial shredding tests and the pre-shredding operations

Two industrial tests, each concerning 250–300 t of ELVs, were performed in 2007 in two different shredding plants in the area of Turin, named as *plant 1* and *plant 2* in the following paragraphs (see Figs. 1 and 2). Plants 1 and 2, belonging to the same property, are characterized by a yield equal to about 70% of ferrous metals (this fraction, that is Product P_4 in Figs. 1 and 2, is defined *Proler*) and about 6% of non ferrous metals, valuable shredding products which are sold to secondary fusion foundries and smelters (these fractions are products P_{18} and P_{21-23} in Fig. 1B and products P_{13} and P_{16-18} in Fig. 2B).

Both plants are usually fed, as common in EU, with ELVs and a heterogeneous material called *Light Collection* (mainly made of ferrous scraps and household appliances) in variable proportions. The shredding phase is followed by the separation of ferrous and non ferrous metals from ASR by means of magnetic, dimensional, electrostatic and densimetric separation steps.

The industrial tests, in the following paragraphs named as *Tests A* and *B*, each lasting about 6 h, were differentiated about the feed, that is the processed ELVs, and the performed pre-shredding operations, as shown in Table 1. Test A was fed by more than 15 years old ELVs, with a standard depollution and dismantling (removal of fluids and batteries, the tires were separated from the ELVs when possible). Test B was fed by less than 10 years old ELVs, on which enhanced pre-shredding operations (removal of tires, fluids, filters, batteries, fuel tanks, and bumpers) were performed.

The *Light Collection,* whose relative abundance in shredding facilities is usually unpredictable, was excluded from the tests. Crashed vehicles, which often make impossible the separation of some recyclable or polluting components, thus reducing the recoverable/recyclable rate of ELVs and polluting the ASR, were included in both trials taking into account that this fraction usually represents an important part of the feed of shredding facilities.

2.2. ASR samples collection

All material fluxes in plants 1 and 2 were weighted at the beginning and at the end of the industrial tests (mass balance of Test B is reported in Table 2) and seven different ASR materials were representatively sampled (UNI, 2004a), obtaining 20–30 kg final samples.

The collected materials are listed below (see Table 1). Sample SR derives from the ELVs and *Light Collection* regularly processed in plant 1, considering the usually performed basic reclamation, consisting in the elimination of batteries and fluids and of about 50% of tires. Sample SR was collected as a reference sample for plant 1.

Samples ASR1 and ASR2 are mixtures of the different products named *Fluff* (products P_1, P_5, P_7, P_9, P_{14}, P_{17}, P_{20} in Fig. 1 compose sample ASR1 and products P_1, P_6, P_8, P_9, P_{10}, P_{12}, P_{15} in Fig. 2 compose sample ASR2), according to their relative abundances (P_1 and P_5 in Fig. 1 and P_1 and P_6 in Fig. 2 account for 89% and 8.5%-wt, respectively, each of the other products accounts for about 1%-wt). Sample ASR1 was collected after Test A.

Samples ASR2, ASR2 < 10 mm, ASR2 10–50 mm and ASR2 > 50 mm (the last three were the products P_8, P_9 and P_{10} in Fig. 2A) and LF, were collected after Test B. The sample ASR2 represents the final product of Test B, obtained after the separation of the magnetic and non-magnetic metallic fractions and the gathering of all fluxes contributing to Fluff. The sample LF was collected from the material separated by the suction plant on the hammer mill (product P_1 in Fig. 2A), which is commonly defined *Light Fluff*.

Table 2
Test B mass balance.

	Amount (kg)	Abundance (%)
ELV average weight	1046	
Depollution/dismantling		
Inflow	2,48,960	100
Batteries	2170	0.87
Bumpers	1350	0.54
Fuel tanks	1800	0.72
Alloy wheels	3725	1.49
Tires	5830	2.34
Fuel	600	0.24
Engine oil	840	0.34
Oil filters	240	0.10
Antifreeze liquid	230	0.09
Brake oil	50	0.02
Glass washing liquid	25	0.01
Total	16,860	6.77
Shredding		
Inflow	232,100	100
Magnetic product (proler)	163,502	70.44
Alluminum	1210	0.52
Heavy metals	12,346	5.32
Stainless steel	430	0.18
Copper	50	0.02
PVC wrapped copper	700	0.30
Fines < 10 mm	590	0.25
Rubber	690	0.30
Fluff	50,432	21.73
Loss	2150	0.93
Final Recycling Rate (RR)[a]		78.64

[a] Calculated according to ISO 22628 (ISO, 2002).

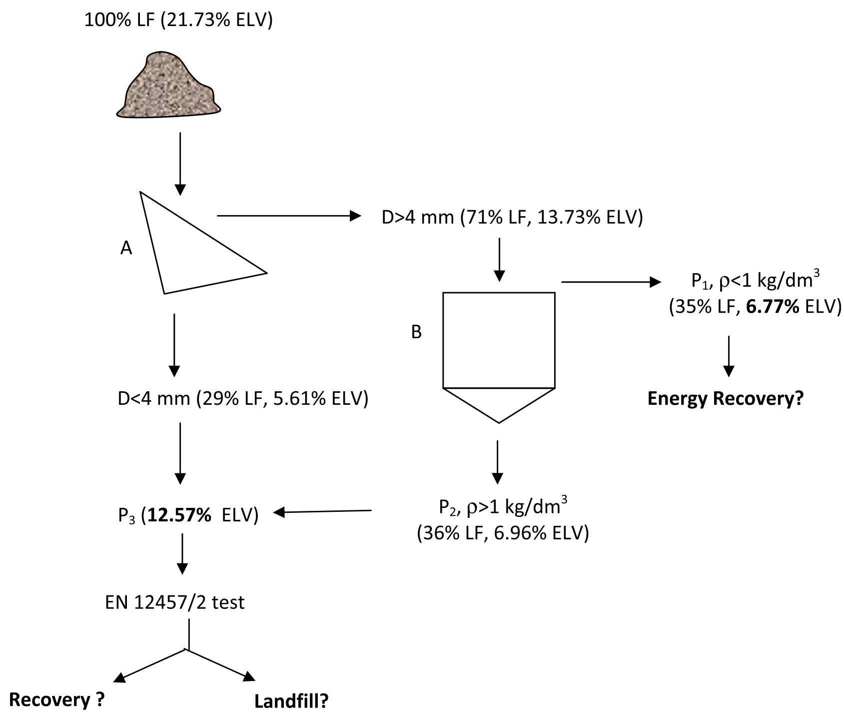

Fig. 3. Treatment process T1. (A) sieving at 4 mm; (B) densimetric separation with water; P_1, floated fraction; P_2, sunk fraction; P_3, $D < 4$ mm + P_2.

2.3. The post-shredding treatment processes

The authors performed two bench scale post-shredding treatment tests on separate aliquots of the LF sample, representatively collected, with the aim of increasing both recycling and recovery rates of the materials coming from the shredding of ELVs. The LF sample was chosen because on one hand it comes from test B, where the best pre-shredding operations were carried out; on the other hand it was already separated during the shredding process and accounting for the main fraction of the ASR components.

The treatment processes were chosen on the grounds of the LF sample characterization results, and were intended to liberate both a valorizable fraction characterized by a high LHV and some valuable components that may be recycled. The treatment T1 (see Fig. 3) was performed on 10 kg of the LF sample and consisted in a separation by sieving at 4 mm and in a densimetric separation at 1 kg/dm^3 with water. Q3

The treatment process T2 (see Fig. 4) was performed on 10 kg of the LF sample and consisted in a separation by sieving at 4 mm of the fine fraction and in consequent magnetic, electrostatic (this step was simulated by manual sorting) and densimetric separation phases. The densimetric separation at 2 kg/dm^3 was simulated manually on the sunk fraction obtained from the densimetric separation with water.

2.4. ASR samples characterization

The ASR samples obtained from the industrial tests and the bench scale post-shredding treatment processes were quartered to smaller amounts in order to undergo the characterization, performed throughout particle-size distribution analysis, product composition analysis (on unsorted samples and on each class coming from the particle-size distribution analysis of the LF sample, with the exception of the below 10 mm fractions), and the determination of the Lower Heating Value (LHV) (on unsorted samples and on each class coming from product composition analysis of SR and ASR1 samples), moisture, oil and metals contents. A densimetric analysis of the LF sample, with the exception of the class having dimensions below 4 mm, was also performed employing liquids having different density values, equal to 1.0 and 1.22 kg/dm^3 (respectively water and a NaCl saturated solution). The so obtained densimetric fractions underwent a further product composition analysis. A product composition analysis was also performed on the products of the post-shredding treatment tests.

EN 12457/2 procedure (acknowledged in Italy by UNI 10802 rule) (UNI, 2004a) was performed to evaluate recovery (according to Italian law DM 5/2/1998) and landfill opportunities (according to the Italian law DLgs 36/2003 that acknowledges EU Directive 1999/31/CE) of the unsorted samples and of the products of the treatment tests. All chemical analyses were performed by means of reference methods (UNI, 2004a,b; EPA, 2007; APHA, AWWA, WEF, 1998). A ThermoFisher Flash 2000 CHNSO Analyzer was employed for the elemental analysis in the following conditions: sample 2–4 mg, furnace 950 °C, oven 65 °C, reference BBOT 2–3 mg. A Perkin Elmer Optima 2000 ICP-OES was employed for metal analyses, a Unicam Helios Alpha UV-Visible spectrometer was used for nitrate, fluoride, chloride and sulfate analyses. The Mineral Oil content was gathered through a gravimetric method (EPA, 2007) and the LHV values were achieved by means of a Mahler calorimeter according to UNI 9903-5 rule (UNI, 2004b).

3. Results

The results of the characterization of the SR/ASR materials collected after the industrial tests and of the materials obtained from the bench scale post-shredding treatment tests are reported in Tables 3–7 and in Figs. 5–9.

4. Discussion

4.1. SR/ASR materials characterization

The results of the particle-size analysis (see Table 3) summarize a rather equal distribution of the coarse fractions for ASR samples.

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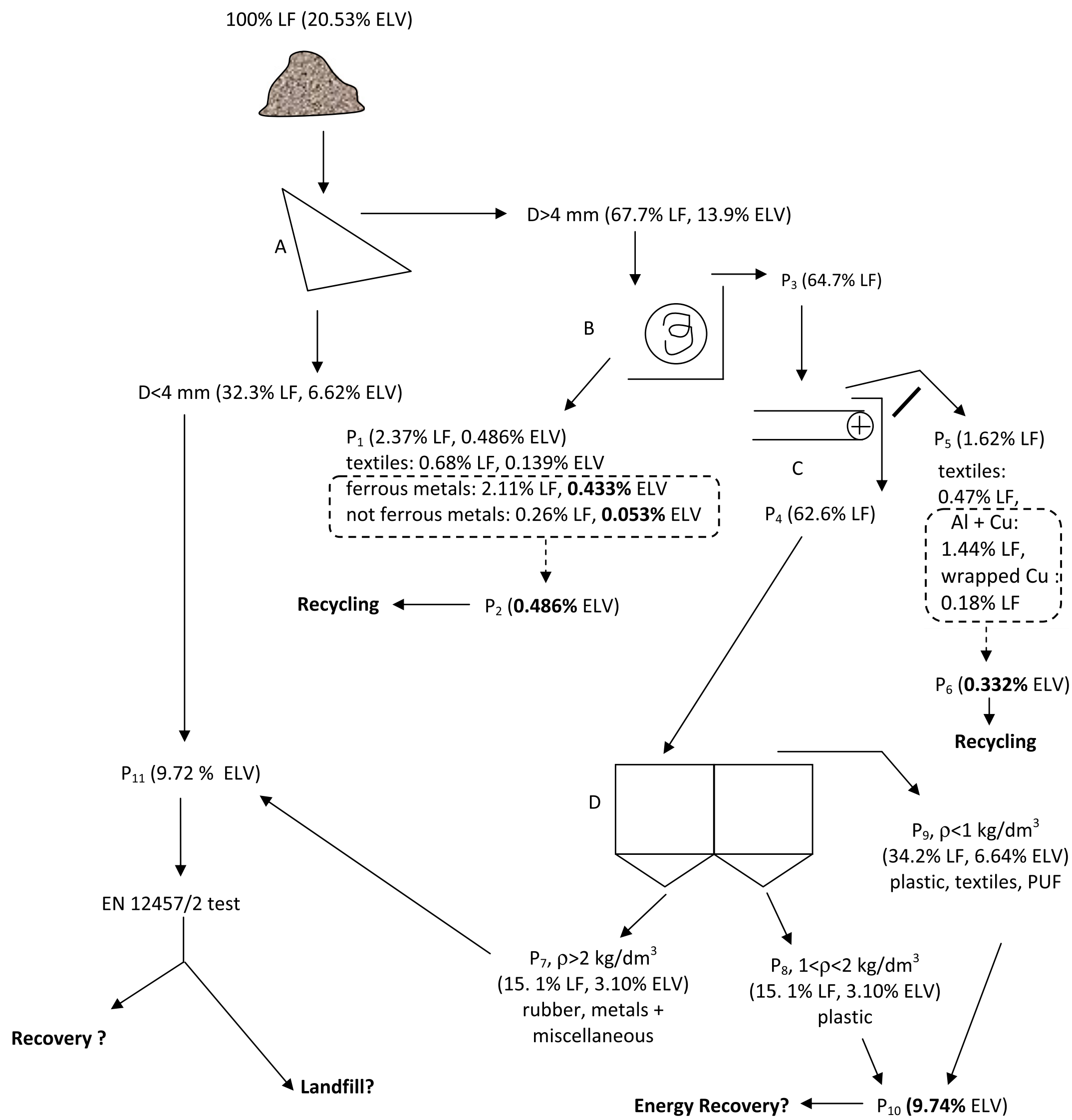


Fig. 4. Treatment T2 (PUF: polyurethane foam). (A) sieving at 4 mm; (B) magnetic separation; (C) electrostatic separation; (D) densimetric separation; P_1, magnetic product; P_2, metallic fraction of magnetic product; P_3, amagnetic product; P_4, not conductive product; P_5, conductive product; P_6, metallic fraction of conductive product; P_7, heavy sunk fraction $\rho > 2$ kg/dm^3; P_8, medium sunk fraction $1 < \rho < 2$ kg/dm^3; P_9, floated fraction $\rho < 1$ kg/dm^3; P_{10}, $P_8 + P_9$; P_{11}, $D < 4$ mm + P_7.

Table 3
Dimensional and chemical characterization of SR/ASR materials.

Sample	Particle-size analysis					Oil (%)	Moisture (%)	N (%)	C (%)	H (%)	S (%)
	<4 mm (%)	<10 mm (%)	<20 mm (%)	<50 mm (%)	<70 mm (%)						
SR	16.3	26.2	34.2	61.3	80.7	4.62	0				
ASR1	10.3	18.5	33.5	68.6	82.2	7.95	3.12				
ASR2	22.1	36.7	48.8	71.3	82.1	3.68	2.76				
LF	29.3	38.0	50.0	71.0	82.0		3.07	1.68	45.97	5.89	0.39
LF < 4 mm								0.47	16.33	1.80	0.40
LF > 4 mm, $\rho < 1$ kg/dm^3						3.48					
Literature data			45.0[a]			2.68[a]	2.2[b]–10.0[a]	0.20[b]	49.50[b]	5.30[b]	0.2[b]

[a] Morselli et al. (2010).
[b] Referred to <2 mm fraction (Mirabile et al., 2002).

ASR2 and LF samples show a larger fraction below 4 mm because of the higher power of the hammer mill of plant 2 compared to plant 1.

The elemental analysis results and metal contents (see Tables 3 and 4) are in line with the literature data (Mirabile et al., 2002; Morselli et al., 2010), although metal contents are slightly lower. The higher aluminum contents detected in samples ASR2 and LF are consistent with the recent predilection of automotive industry for light alloys.

The measured oil contents (see Table 3) are mainly due to a poor depollution of the shredded vehicles, particularly before test

Table 4
Metals contents of SR/ASR materials.

Sample	Al (%)	As (mg/kg)	Ba (mg/kg)	Cd (mg/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (%)	Fe (%)	Mn (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (%)
SR	0.38	11.3	7.90	19.0	3.93	93.0	0.37	1.78	209	72.8	45.8	0.53
ASR1	0.24	12.7	18.1	17.6	5.88	82.2	4.68	1.33	172	100	272	0.19
ASR2	0.99	8.1	33.4	10.3	9.08	172	4.56	1.65	173	75.0	309	0.24
LF	0.76	3.44	36.6	15.2	13.6	226	3.35	3.26	311	111	410	0.31
ASR < 10 mm	1.73	14.2	28.0	19.7	13.3	111	2.34	2.66	301	89.4	1100	0.33
LF < 4 mm	2.48	14.6	34.5	25.4	21.9	169	1.42	4.27	547	197	504	0.66
LF > 4 mm, ρ < 1 kg/dm^3	0.36	2.45	24.6	10.8	8.3	114	0.34	1.67	167	76	139	0.26
Literature values		16.0[b]		6.0[b]		300[b]–800[c]	0.003[b]–1.2[c]	25.7[c]	880[b]	210[b]–700[c]	200[c]–4000[b]	1.9[c]
Italian law limits for RDF (DM 5/2/98)		9		7[a]		100	0.03		400	40		

[a] Sum of Cd and Hg contents.
[b] Morselli et al. (2010).
[c] Referred to *d* < 2 mm fraction (Mirabile et al., 2002).

Table 5
Determination of Lower Heating Value (LHV) on SR/ASR materials.

Sample	LHV (kJ/kg)
SR	22,130
ASR1	24,088
ASR2	21,290
LF	17,000
LF < 4 mm	6800
LF > 4 mm, ρ < 1 kg/dm^3	26,100
LF > 4 mm, ρ > 1 kg/dm^3	18,600
LF > 4 mm, ρ > 1 kg/dm^3 + LF < 4 mm	12618[a]
Literature values	13800[b]–16720[c]
Italian limit for RDF (DM 5/2/98)	15,000
Italian limit for disposal (DLgs 36/2003)	13,000

[a] Calculated considering mass balance.
[b] Morselli et al. (2010).
[c] Referred to *d* < 2 mm fraction (Mirabile et al., 2002).

Table 6
Determination of Lower Heating Value (LHV) on product composition analysis fractions of SR/ASR materials obtained from shredding test A.

Fraction	SR sample LHV (kJ/kg)	ASR1 sample LHV (kJ/kg)
Unaltered sample	22,130	24,088
Unaltered sample (calculated)	22,992[a]	26,343[a]
Paper	–	17,064
Wood	16,019	14,917
Polyurethane foam	27,843	32,855
Textiles (light)	20,139	26,951
Textiles (heavy)	27,691	30,905
Rubber	29,325	31,391
Plastic	36,649	36,967
Miscellaneous (4–10 mm)	14,412	21,051
d < 4 mm	10,441	9918

[a] Value calculated from the experimental LHVs considering the results of product composition analyses.

A. Taking into account that the LHV of a mineral oil may be equal to about 40 MJ/kg, the LHVs measured on the SR/ASR samples (see Table 5), collected after tests A and B, are strictly connected to their oil contents, but also the relative abundance of the high combustible fractions is a main factor. The oil content of the sample ASR1 is about 1.7 times higher than in sample SR, which derives also from *Light Collection*. The ASR2 sample, deriving from improved pre-shredding operations, showed the lowest oil content.

Considering the LHVs of the fractions of samples SR and ASR1 coming from the component analysis (see Table 6), the gathered values are in line with literature data (Perry and Green, 1997). The results schematized in Table 6 highlight the highest LHV fractions (PUF, textiles, rubber and plastic); fine fractions, such as *miscellaneous* (this fraction is composed of 4–10 mm particles of plastic, rubber, polyurethane foam, glass and other unidentified materials that is not possible to separate from each other) and *d* < 4 mm, show LHV values, respectively around 15–20 MJ/kg and around 10 MJ/kg, due to their composition. The higher LHV value of some ASR1 sample's fractions (PUF, textiles and miscellaneous) reflects the oil trend to accumulate in the same fractions, and particularly in the miscellaneous material. For the sample ASR1 the differences between the LHV experimentally determined and the LHV calculated from the LHV of each fraction may be due to the high heterogeneity of the samples.

Considering the results of the product composition analysis performed on SR/ASR samples (see Fig. 5) the predominance of high LHV fractions, i.e. rubber, plastic, textiles and polyurethane foam (PUF) is clear, their sum accounting for 69%-wt of sample SR, 75%-wt of sample ASR1, 55%-wt of samples ASR2 and 51% of sample LF. The data schematized in Fig. 5 show that the rubber content reflects the accuracy of pre-shredding operations, and that SR sample accounts the presence of *Light Collection* with lower contents of plastic, polyurethane foam, textiles, wires and metals compared to ASR samples.

The results of the product composition analysis performed on the dimensional classes of sample LF (see Fig. 6) prove that the coarse fractions (*d* > 70 mm) are made of about 85%-wt of high LHV materials. Moreover plastic accumulates mainly in below 50 mm classes, and heavy textiles concentrate in above 50 mm fractions.

The product composition analysis performed on the SR/ASR samples concerned also the fractions (data not shown) collected at the trommel in plant 2 (see Fig. 2): ASR2 < 10 mm sample is mainly made of miscellaneous (55%-wt), glass (37%-wt) and ferromagnetic metals (8%-wt); ASR2 10–50 mm sample, that is the fraction that undergo the consequent treatments in plant 2, is almost composed of non ferrous metals (99.3%-wt) and a minimal fraction of plastic; ASR2 > 50 mm sample is primarily made of rubber (94%-wt), plastic (5.8%-wt) and textiles (0.2%-wt).

The densimetric analysis of sample LF (see Fig. 7) gives evidence that about 35%-wt has a density below 1 kg/dm^3, about 22%-wt has a density above 1.22 kg/dm^3, and about 14%-wt has an intermediate density (the remaining 29% is made of fine particles below 4 mm, eliminated before the densimetric analysis). The product composition analysis performed on the above cited densimetric classes (see Fig. 7) showed that plastic is widespread in all classes, mostly in the one having the lower density. The product composition fractions representative of each densimetric class are the following: textiles, PUF, plastic and miscellaneous for the lower density fraction; plastic and miscellaneous for the intermediate density fraction; rubber, plastic, wires and metals and miscellaneous in the higher density fraction.

Table 7
Results of EN12457/2 leaching test performed on ASR materials.

Parameter	Unit	SR	ASR1	ASR2	LF	LF < 4 mm	LF > 4 mm, ρ > 1 kg/dm^3 + LF < 4 mm	LF > 4 mm, ρ < 1 kg/dm^3	Italian limits for reuse (DM 5/2/98)	Italian limits for disposal (DM 3/8/05)		
										Inert wastes	Not dangerous wastes	Dangerous wastes
NO_3^-	mg/l	0.47	8.01	14.1	12.9	13.6	12.8	8.47	50	–	–	–
F^-	mg/l	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1,5	1	15	50
$SO_4^=$	mg/l	84.2	80.4	70.0	97.8	93.5	64.1	59.8	250	100	2000	5000
Cl^-	mg/l	27.3	36.1	18.0	21.9	21.3	–	–	100	80	1500	2500
Ba	μg/l	61.5	69.4	71.5	78.6	100	86.2	184	1000	2000	10,000	30,000
Cu	μg/l	194	378	180	210	340	237	317	50	200	5000	10,000
Zn	μg/l	2780	5990	2090	1820	1504	658	2095	3000	400	5000	20,000
Co	μg/l	2.95	4.03	3.39	3.76	4.25	3.87	3.44	250	–	–	–
Ni	μg/l	42.1	82.5	30.7	37.0	50.8	35.4	95.7	10	40	1000	4000
As	μg/l	19.0	10.5	<5.3	<5.3	<5.3	<5.3	<5.3	50	50	200	2500
Cd	μg/l	5.87	21.0	7.09	6.20	6.46	2.31	8.46	5	4	20	200
tot Cr	μg/l	2.68	7.87	4.43	7.01	3.21	2.03	2.22	50	50	1000	7000
Pb	μg/l	227	427	145	175	279	227	147	50	50	1000	5000
Al	μg/l	87.6	102	35.0	46.7	52.7	80.2	28.8		–	–	–
Fe	μg/l	364	309	71.0	83.3	273	351	75.5		–	–	–
Mn	μg/l	193	264	128	152	214	95.2	206		–	–	–
pH		6.46	6.74	6.56	6.67	7.75	7.54	7.70	5.5-12	–	–	–
DOC	mg/l	441	564	198	282	209	198	241		50	80	100
COD	mg/l	–	–	–	690	410	–	530	30	–	–	–

DOC: Dissolved Organic Carbon; COD: Chemical Oxygen Demand.

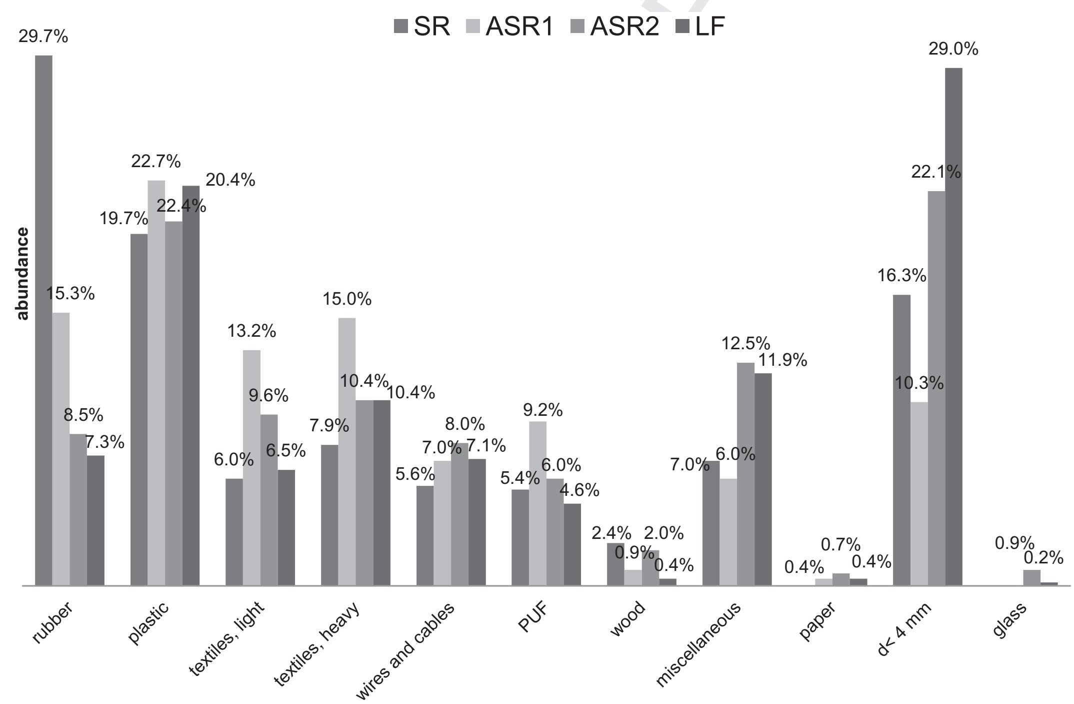


Fig. 5. Results of product composition analysis of SR/ASR materials (PUF: polyurethane foam).

The leaching behavior of LF sample (see Table 7) underlines DOC, cadmium and copper contents as critical parameter for disposal, and LHV should also be considered. Sample ASR1 releases higher metals concentrations, compared to SR and ASR2 samples, probably because of the composition of the alloys employed in the manufacturing of more than 15 years old ELVs and of the high fraction of abandoned ELVs fed in test A.

4.2. Treatment processes tests

The results of the product composition analysis performed on the materials obtained from the treatment test T1 (see Fig. 8) highlight that 89%-wt of the light fraction (ρ < 1 kg/dm^3) is made of high LHV materials, as proved by the detected LHV value (see Table 5). The relevant LHV obtained for the heavy fraction (ρ > 1 kg/dm^3) is connected to the considerable content of plastic, rubber and textiles (see Fig. 9).

Considering the component analysis carried out on the materials derived from test T2 (see Fig. 9), more than 85%-wt of the light fraction (density < 1 kg/dm^3) is composed by high LHV materials. The densimetric separation at 2 kg/dm^3 was manually simulated on the sunk fraction obtained from a separation with water. Considering the data represented in Fig. 9, the authors assume that the sunk fraction of this further densimetric separation should be

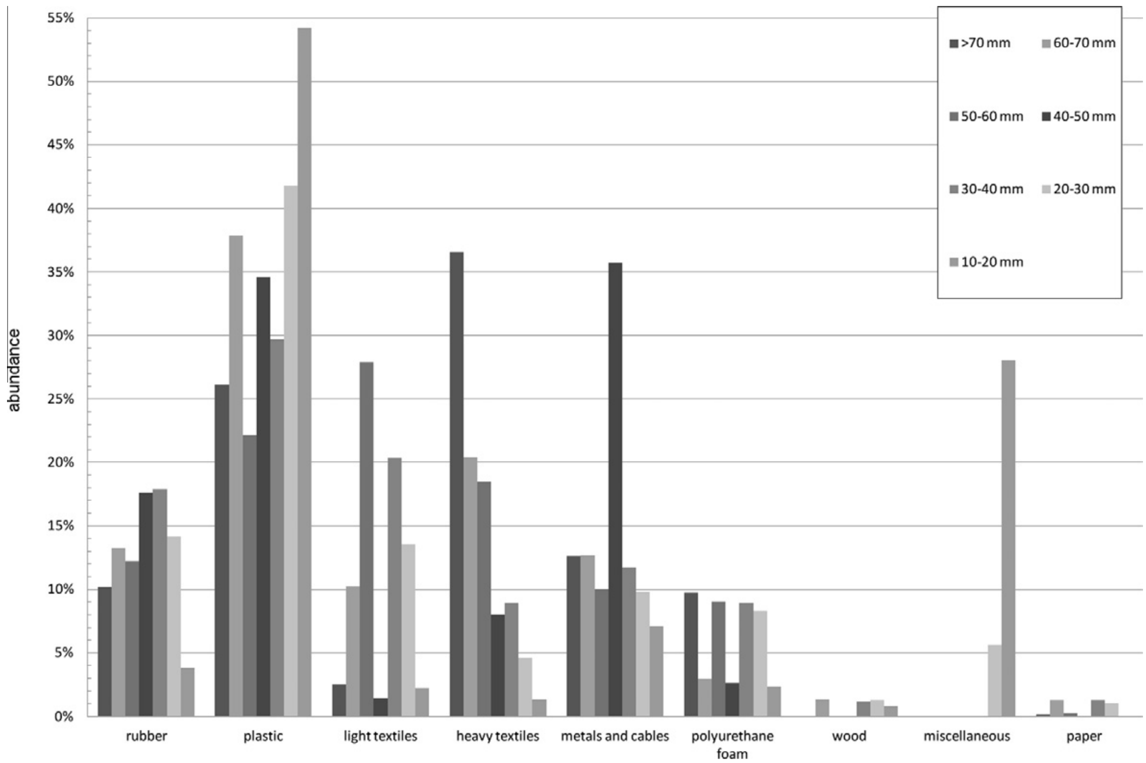


Fig. 6. Results of product composition analysis on dimensional classes of LF sample.

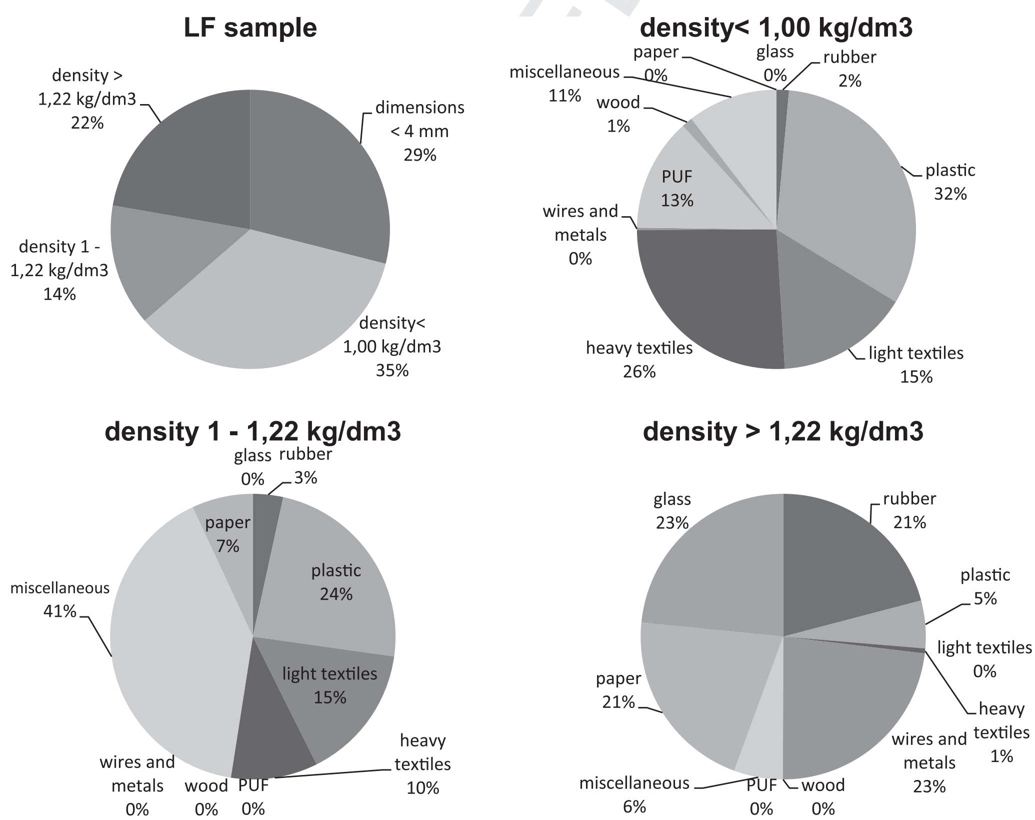


Fig. 7. Results of densimetric analysis of LF sample and of product composition analysis of the densimetric fractions of sample LF (PUF: polyurethane foam; percentage values are referred to LF sample).

made of rubber and metals, while the fraction characterized by a density between 1 and 2 kg/dm^3 should be made of plastic, miscellaneous, heavy textiles and fines below 4 mm liberated by the treatment test.

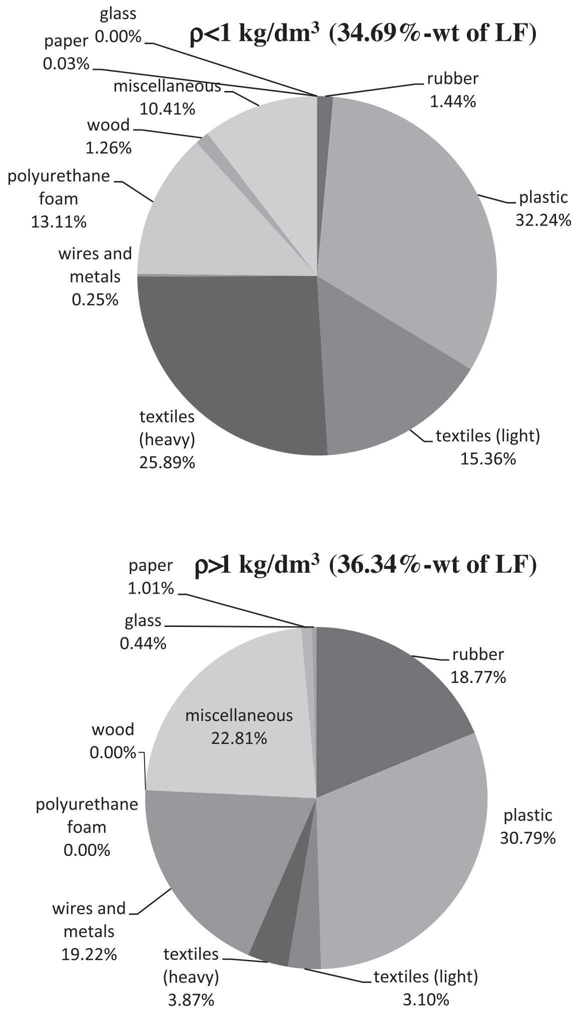


Fig. 8. Results of product composition analysis on the products of treatment process T1.

Taking into account the results of treatment test T1, EU target about energy recovery is satisfied considering both the amount (see Fig. 3) and the LHV (see Table 5), even if Cr, Cu and Ni are critical parameters (see Table 4); disposal is not possible according to EN 12457/2 leachate composition (see Table 7) and to EU amount target.

In view of the treatment test T2, EU targets about energy recovery and LHV requirement for the disposal are fulfilled, the Recycling Rates of ferrous and non ferrous metals are considerably enhanced (see Figs. 4 and 10), while EN 12457/2 leachate composition showed that DOC and metal contents are critical parameters for recovery and disposal (see Table 7) and EU target amount for disposal is not satisfied.

The Recycling Rate (RR) value (see Table 2 and Fig. 10) is an index of the recycle/recovery potential of ELVs that is calculated, according to ISO 22628 (ISO, 2002), as the sum of the depolluted (battery, filters, fuel and fluids), reused (alloy wheels), recycled (tires, fuel tanks, bumpers, rubber) fractions with the ones made of ferrous and not ferrous metals. The average Italian RR, equal to 70.3% in 2006 (Eurostat, 2009a), is actually low, compared to virtuous Countries such as Sweden and The Netherlands, although the periodical take-back incentives promoted by Italian Government, mainly because of the poor and not standardized pre-shredding procedures commonly performed in Italian facilities.

The treatment processes tested in this work failed in fulfilling the EU Directive 2000/53 requirements mainly because of the amounts and the leaching behavior of the fractions destined to disposal, and also the material recovery is not possible because of the leachate composition, but they show an undeniable trend to enhance RR value (see Fig. 10). Anyway, the presence of crashed vehicles decreases the recovery/recycling yields due to the difficulties to perform pre-shredding operations.

4.3. Economical evaluation

A preliminary economical evaluation of the global ELVs processing cycle may be hypothesized considering the costs schematized in Table 8, that exclude the contribute connected with energy recovery and assume that the average weight of an ELV may be equivalent to 1 t.

Dismantling appears to be the most expensive operation, and shredding cost from literature (Santini et al., 2010a; Ireland, 2006) is consistent with the one estimated by the property of the plant that hosted industrial test B. The post-shredding treatments' costs are obviously connected with their complexity.

Hypothesizing a very rough cost balance for the processing of a single ELV, in comparison with the actual treatment (made of dismantling, shredding and of the disposal of ASR), taking into

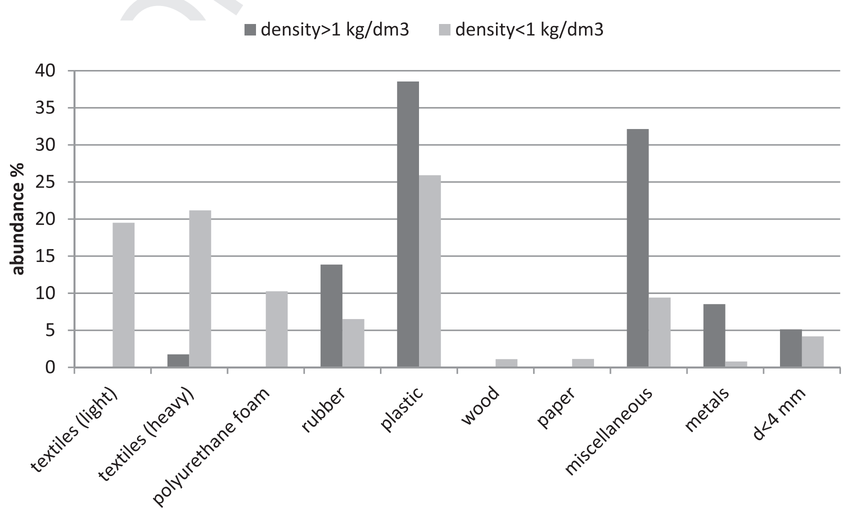
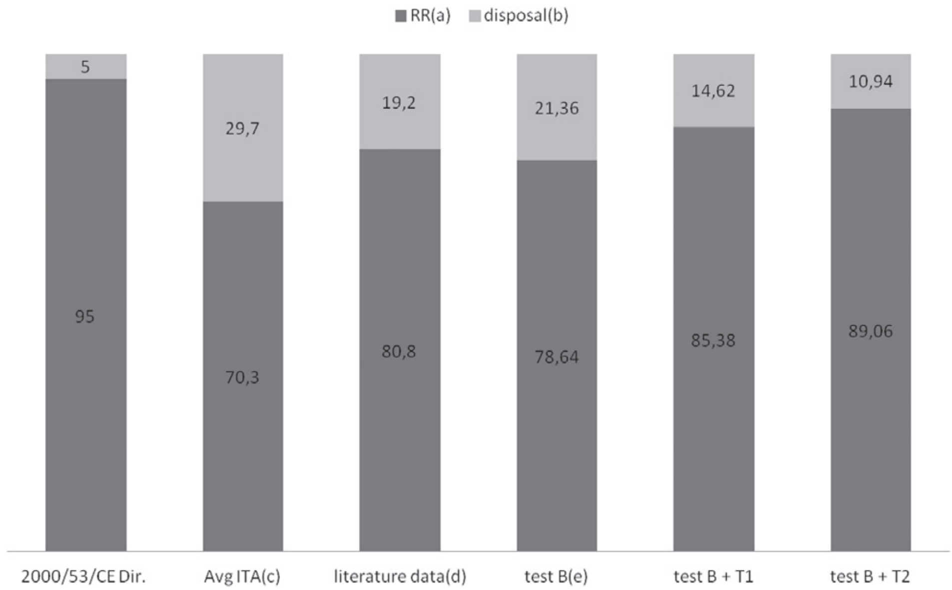


Fig. 9. Results of product composition analysis on the products of treatment process T2.



(a) RR= Recycling/recovery Rate (ISO, 2002).
(b) calculated as (100-RR)
(c) Average Italian RR value in 2006 (Eurostat, 2009a).
(d) (ARN, 2009; Santini et al., 2010a).
(e) see Table 2

Fig. 10. Mass balance of treatment tests.

Table 8
Costs evaluation of the ELVs processing cycle.

Operation	Cost (US$/t)
Dismantling	85–115[a]
Shredding	43[a]
Test B	43[b]
Treatment T1	10–15[b]
Treatment T2	22–29[b]
Disposal (in EU)	170–230[a]
Scraps selling price:	
Steel	150–220[c]
Copper	4000–5500[c]
Brass	3200–5400[c]
Magnesium	140[c]
Aluminum	500–1700[c]

[a] From (Ferrao and Amaral, 2006b).
[b] Estimated by the property of plant 2.
[c] From http://recycleinme.com, accessed 10/17/2011).

account on the one hand the trade of ferrous and not ferrous metals recovered from test T2 (about 4.3 kg of steel and about 3.8 kg of non-magnetic metals for each ton of ELVs, indicated as products P_2 and P_6 in Fig. 4) and the saving connected to the decreasing of ASR fraction destined to disposal, and on the other hand the cost of post-shredding treatment T2, the balance results undeniably positive.

5. Conclusions

The physic-chemical and product composition analyses results presented in this study are intended to fill the existing gaps about SR/ASR materials characterization and consequently to enhance the possibility of liberating valuable components. Some critical issues may be depleted by an enhanced depollution (i.e. the oil content and consequently the LHV may be decreased by an engine washing phase, and also metals contents may be reduced) and ASR abundance and composition may be slightly modified by enhanced dismantling procedures (i.e. the removal of 100% of tires, glass, cabin linings and panels, seats) (Santini et al., 2010b), although the negative effect of improved dismantling operations on shredding economic convenience should be taken into account (Ferrao and Amaral, 2006b).

On the grounds of unavoidable pre-shredding operations, the authors had the purpose of evaluating post-shredding technical solutions based on simple physic-mechanical separation phases, and therefore realizable in common European ELVs shredding plants, and of considering both mechanical sorting and thermal valorization of ASR materials (actually these two strategies have always been divided).

Fine particles represent a relevant fraction of ASR materials (considering ASR1 sample, as a worse case, particles below 4 and 10 mm represent, respectively the 6.3%-wt and the 8.0%-wt of ELV average weight in test B) and concentrate several critical issues, such as metals and other potentially harmful components (i.e. mineral oil and PCBs), therefore any treatment process dedicated to SR/ASR valorization should foresee their elimination. Although the removal of the fine fraction, eventually considering a 10 mm dimension, would surely limit the negative influence of metals in material and energy recovery, it would also potentially exceed the EU Dir. 2000/53 disposal target. A very easy strategic restriction to this critical issue should consider a limitation of the hammer mill power in the shredding facilities.

Directive 2000/53/CE states a more recycling-oriented and dismantling-friendly design of vehicles produced after the end of 2008, thus in the next 10 years a wise strategy to meet EU ELVs reuse/recovery goals should consider both enhanced but economically sustainable pre-shredding operations and the upgrade of post-shredding technologies available for car fluff processing, aimed to the enhancement of the recycling possibilities of the obtained materials. Moreover it is favorable that all EU Governments foresee centralized organizations for the management of the

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complete ELVs cycle, according to the example of the Countries that already fulfilled EU recovery/recycle targets for 2015.

6. Uncited reference

RecycleinMe internet site (2011).

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