



A comprehensive characterization of End-of-Life mobile phones for secondary material resources identification

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ARTICLE INFO

Article history:

Received 12 March 2019

Revised 1 August 2019

Accepted 9 August 2019

Available online 27 August 2019

Keywords:

End-of-life mobile phones

Characterization

Waste electrical and electronic equipment (WEEE)

ABSTRACT

In this paper a full recognition of the different materials and valuable metals constituting mobile phones was performed. To this aim, a sample of 20 end-of-life devices has been dismantled and quantitative and qualitative chemical composition of the individual components was determined.

From dismantling operations, it was found that plastics, metals, electronic components, batteries and displays account for 33%, 11%, 23%, 24% and 9% respectively, as a weighted average.

Plastic parts of each item were analyzed by spectroscopy and then classified according to the plastic polymer type; it was found that polymeric components of mobile phones were made of five polymers: acrylonitrile-butadienestyrene, polycarbonate, polyurethane, polymethylmethacrylate and silicone.

Electronic parts were leached by a twofold aqua regia treatment and the metal composition was determined: 15 elements were identified with concentration >0.2%.

On the basis of these results, some considerations about the recycling context of end-of-life mobile phones were performed.

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1. Introduction

Challenges faced in WEEE (Waste of Electrical and Electronic Equipment) management are not only due to the growing quantities of generated waste, but also to their complexity. Numerous modern technologies are integrated in electrical and electronic products and each one of them is composed of various materials and components: WEEE represent a waste category characterized by high content of heavy metals and harmful substances that are hazardous for human health and the environment. They are produced in high quantities and this implies greater difficulties in the disposal processes; moreover, the extreme heterogeneity of the contained materials makes their recovery challenging (Sun et al., 2016).

The principal items found in WEEE for economic importance are mobile phones (MPs) that every day become a part of the lifestyle of increasing numbers of people everywhere. This growth in popular use is encouraged by technological improvements and by more and better services from the equipment as they become more and more sophisticated each day and lead the users to discard their older models and buy newer, smaller, lighter or more modern handsets.

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There is an enormous growth in MP consumption worldwide which leads to generation of a large volume of MP waste every year (Sarath et al., 2015). It is estimated that in 2017 Europe 28, imported 210,784,723 MPs, for a total weight of 64,210 tons (elaborations from <https://comtrade.un.org/data>). MPs are subject to a continuous technological progress and to frequent replacement with more performing models, so their life time is rather reduced. The characterization of constituent components of the MPs is a crucial step in the disassembly procedure in order to quickly and accurately identify the components for which it may be convenient to attempt a recovery, separating them from the ones that must be stored or disposed of, each according to the more sustainable process.

Materials contained in MPs are variable to some extent, based on the model and its manufacturer, with no fixed formula or list of contents applicable as such; for this reason, the list of materials in an average MP may also be misleading since different/several substances might be used as additives in very low quantities or traces by different manufacturers in the production of microelectronic components. Nevertheless, the general composition of MPs is identical in nature.

Few are recent studies focusing on the fractional composition of MPs: Bhuie et al. (2004) generically cited their material composition but did not identify plastic materials; Tan et al. (2017) established that from manual dismantling it is possible to obtain plastic

(25.75 wt%), batteries (21.12 wt%), printed circuit boards (PCBs) (17.67 wt%), metals (17.30 wt%), and displays (8.37 wt%). This product variability, both over time and from manufacturer to manufacturer, represents a significant issue when dealing with WEEE recycling: a treatment process would instead require constant inputs to ensure optimal performance in terms of efficiency and purity of the recovered materials. Also literature addressing the MPs plastic characterization is not exhaustive: this might be due to the fact that polymer recovery from mobile phones is still in its early stages and then not much interesting in economic terms. Kasper et al. (2011) identified polymeric components by the symbols or codes or both recorded on the surfaces and analyzed the plastic fraction recovered from PCBs by Fourier-transform infrared spectroscopy (FTIR). The Authors found out that the majority of the mobile phone frames and polymeric components were made of one of three types of polymers, acrylonitrile–butadienestyrene (ABS), polycarbonate (PC) and polyamide (PA). Palmieri et al. (2014) carried out a study to investigate the combined utilization of electronic and chemical imaging based techniques to characterize plastic materials from MPs, adopting plastic codes for initial identification of polymers and a combination of Raman spectroscopy, Scanning Electron Microscope (SEM) and Hyper-Spectral Imaging (HIS) to characterize plastic waste. Concerning the frames, these Authors found out that the main polymers are PC–ABS blend (42%) and PC (30%), accounting for 72% of the total plastics; a 17% could not be classified due to the absence of the printed code on the phone frames; considering the transparent screens, it was found that they are mainly composed of PMMA. Maris et al. (2015) focused on the characterization of crushed plastics from Small Waste Electric and Electronic Equipment and they found out that the main polymers are high impact polystyrene (HIPS), ABS and polypropylene (PP). Aquino et al. (2014) analyzed polymer fragments originating from obsolete mobile phones via laser-induced breakdown spectroscopy (LIBS) in order to identify the hazardous materials used in the assembly of these devices. Plastics must be separated before being remolded due to the immiscibility between certain polymers (Froelich et al., 2007) or due to prohibition of hazardous substances (Parliament European directive, 2003).

In terms of characterization, the mobile phone PCBs can be treated by aqua regia and analyzed through Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Camelino et al., 2015) or Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) in order to determine their metal content (Tan et al., 2017). An alternative procedure is to analyze the mobile phone PCBs using spectroscopy specific techniques as Energy Dispersive X-Ray Spectroscopy (EDX) (Hanafi et al., 2012) or X-ray fluorescence analysis (XRF) (Tan et al., 2017), but the last one is not suitable because of the extremely high inhomogeneity of the matrix: this makes extremely difficult to correlate the fluorescence signals to the quantity of the analytes present in the matrix.

In general, PCBs mainly consist of Cu and of smaller quantities of Ag, Au, Cr, Fe, Ni, Pb, Sn, Ti (Bhuie et al., 2004; Tan et al., 2017). Regarding the toxic metal content, the findings suggest that the waste generated from MPs should be considered as hazardous waste (Hira et al., 2018).

The liquid-crystal displays (LCD) screens are composed of different materials, including connectors, adhesives, diffusive sheets, reflective sheets, polarizing film, plastic frame, and LCD panel. The LCD panels consist of Indium-Tin Oxide (ITO), liquid crystals and the two glass plates enclosing these materials (Silveira et al., 2015; Fontana et al., 2015), but currently the recycling rate of indium is under 1% (Ciacci et al., 2014). Regarding the batteries, they have a specific recycling chain (Lv et al., 2018) and in this work the characterization of the related materials has not been addressed and only the mass has been evaluated.

According to European Union, MPs are included in the small information technology and telecommunications equipment category; the directive established the targets of 80% recovery rate and of 70% recycle and reuse rate (Parliament European directive, 2012). Understanding the MPs composition would allow recyclers to target key components to achieve European recycle target with a minimal amount of process steps, thereby improving the economic efficiency of the process. Accurately targeting key components would ensure that the recycling process becomes more streamlined and therefore more cost effective.

The materials thus classified can be effectively recovered and reintroduced into new production cycles to replace the virgin raw material as recommended by the principles of the Green Economy and Circular Economy (Communication from Commission to European Parliament, 2015): this will ensure that both the environment agencies and the recycler are satisfied. For example, Kim et al. (2018) used waste glass as supplementary cementing material in cement mortars; Tang et al. (2019) found out that concrete incorporating solid waste materials can not only promote the recycling of solid waste, but it also provides positive impacts on mechanical and chemical-physical properties.

From an economic recovery point of view, of high interest are the metals contained in PCBs: extensive studies have been carried out on recovering valuable metals, normally performed by hydrometallurgical techniques, consisting in a leaching step aimed at dissolving the metals of interest followed by a separation step (Kim et al., 2011; Kasper et al., 2011b; Petter et al., 2014; Li et al., 2012; Xiu et al., 2015). The PCBs treatment process usually consist in a first milling step followed by a chemical treatment, but Brunori et al. (2015) performed a hydrometallurgical process for the recovery of added value elements on the whole PCB without any mechanical pretreatment. Separated metal concentrates are fed to metallurgical recovery and refining processes, whereas the higher grade recycling of plastics is still under research (Goosey, 2012); in addition the performance of the plastics recycling processes highly depends on its composition (Chancerel and Rotter, 2009).

To establish a knowledge base for new recycling processes of materials, recycling orientated product characterization can be used as a tool. Only by having an accurate quantification of materials contained in MPs it is possible to investigate efficient recovery routes.

The aim of this paper is to outline a detailed material composition of MPs to provide useful information for the eco-design of these products in order to facilitate the separation of materials in the different recovery chains and to assist policymakers and the potential actors involved in material sustainability and future recycling practices.

2. Material and methods

20 different types of end-of-life MPs selected among the most popular brands were collected and first classified taking into account manufacturer and model. These MPs are currently being reused, repaired and sold: in the coming years they will reach their end-of-life stage and will need to be properly treated as well. The collected information (such as producer, model name and year of production) were marked on the casing of the devices.

For the characterization of WEEE and in particular for information and telecommunication equipment no standards are available so far: in order to have a detailed material composition of MPs, it has proposed the work flow illustrated in Fig. 1.

MPs were manually dismantled, separating batteries, electronic parts, metal parts, plastic materials and displays. Characterization was carried out on each component of this sample by chemical

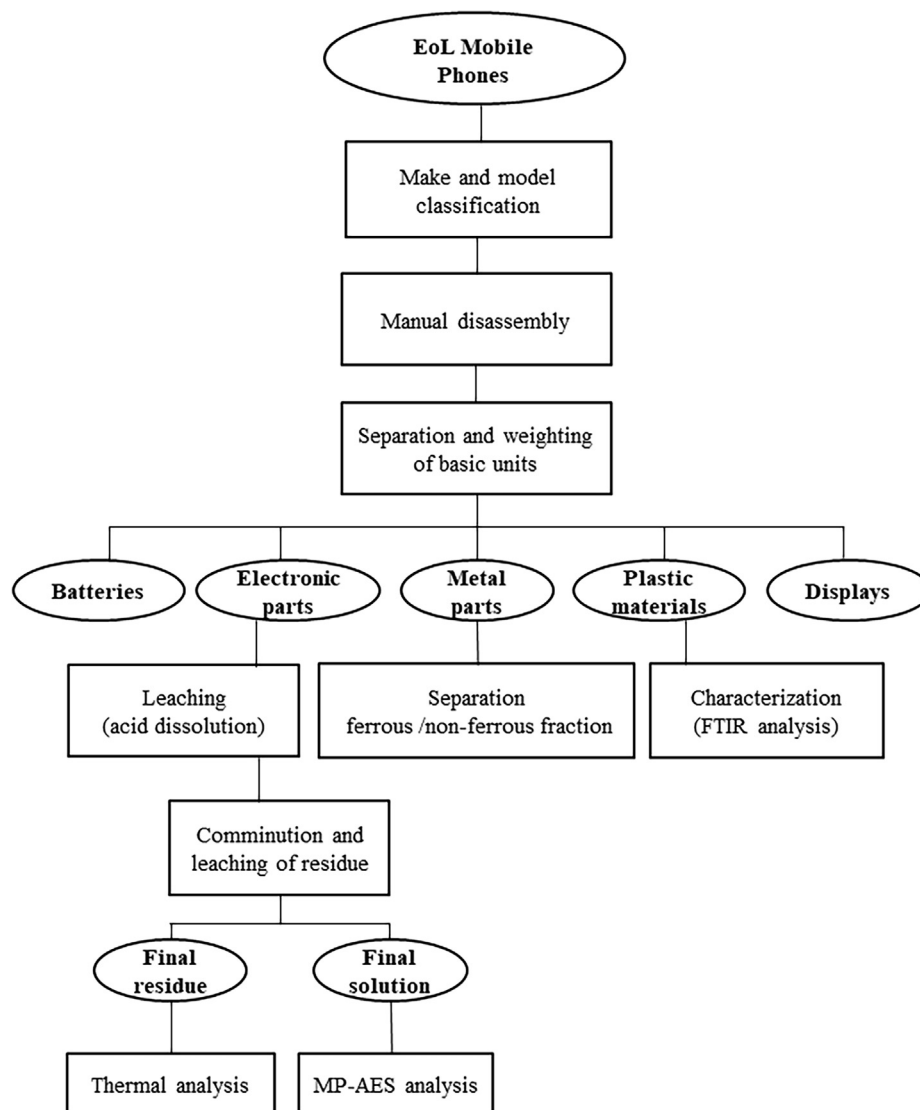


Fig. 1. Flowchart of the MPs materials characterization.

and physical analyses according to the procedure described in the following paragraphs.

It is possible ideally divide the flowchart into the following stages:

- collection and classification of MPs
- disassembly, separation and weighting of basic units
- electronic, plastic and metal parts characterization.

The leaching stage involved the characterization of printed circuit boards and connected components present in the waste materials.

2.1. Manual disassembly

Disassembly/dismantling is the systematic removal of components, parts and/or a group of parts from the end of life item by means of tools such as screwdrivers, hammers and pliers. Attachment regimes of materials encountered in electronic scrap are welding, wrapping, fastening, inserting, plating and coating. Basically a mobile phone is composed of a polymeric frame (sometimes containing a metal coating or lining), a printed circuit board, a battery, a keyboard, a LCD screen that in smartphones also has the

function of the keyboard, an antenna (which may be an integrated circuit) and other accessories, such as video cameras and speakers.

During disassembly each unit was dismantled and separated into its parts as shown in Fig. 2 as an example; five material fractions were collected and their mass determined: metals, plastics, batteries, displays and electronic components. The weight of every appliance and its parts was determined by a thermobalance (Mettler Toledo TGA/DSC1). Samples were placed in a crucible and subjected to a temperature program between 25 and 900 °C at 20 °C min⁻¹ in nitrogen flow (60 mL min⁻¹) and afterwards in air flow (90 mL min⁻¹).

2.2. MPs material analysis

Frames, covers and enclosures were characterized to perform the identification of polymers, whereas PCBs (composed by a variety of different materials), screws, etc. were separately processed in order to identify the different valuable materials and elements.

2.2.1. Plastic materials analysis

Plastic components of each item were analyzed by FTIR spectroscopy and then classified according to the plastic polymer type; no particular preparation of the analyzed samples was necessary.

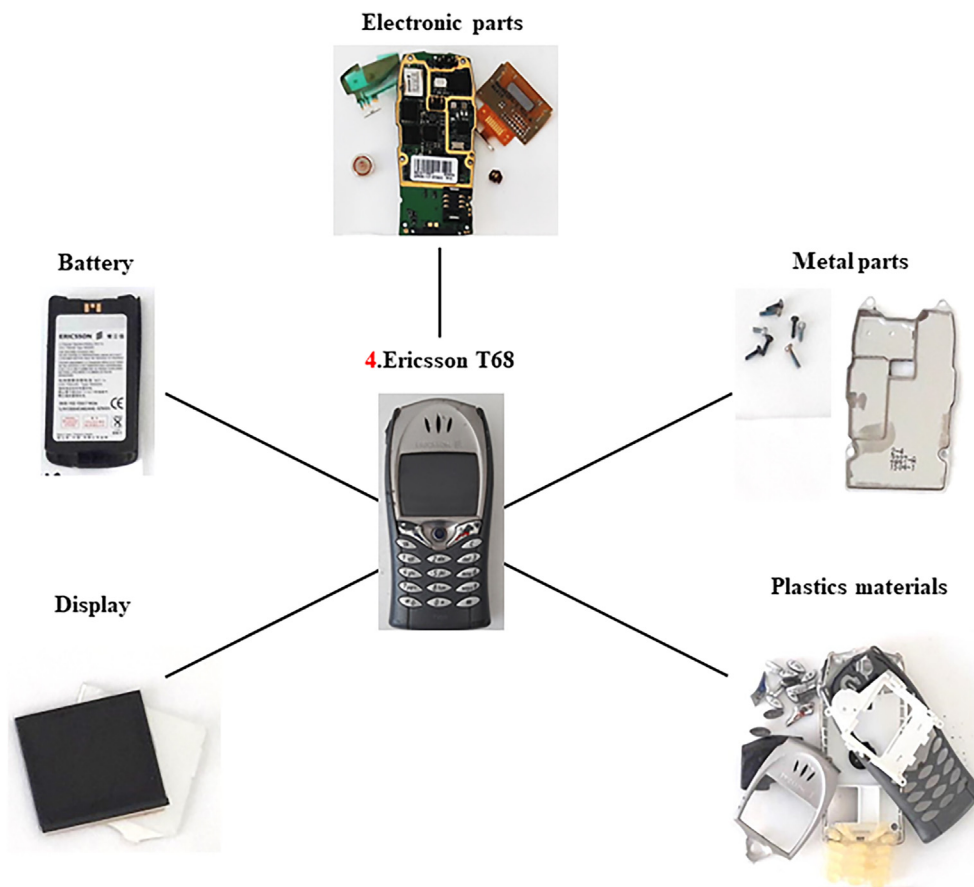


Fig. 2. Sample n. 4 dismantled in its parts.

Infrared spectroscopy measurements were performed using a SHIMADZU IR-Affinity-1 spectrophotometer equipped with ATR MIRACLE 10 device. The spectra were obtained with 45 scans, range of $5000\text{--}600\text{ cm}^{-1}$, and a resolution of 8 cm^{-1} .

10 families of standard polymers usually present in electronic equipment were selected and analyzed in order to build a specific library of spectra. The peaks associated to the characteristic functional groups were identified and the spectra of the analyzed samples were compared with the ones collected.

2.2.2. Electronic parts analysis

All solutions used during the chemical treatments of electronic components were prepared with analytical grade reagents and distilled water. All reagents were purchased from Sigma Aldrich and used as received without further treatments.

Metal ions' concentration was quantified by Microwave Plasma–Atomic Emission Spectrometer (4100 MP-AES, Agilent Technologies) and Atomic Absorption Spectrophotometer (AA-6300, Shimadzu).

All experiments were carried out in quadruplicate as a check on the experimental technique and precision, and the experimental results generally agreed within $\pm 5\%$ as a percentage error.

In order to determine the metal content into the electronic part of MPs, a first leaching of the intact PCB and electronic components was performed at $25\text{ }^{\circ}\text{C}$ using aqua regia (a solution of concentrated HNO_3 and concentrated HCl 1/3 v/v).

After leaching, solid residues and desoldered components were separated from leachate by filtration, washed with distilled water, dried until constant mass and weighted.

Solid residues were comminuted using cutting mill Retch SM300 until a particle size less than 1 mm was reached. Planetary

Ball Mill PM 100 was used to obtain a highest degree of fineness and homogeneity. Samples were then leached again at $25\text{ }^{\circ}\text{C}$ by a new aqua regia solution.

After this second leaching, solid residues were separated from leachates by filtration, washed by distilled water and dried to assess the mass balance.

The content of carbon, hydrogen, nitrogen and sulfur in the solid residue was determined with the unit Macro VARIO Cube operating in CHNS mode, calibrated according to the sulphanilamide standard. The content of oxygen was calculated up to 100%. The samples were pre-treated to assure homogeneity and reproducibility of the carried-out tests. The water and ash content was determined by thermogravimetric analysis (TG/DSC Mettler 2950) from $25\text{ }^{\circ}\text{C}$ to $900\text{ }^{\circ}\text{C}$.

3. Results and discussion

3.1. Manual disassembly

When the MP has reached the end of life stage and it reaches the recycling plant, as a general rule it is shredded as a whole after the removal of the battery, because currently the components are not designed for rapid disassembly to make the process economically viable.

After the analysis undertaken it was established that the overall generic structure of the MP remained similar from device to device, however issues such as screw type, screw position, cable attachment, position of PCBs etc. were subjected to variations

Basically, it is not energy intensive to unlock the associated materials such as glasses and metals with different mechanical properties, depending on the locking regimes of materials

involved. In general, materials locked through fastening by screws, clinks and rivets, etc., inserting, wrapping and packaging can readily be detached. Materials locked by means of coating, binding, welding and encapsulating are relatively difficult to be unlocked and materials locked by alloying and filling cannot be liberated by mechanical means (Zhang and Forssberg, 1997).

From dismantling operations, plastics, metals, electronic parts, batteries and displays were collected: the results are shown in Table 1.

The weighted average which takes into account each of the fractions is shown in Fig. 3.

All the batteries were Li-ion, with the exception of the sample n. 20 which was a Ni-MH.

These results are similar to those found by (Tan et al., 2017) with regard to displays (9% vs. 8.37%), quite similar for batteries (24% vs. 21.12%) and different for the other materials (6–7% difference). This difference is understandable when taking into account the products variability both over time and from manufacturer to manufacturer.

It can be observed that batteries, electronics, plastics and displays percentages do not deviate much from the average value with only the exception of some samples (for instance in sample 1 the battery weight percentage is much higher than the average value). Metal parts on the contrary are quite variable, ranging from 0.6 to 32.1%: when metal content is lower, the corresponding plastic content increases; this is likely due to a technical and strategic choice of the producer that can decide to substitute metal with plastic. In samples n. 18 and 19 (so-called smartphones) it has been observed that producers used glass (8.5% and 12.0% respectively) in addition to other materials.

To perform such a manual dismantling job most efficiently, a preliminary sorting of MPs from WEEE should be carried out in eco-places. This would allow manual dismantling with no preliminary sorting by operators. Unfortunately, at present, in the collecting sites, all WEEE are kept together and are randomly transferred to the trucks for the transport to plants where the sorting before disassembling is time consuming.

3.2. Materials analysis

The following sections outline a material composition analysis undertaken on the disassembled MPs.

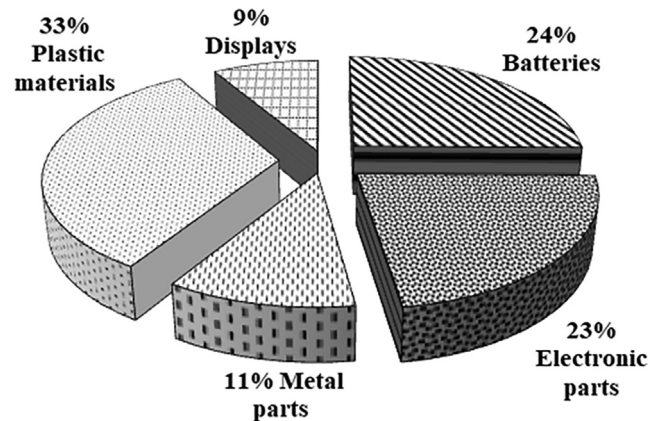


Fig. 3. Material fractions collected by manual dismantling operations (weighted average).

3.2.1. Plastic materials analysis

From dismantling discussion, it is clear that plastic materials are used for structural components such as the case and cover. In addition to enclosures, plastics are used in a wide range of cell phone applications such as mounting brackets, guides, insulator sheets and vibration cushions.

The collected FTIR spectra of standard polymers have been compared with plastics found in MPs reported in order to determine its composition; in Fig. 4 the spectra of dismantled and identified plastics from sample n. 1 are reported as an example.

The analysis on plastic materials shows that there are not many types of plastics used to make phones: it was found that polymeric components of these MPs were made of five distinct and separate polymers: polycarbonate (PC), acrylonitrile–butadienestyrene (ABS), polymethylmethacrylate (PMMA), polyurethane (PU) and silicone; the experimental data are summarized in Table 2.

It is clearly evident from this plastic fraction characterization that PC is in greater quantity.

Evidence suggests that MPs treatment processes with significant low-tech steps (manual disassembly and separation) can currently achieve significantly better plastics recycling than highly mechanized and automated alternatives. Lower-tech approaches

Table 1
Materials obtained from MPs by manual dismantling operations.

Sample (Manufacturer, model, year)	Total weight (g)	Batteries (wt%)	Electronic parts (wt%)	Metal parts: mounts, screws (wt%)	Plastic parts: housing components, cases, enclosures, covers (wt%)	Displays (wt%)
1. Nokia 5110 (1998)	170.5	45.4	24.3	1.5	24.9	3.8
2. Ericsson R380S (2000)	161.0	27.6	24.8	20.2	16.8	10.5
3. Nokia 6210 (2000)	112.0	39.7	29.0	1.3	25.9	4.0
4. Ericsson T68 (2001)	83.5	27.9	24.6	9.6	31.1	6.8
5. Sony Ericsson T230 (2003)	80.5	22.4	32.9	0.6	37.3	6.8
6. Motorola RAZR V3 (2004)	97.5	17.4	17.9	2.6	45.1	16.9
7. LG U8120 (2004)	124.5	25.7	24.1	4.0	37.3	8.8
8. Nokia 1600 (2005)	82.0	26.8	25.0	4.3	38.4	5.5
9. Sagem My 2002X (2005)	77.0	22.1	27.3	5.8	37.7	7.1
10. Nokia 6111 (2005)	91.5	16.9	30.6	9.8	36.6	6.0
11. Samsung SGH-Z510 (2005)	97.5	18.5	19.5	0.5	49.2	12.3
12. Nokia E51 (2008)	100.0	21.5	30.0	18.0	23.0	7.5
13. Nokia 6210 S-1 (2008)	120.0	17.9	23.3	32.1	21.3	5.4
14. Nokia 1616 (2009)	71.0	28.9	20.4	6.3	38.0	6.3
15. Honda X2S (2010)	68.0	25.0	22.1	2.9	43.4	6.6
16. Nokia C2-05 (2011)	98.0	18.4	15.3	29.6	30.6	6.1
17. Alcatel OneT. 217D (2011)	62.5	24.8	22.4	0.8	48.0	4.0
18. Nokia Lumia 620 (2013)	124.0	21.0	15.7	13.1	26.5	15.3
19. Wiko Lenny (2014)	169.0	21.3	10.2	25.2	16.6	14.8
20. Brondi Amico Flip+ (2016)	85.5	21.1	21.4	2.0	45.6	9.9

carry relatively higher costs and may otherwise appear unattractive in a sector where technological advance seems vital, however MPs plastics are especially challenging to recycle and dependent on high-quality collecting processes.

3.2.2. Electronic parts analysis

The results of the characterization of the leached electronic parts coming from the manual dismantling of MPs are reported in [Table 3](#).

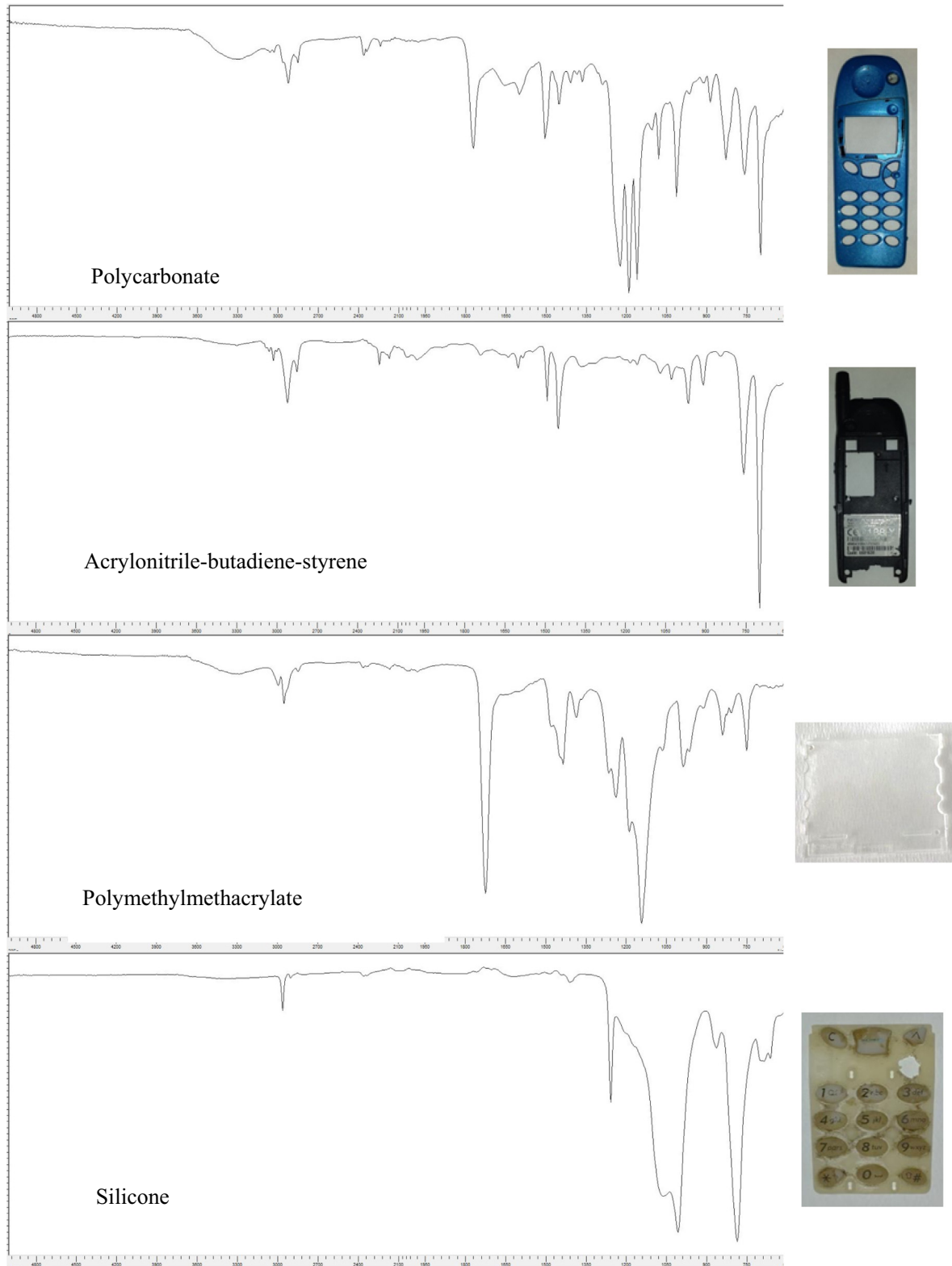


Fig. 4. FTIR spectra of plastic materials – sample n. 1.

Table 2
Polymers in MPs samples.

Sample	Housing components: Case, battery enclosure, cover, frames.	Display window	Keypad	PC %	PMMA %	ABS %	Silicone %	PU %
1	PC, ABS	PMMA	Silicone	75.5	5.5	8.5	10.5	–
2	PC	absent	PC, PMMA	90.3	9.7	–	–	–
3	PC	PMMA	PC	92.8	7.2	–	–	–
4	PC	PMMA	Silicone	74.3	9.2	–	16.5	–
5	PC	PMMA	Silicone	76.0	11.9	–	12.1	–
6	PC	PMMA	Silicone	81.3	8.4	–	10.3	–
7	PC	PMMA	PMMA, PU	86.0	10.2	–	–	3.8
8	PC	PMMA	Silicone	76.2	4.6	–	19.2	–
9	PC	PMMA	Silicone	70.6	5.0	–	24.4	–
10	PC, PMMA	PMMA	Silicone, PC	72.3	21.3	–	6.4	–
11	PC	PMMA	PMMA, PU	87.8	10.7	–	–	1.5
12	PC	PMMA	Silicone, PC	79.3	14.5	–	6.2	–
13	PC	PMMA	PC	83.0	17.0	–	–	–
14	PC	PMMA	Silicone	82.7	6.3	–	11.0	–
15	PC	PMMA	Silicone	78.6	9.2	–	12.2	–
16	PC	Silicone	Silicone, PC	87.4	–	–	12.6	–
17	PC, ABS	PMMA	Silicone	36.0	6.5	36.0	21.5	–
18	PC	glass	absent	100	–	–	–	–
19	PC	glass	absent	100	–	–	–	–
20	PC	PMMA	Silicone, PU	79.5	6.0	–	13.0	1.5
Average				80.5	8.2	2.2	8.8	0.3

Table 3
Metal content percentage in the electronic parts of MPs.

Sample	Ag (%)	Al (%)	Au (%)	Ca (%)	Co (%)	Cr (%)	Cu (%)	Fe (%)	Mn (%)	Ni (%)	Pb (%)	Sn (%)	Ti (%)	Zn (%)	Other metals <0.2%
1	0.20	0.50	0.19	0.25	0.88	0.51	62.50	17.16	0.26	7.80	1.94	3.59	0.47	3.70	0.05
2	0.17	0.70	0.16	0.34	0.69	0.57	63.04	18.29	0.33	4.14	2.69	4.65	0.73	3.44	0.05
3	0.08	0.58	0.10	0.25	0.03	0.57	60.17	12.31	0.12	9.64	1.57	2.84	0.34	11.29	0.07
4	0.30	1.30	0.25	0.52	1.32	1.29	62.89	18.10	0.37	3.91	2.49	3.91	0.68	2.56	0.11
5	0.10	0.66	0.12	0.29	0.05	1.01	43.76	45.26	0.30	1.67	1.42	3.73	0.35	1.22	0.06
6	0.14	1.13	0.13	0.38	0.11	1.43	41.76	44.93	0.17	2.92	0.12	5.95	0.41	0.33	0.08
7	0.15	0.61	0.14	0.26	<0.01	2.00	57.63	28.67	0.35	3.80	1.99	3.46	0.35	0.55	0.05
8	0.15	1.05	0.06	0.40	<0.01	0.46	67.40	14.64	0.15	7.07	0.11	2.23	0.41	5.79	0.07
9	0.16	0.74	0.09	0.32	0.08	1.39	58.30	23.95	0.32	6.49	0.10	3.03	0.36	4.59	0.06
10	0.18	0.52	0.16	0.35	0.07	2.18	63.34	20.89	0.13	6.82	0.10	0.32	0.37	4.52	0.06
11	0.16	1.07	0.20	0.41	0.14	1.70	55.45	21.86	0.18	3.35	1.17	3.58	0.49	10.10	0.14
12	0.15	0.56	0.11	0.31	0.12	0.29	64.21	13.77	0.25	7.45	0.09	4.71	0.36	7.44	0.18
13	0.10	0.46	0.13	0.24	0.08	0.78	59.80	16.97	0.10	7.97	0.08	3.74	0.29	9.22	0.05
14	0.12	0.81	0.08	0.48	<0.01	1.61	47.14	42.17	0.21	2.86	0.15	2.92	0.48	0.87	0.10
15	0.14	0.92	0.08	0.53	<0.01	1.00	65.09	19.87	0.51	3.70	0.15	4.68	0.44	2.79	0.09
16	0.13	0.82	0.13	0.43	0.12	2.49	51.52	36.37	0.19	2.71	0.14	3.03	0.45	1.39	0.09
17	0.13	1.26	0.08	0.49	<0.01	1.53	53.32	35.84	0.21	2.27	0.16	3.48	0.47	0.66	0.10
18	0.11	0.59	0.10	0.37	0.86	1.06	61.64	17.94	0.14	6.68	0.10	4.65	0.39	5.29	0.06
19	0.16	0.58	0.06	0.35	0.06	1.36	57.59	20.79	0.39	6.65	0.11	3.69	0.37	7.79	0.07
20	0.13	0.69	0.06	0.36	<0.01	1.91	45.92	42.81	0.16	1.88	1.05	3.27	0.30	1.38	0.07
Range	0.10–0.30	0.50–1.26	0.06–0.25	0.25–0.53	<0.01–1.32	0.29–2.49	41.76–67.40	12.31–45.26	0.12–0.39	1.67–9.64	0.08–2.69	0.32–5.95	0.29–0.73	0.33–11.29	0.05–0.18
Weighted average	0.15	0.77	0.12	0.36	0.23	1.21	57.47	25.23	0.24	5.10	0.85	3.49	0.42	4.29	0.08

Among the most valuable metals, palladium, generally used in connectors to improve conductivity (Reuter et al., 2013) as well as in ceramic capacitors (Chancerel and Rotter, 2009; Delfini et al., 2011; Fontana et al., 2018), should be present, but in MPs that kind of electronic components constitute an extremely small fraction of the electronic parts, therefore the quantity of Pd is below the limits of the instruments' detectability. Other metals <0.2% are Cd, Mo, Pt, V and Mg.

The content of carbon, hydrogen, nitrogen and sulfur in the solid residue was measured as explained in experimental paragraph and occurred being respectively 29%, 2.4%, 1.2% and 0.6%. The oxygen was calculated as 20.8%. The water and ash content was determined by thermogravimetric analysis, corresponding to 2% and 44% respectively.

3.3. Recycling potentials of end-of-life MPs

An area of discussion in a recycling framework is the economic viability of recycling; for any recycling initiative to be successful, it has to be economically suitable as well, besides fulfilling the environmental constraints. “To recycle or not to recycle” is a big question when it comes to scrap recycling: the reason becomes clear when examining the costs, the complexity and the low yield of recycling. The retrieved raw materials barely pay for the associated process costs, which include collection, transport, sorting, shredding, separation of metallic and non-metallic materials, neutralizing hazardous substances, smelting, and purification of the recovered metals; in addition, some components are not even recycled because it is not economically feasible.

Table 4

Potential revenue from higher value materials in MPs recycling.

Most valuable materials	Mass per ton pf MPs (kg)	Material price (€/kg)	Value (€/t)
Au	0.276 (from electronic parts)	33,612 (http://www.legor.com/it/quotazione-metalli)	9277
Cu	132 (from electronic parts)	6.56 (http://www.legor.com/it/quotazione-metalli)	867
Ag	0.345 (from electronic parts)	416 (http://www.legor.com/it/quotazione-metalli)	144
Ni	11.7 (from electronic parts)	11.75 (http://www.legor.com/it/quotazione-metalli)	138
Sn	8 (from electronic parts)	18.9 (https://www.ilsole24ore.com/finanza-mercato/materie-prime.shtml)	151
Al	100 (from metallic parts)	0.46 (http://www.borsinorifiuti.com)	46
Plastics	330	1 (http://www.borsinorifiuti.com)	330
Batteries	240	0.12 (http://www.borsinorifiuti.com)	29
Displays	90	Not available	Not available

Moreover, as a general rule, it is very difficult to get information about scrap prices: due to their complexity and different grade, they can change daily and between local markets.

Considering all materials found in MPs, gold constitutes the vast majority of the total value, although present in the electronic parts as a weighted average of only 0.12% (Table 4): the value of recoverable Au from 1 t of MPs (overall 276 g) is estimated to be about 9300 € (<http://www.legor.com/it/quotazione-metalli>; <https://www.ilsole24ore.com/finanza-e-mercato/materie-prime.shtml>). Copper is present in this fraction in a higher amount (132 kg/t) and contributes about 870 euros to the total value. Profit margin could be increased through the recovery of other metals (such as nickel and tin) in addition to the currently recycled gold and copper which already make up most of the metal value of MPs.

Metal parts have been mainly identified as non-ferrous (with the exception of screws) and in particular as aluminum (Al) and their value is about 460 €/t (<http://www.borsinorifiuti.com>).

Plastic materials, although of different types, have a similar value of about 1 €/kg (<http://www.borsinorifiuti.com>) when properly separated during the collection; currently they are not differentiated so their management is a cost and not an added value.

From personal communication with WEEE recycling plants, it can be assumed that the scrap value of batteries is around 120 € per t (value confirmed from <http://www.borsinorifiuti.com>); if so, the cost of collecting, sorting and shipping used batteries to a recycler exceeds the scrap value, so batteries tend to be disposed of.

For the displays it is very difficult to find information about the scrap value; probably the most similar market for these materials is that of the LCD monitors that, however, seem to be not industrially exploited yet. These considerations are summarized in Table 4.

It is clear that the most of the economic value is concentrated in the electronic parts, but it is evident from Table 4 that there are still margins to increase the potential revenue, for example addressing further investigation towards the development of a proper system to collect separately plastics and to recycle displays; taking into account that 1 t of MPs contains materials with a potential value of more than 10,000 euros, their whole recycling can generate more value and profit according to Circular Economy.

4. Conclusions

The aim of this paper is to provide a detailed material composition of MPs as this information is critical to establishing the needs of a recycling process: as products grow in complexity and variety of materials, this type of analysis provides insights for policymakers and those interested in material sustainability into macro-level trends of material use and future recycling practices.

The analyses show that the materials variability of MPs that have been investigated (manufactured by the world's largest manufacturers from 2001 to present, which are largely now dismissed as outdated) is significant and this variation has considerable effects on the disassembly step.

The experiments show in which parts individual materials are concentrated demonstrating that a proper dismantling prior to the actual treatment process could provide a better selectivity and thus, a better recovery.

It was found that the most abundant fraction is plastic 33%; other materials are: batteries 24%, electronic parts 23%, metal parts 11% and displays 9% with a potential value of more than 10,000 €/t.

By targeting these parts, the following strategic goals can be simultaneously achieved: preservation of natural resources, removal of heavy metals from the natural environment, reduction of emissions of gases causing the greenhouse effect, environmental protection and job creation according to Circular Economy.

Key factors for making such a circular treatment economically and technically feasible are standardizing components and moving to disassembly-friendly product designs to decrease the labor needed to extract them; MPs should be then designed with a view to End-of-Life material recovery to rank highly on Lansink's ladder (Lansink, 1980).

However, this does not address the issue of millions of MPs currently in production and use worldwide because with the pressing goals of cost reduction and improved functionality, it would be quite difficult for product designers to alter their designs with end-of-life characteristics taking precedence, so policy tools may encourage designers to work with product end-of-life in mind.

References

- Aquino, F.W.B., Pereira, F., Edenir, R., 2014. Analysis of the polymeric fractions of scrap from mobile phones using laser-induced breakdown spectroscopy: chemometric applications for better data interpretation. *Talanta* 134, 65–73. <https://doi.org/10.1016/j.talanta.2014.10.051>.
- Bhuie, A.K., Ogunseitan, O.A., Saphores, J.D.M., Shapiro, A.A., 2004. Environmental and economic trade-offs in consumer electronics products recycling: a case study of cell phones and computers. In: *Proceedings of the IEE International Symposium on Electronics and Environment*, pp. 74–79. <https://doi.org/10.1109/ISEE.2004.1299691>.
- Brunori, C., Cafiero, L., De Carolis, R., Fontana, D., Guzzinati, R., Pietrantonio, M., Pucciarmati, S., Torelli, G.N., Trinca, E., Tuffi, R., 2015. Innovative technologies for metals recovery and plastic valorisation from electric and electronic waste: an integrated approach. *Environ. Eng. Manag. J.* 14, 553–1562.
- Camelino, S., Rao, J., Padilla, R.L., Lucci, R., 2015. Initial studies about gold leaching from printed circuit boards (PCBs) of waste cell phones. *Procedia Mater. Sci.* 9, 105–112. <https://doi.org/10.1016/j.mspro.2015.04.013>.
- Chancerel, P., Rotter, S., 2009. Recycling-oriented characterization of small waste electrical and electronic equipment. *Waste Manag.* 29, 2336–2352. <https://doi.org/10.1016/j.wasman.2009.04.003>.
- Ciacchi, L., Reck, B.K., Nassar, N.T., Graedel, T.E., 2014. Lost by design. *Environ. Sci. Technol.* 49, 9443–9451. <https://doi.org/10.1021/es505515z>.
- Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the Committee of the regions: Closing the loop - An EU action plan for the Circular Economy COM (2015) 614. - December 02, 2015.
- Delfini, M., Ferrini, M., Manni, A., Massacci, P., Piga, L., Scopettuolo, A., 2011. Optimization of precious metal recovery from waste electrical and electronic equipment boards. *J. Environ. Prot.* 2, 675–682. <https://doi.org/10.4236/jep.2011.26078>.
- Fontana, D., Forte, F., De Carolis, R., Grosso, M., 2015. Materials recovery from waste liquid crystal displays: a focus on indium. *Waste Manag.* 45, 325–333. <https://doi.org/10.1016/j.wasman.2015.07.043>.

- Fontana, D., Pietrantonio, M., Pucciarmati, S., Torelli, G.N., Bonomi, C., Masi, F., 2018. Palladium recovery from monolithic ceramic capacitors by leaching, solvent extraction and reduction. *J. Mater. Cycles Waste Manage.* 20, 1199–1206. <https://doi.org/10.1007/s10163-017-0684-3>.
- Froelich, D., Maris, E., Haoues, N., Chemineau, L., Renard, H., 2007. State of the art of plastic sorting and recycling: Feedback to vehicle design. *Miner. Eng.* 20, 902–912. <https://doi.org/10.1016/j.mineng.2007.04.020>.
- Goosey, M., 2012. The materials of WEEE. *WEEE Handbook*. 123–144. doi:10.1533/9780857096333.2.123.
- Hanafi, J., Jobiliongb, E., Christianib, A., Soenartab, D.C., Kurniawanb, J., Irawanc, J., 2012. Material recovery and characterization of PCB from electronic waste. *Procedia Soc. Behav. Sci.* 57, 331–338. <https://doi.org/10.1016/j.sbspro.2012.09.1194>.
- Hira, M., Yadav, S., Morthekai, P., Linda, A., Kumarb, S., Sharma, A., 2018. Mobile Phones—An asset or a liability: a study based on characterization and assessment of metals in waste mobile phone components using leaching tests. *Hazard. Mater.* 342, 29–40. <https://doi.org/10.1016/j.jhazmat.2017.08.008>.
- Kasper, A.C., Bernardes, A.M., Veit, H.M., 2011a. Characterization and recovery of polymers from mobile phone scrap. *Waste Manag. Res.* 29 (7), 714–726. <https://doi.org/10.1177/0734242X10391528>.
- Kasper, A.C., Berselli, G.B.T., Freitas, B.D., Tenorio, J.A.S., Bernardes, A.M., Veit, H.M., 2011b. Printed wiring boards for mobile phones: characterization and recycling of copper. *Waste Manag.* 31, 2536–2545. <https://doi.org/10.1016/j.wasman.2011.08.013>.
- Kim, S.K., Hanif, A., Jang, I.Y., 2018. Incorporating liquid crystal display (LCD) glass waste as supplementary cementing material (SCM) in cement mortars—rationale based on hydration, durability, and pore characteristics. *Materials* 11, 2538. <https://doi.org/10.3390/ma11122538>.
- Kim, E., Kim, M., Lee, J., Pandey, B.D., 2011. Selective recovery of gold from waste mobile phone PCBs by hydrometallurgical process. *J. Hazard. Mater.* 198, 206–215. <https://doi.org/10.1016/j.jhazmat.2011.10.034>.
- Lansink, A., 1980. *Vergaderjaar*, 15–80.
- Li, J., Xu, X., Liu, W., 2012. Thiourea leaching gold and silver from the printed circuit boards of waste mobile phones. *Waste Manag.* 32, 1209–1212. <https://doi.org/10.1016/j.wasman.2012.01.026>.
- Lv, W., Wang, Z., Cao, H., Sun, Y., Zhang, Y., Sun, Z., 2018. A critical review and analysis on recycling of spent Lithium-ion batteries. *ACS Sustain. Chem. Eng.* 6 (2), 1504–1521. <https://doi.org/10.1021/acssuschemeng.7b03811>.
- Maris, E., Botané, P., Wavrer, P., Froelich, D., 2015. Characterizing plastics originating from WEEE: a case study in France. *Miner. Eng.* 76, 28–37. <https://doi.org/10.1016/j.mineng.2014.12.034>.
- Palmieri, R., Bonifazi, G., Serranti, S., 2014. Recycling-oriented characterization of plastic frames and printed circuit boards from mobile phones by electronic and chemical imaging. *Waste Manag.* 34, 2120–2130. <https://doi.org/10.1016/j.wasman.2014.06.003>.
- Parliament European Directive 2002/95/EC. - January 27, 2003.
- Parliament European Directive 2012/19/UE. - July 24, 2012.
- Petter, P.M.H., Veit, H.M., Bernardes, A.M., 2014. Evaluation of gold and silver leaching from printed circuit board of cellphones. *Waste Manag.* 34, 475–482. <https://doi.org/10.1016/j.wasman.2013.10.032>.
- Reuter, M., Hudson, C., Van Schaik, A., Heiskanen, K., Meskers, C., Hagelüken, C., 2013. United Nations Environment Programme UNEP Metal recycling: opportunities, limits, infrastructure. A report of the working group on the global metal flows to the international resource panel.
- Sarath, P., Bonda, S., Mohanty, S., Navak, S.K., 2015. Mobile phone waste management and recycling: views and trends. *Waste Manag.* 46, 536–545. <https://doi.org/10.1016/j.wasman.2015.09.013>.
- Silveira, A.V., Fuchs, M.S., Pinheiro, D.K., Tanabe, E.H., Bertuol, D.A., 2015. Recovery of indium from LCD screens of discarded cell phones. *Waste Manag.* 45, 334–342. <https://doi.org/10.1016/j.wasman.2015.04.007>.
- Sun, L., Zenga, X., Lia, J., 2016. Pollutants release and control during WEEE recycling: a critical review. *Procedia Environ. Sci.* 31, 867–872. <https://doi.org/10.1016/j.proenv.2016.02.100>.
- Tang, Z., Li, W., Ke, G., Zhou, J.L., Tam, V.W.Y., 2019. Sulfate attack resistance of sustainable concrete incorporating various industrial solid wastes. *J. Clean. Prod.* 218, 810–822. <https://doi.org/10.1016/j.jclepro.2019.01.337>.
- Tan, Q., Dong, Q., Liu, L., Song, G., Liang, Y., Li, J., 2017. Potential recycling availability and capacity assessment on typical metals in waste mobile phones: a current research study in China. *J. Clean. Prod.* 148, 509–517. <https://doi.org/10.1016/j.jclepro.2017.02.036>.
- Zhang, S., Forssberg, E., 1997. Mechanical separation-oriented characterization of electronic scrap. *Resour. Conserv. Recycl.* 21, 247–269. [https://doi.org/10.1016/S0921-3449\(97\)00039-6](https://doi.org/10.1016/S0921-3449(97)00039-6).
- Xiu, F., Qi, Y., Zhang, F., 2015. Leaching of Au, Ag, and Pd from waste printed circuit boards of mobile phone by iodide lixiviant after supercritical water pretreatment. *Waste Manag.* 41, 134–141. <https://doi.org/10.1016/j.wasman.2015.02.020>.
- <https://comtrade.un.org/data/>. Accessed 30th July 2019.
- <http://www.legor.com/it/quotazione-metalli>. Accessed 2nd October 2018.
- <https://www.ilssole24ore.com/finanza-e-mercato/materie-prime.shtml>. Accessed 2nd October 2018.
- <http://www.borsinorifiuti.com>. Accessed 2nd October 2018.