



Proceeding Paper From Mineral Processing to Recycling: The Case of End-of-Life Printed Circuit Boards' Physical Processing ⁺

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Abstract: The treatment of end-of-life printed circuit boards (EoL PCBs) presents a contemporary recycling challenge with significant environmental, economic and social dimensions. This reality has attracted interest in the development of sustainable treatment processes, founded on mineral processing and metallurgical processes. The present paper reviews the applications of mineral processes in the treatment of end-of-life printed circuit boards (magnetic, electromagnetic, gravity and flotation processes), highlighting their strengths, weaknesses and limitations in the processing of EoL PCBs.

Keywords: end-of-life printed circuit boards (EoL PCBs); mineral processing; physical recycling

1. Introduction

End-of-life printed circuit boards (EoL PCBs) represent a waste stream where their treatment is of special interest. Their disposal presents a recycling challenge with significant environmental, economic, and social dimensions. For this reason, instead of being considered a waste stream, they are considered to be a type of ore and, as with industrial ores, hold significant market value [1]. This reality has attracted interest regarding the development of sustainable treatment processes, founded on pyrometallurgical, hydrometallurgical and mineral processing techniques.

After the removal of valuable and hazardous components from printed circuit boards, as well as their size reduction and separation, the created material flow is addressed in physical recycling or upgrading processes. When exploiting the different physicochemical properties (size, density, magnetism, electromagnetism, gravity, hydrophobia/hydrophilia, etc.) of the various materials contained in printed circuit boards, magnetic, electromagnetic, gravity and flotation processes are all deployed in the treatment of EoL PCBs. The main objective of all these processes is the separation of processed material flow into metallic and non-metallic fractions.

Seeking to highlight the strong dependency of mineral processing and recycling, the present paper reviews the applications of mineral processes in the treatment of the waste stream of end-of-life printed circuit boards. An analysis of their outcomes is used to highlight their prospects, strengths, weaknesses and limitations regarding the processing of a challenging waste stream, such as that presented by end-of-life printed circuit boards.

2. Magnetic Separation Processing

In the pulverized material flow of EoL PCBs, many elements and materials with magnetic and susceptible magnetic properties are included. The significant presence of ferromagnetic materials (Fe, Ni, Co) provides favorable conditions for the effective application of magnetic separation processing. During its application, magnetic particles are separated from nonmagnetic particles. In the case of EoL PCB treatment, magnetic separators are used for the isolation of ferromagnetic materials contained within the



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). processed material flow. Using such a method, the separation of non-ferrous metals and other non-magnetic waste from ferromagnetic metals can be achieved [2].

For magnetic separation, the equipment used is classified into two categories: lowintensity and high-intensity separators. Low-intensity separators use either permanent magnets or electromagnets, which provide high magnetic strengths, while high-intensity separators are suitable for wet separation processes [3]. According to Sohaili et al. [4] and Hanafi et al. [5], low-intensity drum separators are used extensively for the separation of ferromagnetic metals from the rest of the material flow, while high-intensity drum separators are used for the separation of paramagnetic materials of lower magnetic susceptibility (copper alloys), contained in printed circuit boards.

Despite these techniques, one significant obstacle for the efficient application of magnetic separation processing in EoL PCBs is the agglomeration of ferrous particles with other non-ferrous materials contained in the processed material flow, leading to low efficiency in the separation process. To limit this identified burden, the research and technology community has sought out practices that support the efficient separation of magnetic and non-magnetic materials, with significant results. Yazici et al. [6] indicated that the magnetic separation recovery potential can reach up to 96% for Fe and 93% for Ni, while losses of more than 60% of copper, gold and palladium occur due to their attachment to iron alloys.

3. Electrostatic Separation Processing

Similarly, diamagnetic and paramagnetic recovery can be achieved with the application of electrostatic separation processes (eddy current, corona electrostatic and triboelectrostatic separation). Based on the experience gained from their application in the processing of monazite, spinel, sillimanite, tourmaline, garnet, zircon, rutile, and ilmenite from heavy leach/stream placer sand [7], an individual particle of a processed material flow may be electrostatically charged via the mechanisms of conductance charging, high-tension or ion bombardment charging, and contact or frictional charging [8].

Their potential for high recovery rates, combined with the advantages of fewer environmental hazards, low energy consumption, and easy operation and control [9], means that electrostatic processes can be considered a promising separation process for a significant proportion of the materials contained within a stream of pulverized end-of-life printed circuit boards.

Early research has proved that applying this process can contribute to the recovery of Cu, Al, Pb, Sn and iron particles and of a certain number of precious metals from end-of-life printed circuit boards [10]. This is particularly true in the case of copper recovery; Burat and Özer [11] reported a copper recovery rate of 98%, thanks to the application of sequential electrostatic processing of end-of-life printed circuit boards.

3.1. Eddy Current Separation Process

An eddy current-based electrostatic separator can be applied to EoL PCBs, aiming for the separation of ferrous and non-ferrous metals, as well as the removal of plastic particles contained within the metal/plastic mass of the pulverized processed material [12].

Besides the shape and size of a particle, one critical factor that determines the deflection behavior of a material is the deflection coefficient of a particle (conductivity to density (σ/ρ)) of a conductive material, which influences the magnitude of the repulsive force (Lorentz force) that is exerted on each particle.

The significant presence of materials with a high ratio of electrical conductivity/density in EoL PCBs, as presented in Table 1, makes eddy current separation processes a promising alternative solution for the recovery of a significant part of the metallic fraction of this specific waste stream, including copper and aluminum particles. On the contrary, in the case of materials with extremely low values of conductivity/density ratio, such as stainless steel, plastic, and glass, the use of eddy current separators is inappropriate [13,14].

Metal/Material	Conductivity (σ)/Density Ratio (ρ)	Metal/Material	Conductivity (σ)/ Density Ratio (ρ)	
Aluminium (Al)	13.0	Tin (Sn)	1.2	
Copper (Cu)	6.7	Iron (Fe)	1.2	
Silver (Ag)	6.0	Lead (Pb)	0.45	
Zinc (Zn)	2.4	Glass	0.00	
Gold (Au)	2.1	Plastics	0.00	
$\sigma=$ Electrical conductivity $ imes 10^{6}~\Omega^{-1}m^{-1}$, $ ho=$ Density $ imes 10^{3}~kg/m^{3}$				

Table 1. Deflection coefficients for metals/materials (Source: Yazici et al. [15]).

Initially, Zhang et al. (1999) reached the conclusion that non-ferrous material (Cu and Al) recoveries ranged from 48% to 98%, depending on the different technological versions of eddy current separators used for pulverized EoL PCBs with a size of less than 10mm. Later research [16,17], showed significant potential for the separation of large amounts of coarse non-ferrous metallic particles (Cu and Al) in a wider size range (2 to 50 mm) that are contained within EoL PCBs.

3.2. Corona Electrostatic Separation Process

The differences in density and electrical conductivity between plastics, metals and ceramics provide excellent conditions for the application of a corona electrostatic separator [18], seeking the separation of metallic particles (including non-ferrous particles) from plastic ones contained in the waste stream.

The operation of the process is based in the corona discharge phenomenon. The passing of processed material through a corona field leads to the charging of non-conductive (non-metallic) particles only. The separating capability depends on the difference in polarity and the amount of charge acquired by those particles to be separated. In such a way, non-metallic particles are attached to the drum, falling off into storage bins, whereas the conducting (metallic) particles discharge rapidly in the direction of the earthed electrode.

Although in certain cases, the generation of toxic compounds, such as nitrogen oxide and ozone [13], 2020, was reported, corona separators are still considered an environmentally friendly, high-efficiency, and cost-effective separation process [19], representing the most effective separation technology for metallic and non-metallic fractions [20].

However, its application does not support the recovery of precious metals, since the recovered metallic fraction is a mixture of various metals, comprising Cu, Al, Pb, Au, Ag, etc. [21]. This reality highlights one weakness of using corona electrostatic separators in the treatment of EoL PCBs, which is the presence of middling products with high metal content, requiring further treatment.

According to the literature review, the combination of corona electrostatic processes with other processes can offer significant advantages in the final outcome. He and Xu [22], in their study of the application of a chlorination process to recycle gold and copper from EoL PCBs, concluded that the application of corona electrostatic separators is a necessary pre-treatment stage that contributes significantly to the increase in specific particle recovery [19].

3.3. Triboelectrostatic Separation Process

To deal with the challenge of the separation of materials with similar conductivities, contained within EoL PCBs, triboelectrostatic separation applications were assessed. Although their application presents limited treating capacity and, therefore, limited potential for extensive industrial use (He et al., 2015), the process has attracted the interest of the research and industrial community because of the fact that it is a dry separation process that does not require wastewater treatment processes.

Based on the surface charge transfer phenomenon, polarized or charged particles can be sorted under the influence of an electric field, based on their surface charging characteristics [23]. In such a method, the polymeric/plastics materials of EoL PCBs can

be charged either by frictional electrification (or tribocharging) or by rubbing polymeric materials together [24], developing polarities that permit their separation from the rest of the processed flow.

Through this process, it is possible to achieve the recovery of high-impact polystyrene and acrylonitrile butadiene styrene, identified frequently in EoL PCBs [25,26]. Moreover, this process allows the recovery of metals with high conductivity, like Al and Cu (e.g., cable and wire waste) from the mixtures [23]. However, the research results showed limitations in their applicability, in terms of the size [27] and shape [28] of particles.

4. Gravity Separation Processing

The different densities of materials contained within EoL PCBs, as shown in Table 2, support the application of various gravity separation processes. During these processes, materials of different specific gravities are separated by their relative movement in response to the force of gravity and one or more other forces of an external fluid that acts as a separation medium and can be either water or air. Particle movement into the air or the fluid depends mainly on particle density. However, the size and the shape of the particle are also contributing factors [29].

Materials	Specific Gravity g/cm ³	Materials	Specific Gravity g/cm ³
Copper	8.96	Gold	19.3
Iron	7.87	Bismuth	9.79
Glass fibber	2.7	Chromium	7.15
SiO2 filler	2.65	Lead	11.3
Plastics	2.0	Nickel	8.90
Ferrite	5.0	Silver	10.5
Phenolic	1.23-1.24	Tin	7.26
Aluminium	2.7	Zinc	7.14

Table 2. Specific gravities of materials contained in printed circuit boards.

Based on their applications in the mineral-processing sector, gravity separation processes are characterized by their low installation capital and operating cost requirements, while the absence of chemical reagents and no need for additional heating make them an environmentally friendly group of processes that are commonly used in the physical separation of metals and non-metals contained within EoL PCBs [18].

Depending on the deployed medium, gravity separation processes can be divided into two main categories; air and fluid separation processes [13].

Air classification techniques are founded on the suspension of the particles in a flowing air stream. During the application of the separation process, both gravity and drag forces are exerted in two opposite directions on the processed particles. In the case of low-density particles, gravitational forces are lower than the drag forces; thus, the particles move upward. Conversely, in the case of high-density particles, gravitational forces are higher than the drag forces, permitting their downward movement. With appropriate adjustments, the separation of different specific gravity particles can be achieved [30], moving heavy particles downward against the air stream, while the light particles rise along with the air stream to the top of the column [31].

In terms of EoL PCBs, separators using material density, such as air tables, air cyclones, and centrifugal separators, are applicable when seeking the recovery of base metals from non-metal fractions, such as Cu, Au, and Ag [13]. Zheng et al. [32] studied the separation of the metallic and non-metallic particles of EoL PCBs, applying an air separation process. The results of their study showed that the application of an air separation process is appropriate for copper particle separation.

Moreover, besides gravity forces, the plastic and metallic fraction of EoL PCBs can be separated with the use of viscous liquid. Similar to air-based classifiers, the motion of a particle in a fluid is dependent not only on the particle's density but also on its size and shape [4]. Using different heavy liquids, it is possible to further separate the metals contained within the metallic fraction of EoL PCBs [33]. In these cases, the application of the separation process takes place via separation tables that exploit differences in the specific gravity and particle size to achieve the desired separation. Veit et al. [34] studied the use of a Mozley concentrator for the pre-treatment of processed EoL PCBs, obtaining high recovery rates of copper (85%), tin (95%), nickel (96%) and silver (98%), while aluminum and gold could not be recovered, due to their density and lamellar form, respectively.

Based on the work of Cui and Forssberg [35] on the use of a wet shaking table for the separation of copper/plastic fractions from cable scrap, Burat and Özer [11] studied the efficiency of wet shaking table separation (with a Wilfley shaking table) as a pre-treatment stage for different-sized fractions of EoL PCBs. Their work showed that a concentrate grade of over 58% total metals (Cu, Au, Ag, Fe and Al) was obtained at -1 + 0.3 mm fraction, and the total metal content of the heavy product dramatically increased to over 95% at the finest fraction. The highest grade (49.08%) of the recovered metal was reported in the case of copper, at -1 + 0.3 mm size fraction.

5. Flotation Separation Processing

The principle behind flotation processing is the exploitation of the different hydrophobic and hydrophilic properties presented among different particles that are contained in a processed material flow. The most popular version of flotation processing is the froth flotation process, which is extensively used in the mineral-processing sector. Its application has permitted the exploitation of low-grade and complex ore bodies that would have otherwise been regarded as of limited economic interest. Nowadays, its use and application are expanded to treat greater tonnages and to cover new fields of technical interest [36].

The reported alternative versions of the flotation process include dispersed air flotation (DPAF), dissolved air flotation (DAF), pneumatic flotation, electrolytic flotation, bacterial leaching and the column flotation process.

From the literature review, the only flotation process where its application regarding EoL PCBs was assessed is the froth flotation process. The most common outcome of all these research initiatives is that froth flotation is considered a promising process to face the challenge of low recovery rates of base and precious metals obtained by the application of other separation processes in fine fractions below 74 μ m [33]. As a result of particles having similar physical properties, in fine fractions, the efficiency of gravity separation, magnetic separation and electrostatic separation processes is limited [37]. Hence, research endeavors have attempted to deal with this challenge, assessing it as a mineral-processing problem, seeking the optimum combination of operational conditions that will boost the recovery rates of metals.

Ogunniyi and Vermaak [38] examined the application of froth flotation processes in pulverized, fine-grained EoL PCBs. In the course of their research, they noticed that many metallic elements were found to concentrate in the sinking phase, while others gathered in the froth phase. Remarkable rates of recovery of gold and palladium were recorded for the sink, with about a 64% recovery rate at an enrichment ratio of 3.1 (676 ppm in the actual assay) for Au.

Tsakalakis et al. [36] assessed the application of froth flotation process in EoL PCBs, focusing on the recovery of Cu, Au, Pd and Ag. Their results regarding the processing of fine-sized fractions (-0.5 mm) showed the recovery of metallic particles in the floating fraction were 80.5% for Au, 83.0% for Pd, 37.5% for Ag and 76.3% for Fe, while in the sinking fraction, Cu recovery reached 74% and Ag reached 46.4%. In the case of Ag, indifferent behavior was noted between floating and sinking fractions. In this way, the conclusion was verified that the natural hydrophobicity of metals contained in PCB-pulverized material, as well as the production of stable froth, could be achieved even without the addition of any frothing reagent.

Regarding the optimal size of the processed material, Vidyadhar and Das [39] reached the conclusion that froth flotation is an appropriate separation process for the entire -1.0 mm fraction of EoL PCBs, resulting in a pre-concentrate product and achieving a 90% recovery rate of metal with a loss of less than 4%, while the presence of reagents was negligible, supporting the environmentally friendly characteristics of the specific process. In the course of their work, He and Duan [40] reached the conclusion that the optimum size fraction for the application of the froth flotation process was 0.074–0.25 mm, which ensured the recovery of metallic concentrations higher than 84%. In such a way, they reaffirmed that reverse froth flotation can be considered an efficient alternative approach to recycling EoL PCBs, in terms of fine fractions.

6. Conclusions

The challenge of end-of-life printed circuit board treatment has attracted the interest of both international researchers and the industrial community. Significant initiatives were undertaken with the aim of developing processes that ensure the maximum recovery rate of metallic particles contained within the waste stream of EoL PCBs. All these initiatives are based on the adoption of metallurgical and mineral processing methods in the treatment of EoL PCBs.

Mineral processing processes are used for the development of the physical recycling of EoL PCBs, which is now critical, and their performance influences either the direct recovery of the selected materials or the performance of the next stages in the recycling process. This attribute has caused several scientists and researchers to consider physical recycling processes as a sustainable alternative engineering approach offering significant prospect challenges.

Given the length limitations of this paper, the present study presents an overview and analysis of the different EoL PCB recycling methods that are used for the recovery of the various materials contained within the waste stream of EoL PCBs and that can be derived via the mineral processing methods that are reviewed herein.

Through the present review, we attempt to highlight the contribution of mineral processing methods in the treatment of EoL PCBs. Analyzing the limitations, strengths and weaknesses of each process, this paper seeks to contribute to the continuous efforts of the research and industrial communities to find optimal technical solutions to the contemporary challenge of recycling EoL PCBs.

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References

- Castro, M.B.; Remmerswaal, J.A.M.; Brezet, J.C.; Van Schaik, A.; Reuter, M.A. A simulation model of the comminution–liberation of recycling streams: Relationships between product design and the liberation of materials during recycling. *Int. J. Miner. Process.* 2005, 75, 255–281. [CrossRef]
- 2. Zhu, X.N.; Nie, C.C.; Wang, S.S.; Xie, Y.; Zhang, H.; Lyu, X.J.; Qiu, J.; Li, L. Cleaner approach to the recycling of metals in waste printed circuit boards by magnetic and gravity separation. *J. Clean. Prod.* **2020**, *248*, 119235. [CrossRef]
- 3. Rao, S.R. Resource Recovery and Recycling from Metallurgical Wastes; Elsevier: Amsterdam, The Netherlands, 2011; pp. 56–61.
- Sohaili, J.; Muniyandi, S.K.; Mohamad, S.S. A review on printed circuit board recycling technology. J. Emerg. Trends Eng. Appl. Sci. 2012, 3, 12–18.
- Hanafi, J.; Jobiliong, E.; Christiani, A.; Soenarta, D.C.; Kurniawan, J.; Irawan, J. Material recovery and characterization of PCB from electronic waste. *Procedia-Soc. Behav. Sci.* 2012, 57, 331–338. [CrossRef]
- 6. Yazici, E.Y.; Devici, H.; Yazici, R. Base and precious metal losses in magnetic separation of waste printed circuit boards. *Proc. EMC* **2015**, *2*, 649–662.
- 7. Haldar, S.K. Mineral Exploration: Principles and Applications; Elsevier: Amsterdam, The Netherlands, 2018; pp. 275–276.
- 8. Gupta, A.; Yan, D.S. *Mineral Processing Design and Operations: An Introduction;* Elsevier: Amsterdam, The Netherlands, 2016; p. 666.
- 9. Wei, J.; Realff, M.J. Design and optimization of free-fall electrostatic separators for plastics recycling. *AIChE J.* **2003**, *49*, 3138–3149. [CrossRef]
- 10. Zhang, S.; Forssberg, E. Intelligent liberation and classification of electronic scrap. *Powder Technol.* 1999, 105, 295–301. [CrossRef]

- 11. Burat, F.; Özer, M. Physical separation route for printed circuit boards. Physicochem. Probl. Miner. Process. 2018, 54. [CrossRef]
- 12. He, J.F.; Duan, C.L.; He, Y.Q.; Zhang, H.J. Recovery of valuable metal concentrate from waste printed circuit boards by a physical beneficiation technology. *Int. J. Environ. Sci. Technol.* **2015**, *12*, 2603–2612. [CrossRef]
- 13. Vermeşan, H.; Tiuc, A.E.; Purcar, M. Advanced Recovery Techniques for Waste Materials from IT and Telecommunication Equipment Printed Circuit Boards. *Sustainability* **2020**, *12*, 74. [CrossRef]
- Hazra, A.; Das, S.; Ganguly, A.; Das, P.; Chatterjee, P.K.; Murmu, N.C.; Banerjee, P. Plasma Arc Technology: A Potential Solution Toward Waste to Energy Conversion and of GHGs Mitigation. In *Waste Valorisation and Recycling*; Springer: Singapore, 2019; pp. 203–217.
- Yazici, E.Y.; Deveci, H.; Yazici, R.; Greenway, R.; Akcil, A. Recovery of copper from scrap TV boards by eddy current separation. In *Proceedings of the 15th Conference on Environment and Mineral Processing (EaMP)*; Part, I.; VSB Tech. University of Ostrava: Ostrava, Czech Republic, 2011; pp. 27–33.
- Settimo, F.; Bevilacqua, P.; Rem, P. Eddy current separation of fine non-ferrous particles from bulk streams. *Phys. Sep. Sci. Eng.* 2004, 13, 15–23. [CrossRef]
- 17. Schlett, Z.; Claici, F.; Mihalca, I.; Lungu, M. A new static separator for metallic particles from metal–plastic mixtures, using eddy currents. *Miner. Eng.* 2002, *15*, 111–113. [CrossRef]
- 18. Ghosh, B.; Ghosh, M.K.; Parhi, P.; Mukherjee, P.S.; Mishra, B.K. Waste printed circuit boards recycling: An extensive assessment of current status. *J. Clean. Prod.* 2015, *94*, 5–19. [CrossRef]
- 19. Lu, Y.; Xu, Z. Precious metals recovery from waste printed circuit boards: A review for current status and perspective. *Resour. Conserv. Recycl.* **2016**, *113*, 28–39. [CrossRef]
- 20. Hadi, P.; Gao, P.; Barford, J.P.; McKay, G. Novel application of the nonmetallic fraction of the recycled printed circuit boards as a toxic heavy metal adsorbent. *J. Hazard. Mater.* **2013**, 252, 166–170. [CrossRef] [PubMed]
- 21. Huang, K.; Guo, J.; Xu, Z. Recycling of waste printed circuit boards: A review of current technologies and treatment status in China. *J. Hazard. Mater.* **2009**, *164*, 399–408. [CrossRef]
- He, Y.; Xu, Z. Recycling gold and copper from waste printed circuit boards using chlorination process. *Rsc Adv.* 2015, 5, 8957–8964. [CrossRef]
- 23. Li, L.; Liu, G.; Pan, D.; Wang, W.; Wu, Y.; Zuo, T. Overview of the recycling technology for copper-containing cables. *Resour. Conserv. Recycl.* **2017**, *126*, 132–140. [CrossRef]
- 24. Iuga, A.; Samuila, A.; Morar, R.; Bilici, M.; Dascalescu, L. Tribocharging Techniques for the Electrostatic Separation of Granular Plastics from Waste Electric and Electronic Equipment. *J. Part. Sci. Technol.* **2015**, *34*, 45–54. [CrossRef]
- Li, J.; Wu, G.; Xu, Z. Tribo-charging properties of waste plastic granules in process of tribo-electrostatic separation. *Waste Manag.* 2015, 35, 36–41. [CrossRef] [PubMed]
- Miloudi, M.; Dascalescu, L.; Li, J.; Medles, K.; Tilmatine, A. Improved overall performances of a tribo-aero-electrostatic separator for granular plastics from waste electric and electronic equipment. *IEEE Trans. Ind. Appl.* 2015, 51, 4159–4165. [CrossRef]
- Iuga, A.; Samuila, A.; Neamtu, V.; Morar, R.; Beleca, R.; Das, S.; Dascalescu, L. Removal of metallic particles from acrylonitrile butadiene styrene wastes using electrostatic separation methods. *IEEE Trans. Ind. Appl.* 2010, 47, 322–330. [CrossRef]
- 28. Wu, G.; Li, J.; Xu, Z. Triboelectrostatic separation for granular plastic waste recycling: A review. *Waste Manag.* 2013, *33*, 585–597. [CrossRef]
- He, J.F.; He, Y.Q.; Ge, W.S.; Duan, C.L.; Wu, X.B. Research on the Recycling of Valuable Metals from Waste Printed Circuit Boards by Eddy Current Separation. In *Advanced Materials Research*; Trans Tech Publications Ltd.: Bäch, Switzerland, 2010; Volume 113, pp. 367–371.
- 30. Eswaraiah, C.; Kavitha, T.; Vidyasagar, S.; Narayanan, S.S. Classification of metals and plastics from printed circuit boards (PCB) using air classifier. *Chem. Eng. Process. Process. Intensif.* **2008**, *47*, 565–576. [CrossRef]
- 31. Shapiro, M.; Galperin, V. Air classification of solid particles: A review. *Chem. Eng. Process. Process. Intensif.* **2005**, 44, 279–285. [CrossRef]
- 32. Zheng, Y.; Shen, Z.; Cai, C.; Ma, S.; Xing, Y. The reuse of nonmetals recycled from waste printed circuit boards as reinforcing fillers in the polypropylene composites. *J. Hazard. Mater.* **2009**, *163*, 600–606. [CrossRef]
- Kaya, M. Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. *Waste Manag.* 2016, 57, 64–90. [CrossRef]
- 34. Veit, H.M.; Juchneski, N.C.D.F.; Scherer, J. Use of gravity separation in metals concentration from printed circuit board scraps. *Rem Rev. Esc. De Minas* 2014, 67, 73–79. [CrossRef]
- 35. Cui, J.; Forssberg, E. Mechanical recycling of waste electric and electronic equipment: A review. J. Hazard. Mater. 2003, 99, 243–263. [CrossRef]
- 36. Tsakalakis, K.G.; Benardos, A.; Sammas, I. Metals Recovery from Pulverized Printed Circuit Boards (PCBs) by Flotation. In Proceedings of the 3rd Symposium on Urban Mining and Circular Economy-SUM Bergamo, Bergamo, Italy, 21–23 May 2016.
- 37. Cui, H.; Anderson, C.G. Literature review of hydrometallurgical recycling of printed circuit boards (PCBs). *J. Adv. Chem. Eng.* **2016**, *6*, 1–11.
- 38. Ogunniyi, I.O.; Vermaak, M.K.G. Froth flotation for beneficiation of printed circuit boards comminution fines: An overview. *Miner. Process. Extr. Metall. Rev.* **2009**, *30*, 101–121. [CrossRef]

- 39. Vidyadhar, A.; Das, A. Kinetics and efficacy of froth flotation for the recovery of metal values from pulverized printed circuit boards. In Proceedings of the XXVI International Mineral Processing Congress (IMPC), New Delhi, India, 24–28 September 2012.
- 40. He, J.; Duan, C. Recovery of metallic concentrations from waste printed circuit boards via reverse floatation. *Waste Manag.* 2017, 60, 618–628. [CrossRef] [PubMed]