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DOI
10.23919/EGG62010.2024.10631232

Publication date
2024

Document Version
Final published version

Citation (APA)
van Beek, M. C., Wu, Y., & Rem, P. (2024). *Mechanically Sorting Electronic Components from Discarded Printed Circuit Boards to Enable Recycling of Critical Raw Materials*. Paper presented at Electronics Goes Green 2024+, Berlin, Germany. https://doi.org/10.23919/EGG62010.2024.10631232

Mechanically sorting electronic components from discarded printed circuit boards to enable recycling of critical raw materials

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***Abstract*—Critical raw materials (CRMs) are one of the enablers of a sustainable future due to their importance in green technologies. Yet, their own circularity and end-of-life recycling rates have been lacking as their concentrations are too low in waste products to be efficiently recycled. This is not the case, however, for discarded printed circuit boards where different types of electronics components (ECs) use specific CRMs in high concentrations. Furthermore, due to worldwide manufacturing standards these ECs are consistent between different printed circuit boards (PCBs) in their physical characteristics such as size, shape and material composition. Yet at the moment no sorting methods exist that can separate ECs from modern PCBs. Therefore, we aim to evaluate multiple simple yet effective mechanical separation methods to sort said ECs with CRM recovery in mind. First of all, ECs from flat-panel displays were sieved into a small (<4 mm), medium (4 - 10 mm) and large fraction (>10 mm). This was followed by a roll sorter to separate thinner components, like IC chips, from similarly sized thicker ECs. In order to separate the components based on ferromagnetic composition an innovative overbelt ferromagnetic separator was developed where the magnetic field strength continuously decreased over the length of the belt. Lastly, the different types of ECs were analysed by laser-induced breakdown spectroscopy to identify the presence of any CRMs. Our study shows that by combining these three different sorting technologies it is possible to sort the ECs in a way that the majority of CRM containing components are concentrated in only 21.09 wt% of the total weight. This in turn results in significantly higher CRM concentrations, thus removing a major limitation to their recovery and improving CRM circularity for a more sustainable future.**

***Index Terms*—Critical raw materials, Printed circuits boards, Electronics, Electronic components, Recycling, Roll sorting, Ferromagnetic separation, LIBS**

I. INTRODUCTION

Critical raw materials (CRMs) have recently become a prominent topic in Europe due to their importance in advanced and sustainable technologies while suffering from scarcity caused by Covid [1], difficulties in global logistics and other geopolitical developments [2], [3]. A material becomes a CRM if it satisfies two criteria: 1) significant importance to the European economy (Economic Importance) and 2) being potentially restricted in supply (Supply Risk) [4]. This second factor is often caused by production of the CRM being limited to a few countries, such as China for the rare earth elements and Congo for cobalt. Therefore, CRM recovery through recycling from secondary sources has been suggested as a major opportunity to reduce supply risk and foreign dependency [5].

One potential source of CRMs is discarded electronics, also known as E-waste or WEEE (Wasted Electrical and Electronical Equipment), due to their continuously increasing consumption in Europe, from only 7.65 Mton in 2011 to 13.51 Mton in 2021 [6], and use of CRMs as high-tech materials in their printed circuit boards (PCBs) [7]. Yet at the moment, CRMs are not extracted from PCBs as the concentrations are too low to be economically viable [8]. However, the CRMs are not evenly distributed over the whole PCB, but are concentrated in only a few types of electronic components (ECs) [9]–[11]. Examples are tantalum in tantalum capacitors and titanium in inductors. Furthermore, the same type of EC between different PCBs is remarkably consistent in regards to size, shape, and composition, due to worldwide manufacturing standards [12]. Therefore, by sorting the ECs from discarded PCBs significantly higher CRM concentrations, and thus metallurgical recoveries, can be achieved.

A popular method in waste separation is sensor-based sorting, often in the form of vision combined with a neural network [8]. However, as a result of too much intratype variation and intertype similarity this method's effectiveness can be quite limited on its own [13]–[15]. Thus, the addition of simple and cheap mechanical sorting methods can be quite beneficial and potentially even enough to achieve acceptable sorting results.

In 2012 the topic of mechanical sorting was already explored to great success by Lee et al. for through hole components (THCs) from video recorders [16] and in 2013 by Oki to recover Tantalum capacitors [17]. However, over time a shift has occurred in the ECs used on PCBs from mostly THCs to surface mounted devices (SMDs). Furthermore, a strong reduction in the number of tantalum capacitors has taken place [18].

This research was carried out under project number N21006 in the framework of the Partnership Program of the Materials innovation institute M2i (www.m2i.nl) and the Dutch Research Council (www.nwo.nl).

ISBN 978-3-00-079330-1 — Presented at the Electronic Goes Green 2024+ Conference

On the other hand the number of processing chips has grown which were previously difficult to separate from other ECs [16]. Therefore, we present two novel sorting technologies, the roll sorter and angled ferromagnetic separator, and apply them to sort the ECs from flat-panel displays.

II. Methods

A total of 23 PCBs from discarded flat-panel displays were collected and manually depopulated (removed) for their ECs using a heat gun, screwdriver and pliers. To identify the different ECs, a modified version of the Peacoc Project's categories were created (see appendix) and applied to determine the distribution after each separation step [19]. Furthermore, the recovery (R%) and grade (G%) of a component were calculated as:

$$Recovery\ of\ EC\ X\ in\ sorted\ category\ Y\ (R\%) = mass\ of\ EC\ X\ in\ sorted\ category\ Y/total\ mass\ of\ EC\ X\ in\ complete\ sample \tag{1}$$

and

$$Grade\ of\ EC\ X\ in\ sorted\ category\ Y\ (G\%) = mass\ of\ EC\ X\ in\ sorted\ category\ Y/total\ mass\ of\ all\ components\ in\ sorted\ category\ Y \tag{2}$$

A. Sieving

The first separation method employed was sieving of the components to determine their sizes (small, medium and large). However, only a rough separation was aimed for as sieving separates particles based on their second smallest dimension and loses accuracy when particles are elongated [20]. As it was not initially clear what the two optimal sieves would be, a total of 10 round-hole sieve sizes were evaluated (1.0, 2.0, 3.0, 4.0, 6.0, 8.0, 10.0, 12.5, 16.0 and 28.0 mm). The (still) mixed components were fed to the sieves which were shaken by hand until no ECs fell through the sieves anymore. Each batch was then separately collected, weighed and stored for the subsequent separation steps.

B. Roll sorting

Similarly to sieving, the roll sorter (RS) is a size separation technology, but for the smallest dimension (thickness). The roll sorter encompasses two angled counter rotating cylinders with a gap between them at a downwards slope (see Fig. (2)). Through decreasing the roller diameter or placing them divergent this gap increases over the length of the machine. Each component will then be sorted by falling in between the rollers when it reaches a gap that is equal in size to its thickness [21]. A consistent result is achieved as the ECs will align themselves between the rollers in their most stable position (longest dimension parallel to the rollers).

In order to improve on our previous research, a new roll sorter was developed which can increase the gap size in discrete steps of 1.0 mm up to 20.0 mm in total by decreasing the diameter of the rollers [19]. The vertical angle of the rollers was set at 7.5°and their speed to 120 RPM. For each batch of the sieving step a separate run on the roll sorter was performed and the components were collected in trays placed 13.0 cm under the rollers.

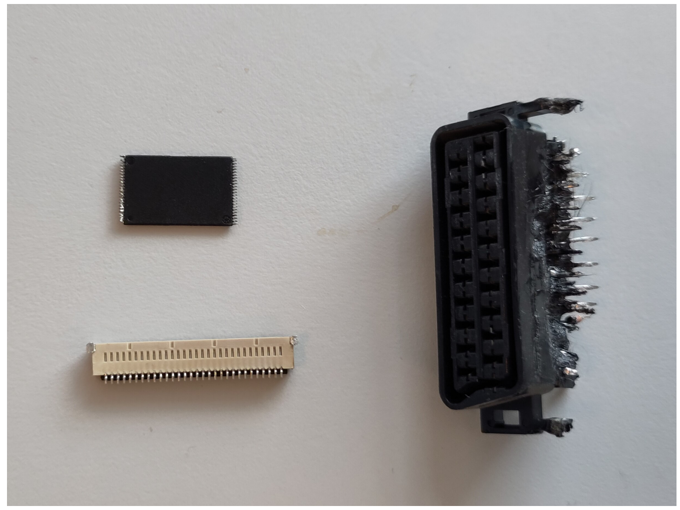

Fig. 1. Three examples of elongated electronic components (chip, plastic connector and SCART port).

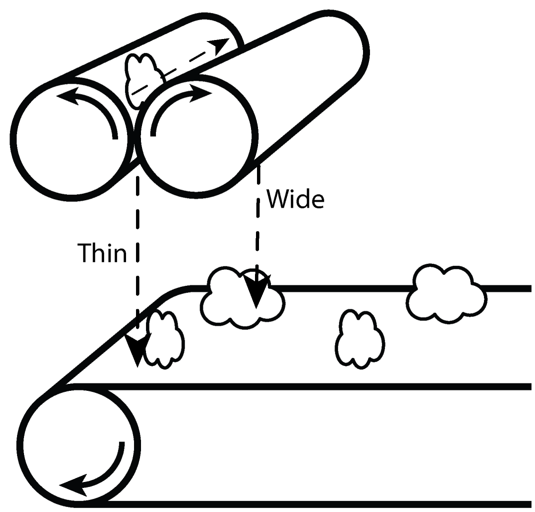

Fig. 2. A schematic overview of a divergent roll sorter.

C. Ferromagnetic sorting

The last separation method used in this research was a new type of overbelt ferromagnetic separator (FMS). Similarly to a normal overbelt magnet, non-ferromagnetic ECs are immediately separated from the ferromagnetic ECs as they are not attracted to the magnet. However, a separation within

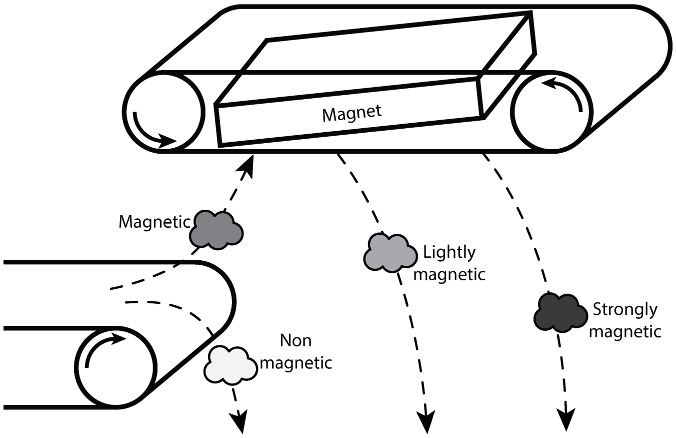

Fig. 3. A schematic overview of the new angled ferromagnetic separator.

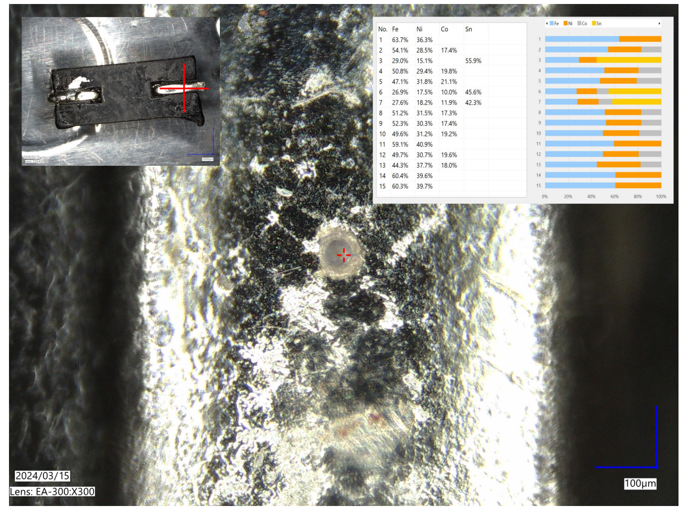

Fig. 4. The result of a LIBS analysis of the connector from a *Quartz resonator*.

the ferromagnetic ECs can also be achieved based on their (ferromagnetic) composition. Normally shape and size would also play an important role, but due to the presorting with the sieves and roll sorter this factor can be eliminated. By placing a flat field permanent magnet (0.6 Tesla) at an angle (8°), the field strength on the overbelt continually decreases over its length (see Fig. (3)). Therefore, ferromagnetic ECs will drop from the belt at different spots depending on their composition. For instance, an *Aluminium electrolytic capacitor* is less susceptible to the field compared to a *Quartz resonator* and will thus drop first from the belt.

Once again, each batch of the previous machines was run separately and fed to the FMS using a vibratory feeder at 20 Hz. The vertical distance from the feeder to the belt was 1.4 cm for ECs thinner than 8.0 mm and 2.8 cm for the thicker ECs. The belt was set to a speed of 21.83 cm/s. Lastly, the ECs were collected every 10 cm on a plank, with a piece of cloth to reduce bouncing, 34.5 cm below the belt.

D. LIBS analysis

In order to determine the material composition of the ECs and identify sources of CRMs, a Keyence Microscope (VHX-7000) LIBS (EA-300) combination was used. The LIBS fires a high intensity laser (355 nm) at the particle ablating its surface and creating a plasma which is then spectroscopically analysed for its elemental composition [22]. From each EC category between two and six samples were analysed on the outside and inside after cutting them open. Furthermore, by using the Keyence drilling function (3 bursts of 5 shots each) it was possible to determine if a material was a coating or a bulk material.

III. Results and Discussion

After depopulating all 23 boards a total of 3000.68 grams of ECs were collected. In most cases the components were removed intact with limited damage, some exceptions due to overheating or mechanical stress can be found in the appendix. Through the LIBS analysis it was possible to identify a total of 10 CRMs distributed over 8 component types (out of a total of 18 types), which will be the main targets during mechanical sorting (see Table I). Moreover, the separation of *Central Processing Units (CPUs)* and *IC chips and transistors* will also be taken into account due to their usage of gold.

A. Sieving

By choosing a sieve size of 4.0 mm it was possible to effectively concentrate all the *MLCCs + Ta capacitors* (grade increase from 3.1 G% to 65.2 G%) with only a small amount of other components such as *IC chips and transistors* (11.0 G%) and *Others* (23.2 G%). A similar result was achieved by choosing the second boundary at 10.0 mm as this is where bigger components, such as *Heatsinks*, started appearing. Furthermore, this also concentrated some components in the middle fraction (4.0 - 10.0 mm). For instance, a near perfect recovery was achieved for *Blue capacitors* (95.4 R%), *Resistors* (93.0 R%) and *Quartz resonators* (100.0 R%).

TABLE I
An overview of which CRMs were found in the different component types as a coating (C) or bulk material (B).

Component type	Ba	Ti	Nd	Ta	Mg	Mn	Bi	Co	B	Li
Central processing units (CPUs)	B									
MLCCs + Ta capacitors	B	B	B	B	C	B				
Golden connectors							C			
Inductors and transformers		C								
Blue capacitors	B	B				B				
Resistors	B	B			B					
Quartz resonators								B	B	B
Heatsinks					B					

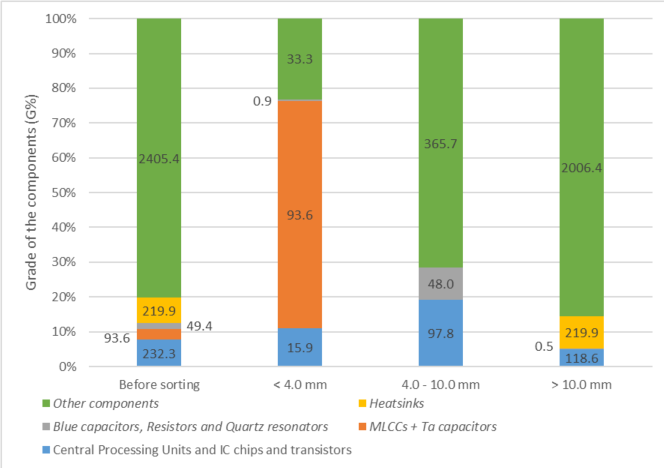

Fig. 5. A comparison of the effectiveness at improving the grade (G%) due to sieving (4.0 and 10.0 mm) the components with the datalabels indicating the weight in grams.

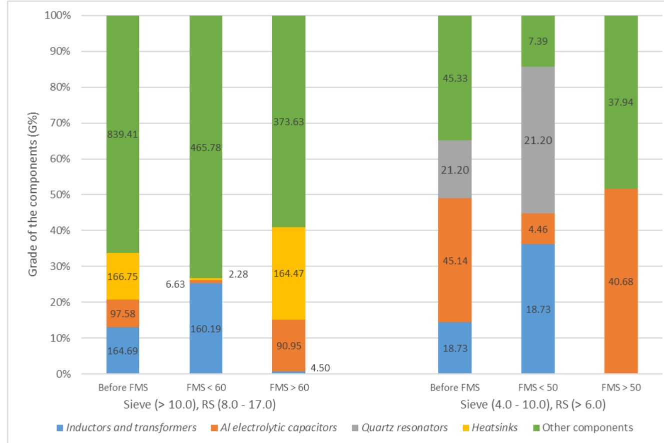

Fig. 6. Two examples (Sieve 4.0 - 10.0, RS 8.0 - 17.0 and Sieve >10.0, RS >6.0) showing the grade improvement (G%) due the FMS with the datalabels indicating the weight in grams.

B. Roll sorting

As Table (II) shows, the roll sorter is very effective at separating *Central Processing Units* and *IC chips and transistors* from other components since both categories are relatively thin for their size. For example, a CPU of 35 by 35 mm in size is only 3.17 mm thick. However, its effectiveness is more limited for a component like *Heatsinks* or *Quartz resonators* and completely ineffective for *Inductors and transformers*. Therefore, the last sorting technology (ferromagnetic separation) is also necessary to achieve optimal results.

C. Ferromagnetic separation

As is expected from an overbelt magnetic separator, the FMS is quite effective in separating ferromagnetic and non-magnetic from each other. For instance, on the left of Fig. (6) it can be seen that the nonmagnetic *Heatsinks*, often made from aluminium, are separated from the *Inductors and transformers* which have an iron core.

TABLE II
TWO EXAMPLES OF THE COMBINED EFFECT OF SIEVING AND ROLL SORTING ON SEPARATING THE ELECTRONIC COMPONENTS. WEIGHTS PRESENTED IN GRAMS.

Sieve size (mm)	4.0 - 10.0		>10.0		
Roll sorter size (mm)	<4.0	>4.0	<8.0	8.0 - 17.0	>17.0
Central Processing Units (CPUs)	0.87	0	33.48	0	0
IC chips and transistors	89.27	7.69	85.14	0	0
Inductors and transformers	22.12	57.09	33.79	164.69	49.00
Quartz resonators	4.12	21.20	0	0	0
Heatsinks	0	0	53.13	166.75	0
Other components	76.07	233.12	107.28	936.99	715.16

However, on the right it can also be seen that the *Inductors and transformers* and *Quartz resonators* can be parted from the *Al electrolytic capacitors*. Even though all three components are partly iron, and thus attracted to the magnet, the later drops earlier and can be separated as its ferromagnetic fraction is less than the other two. Therefore, showing that this new type of FMS is also able to separate components based on their relative ferromagnetic composition and thus create a non-binary but continuous degree of separation.

D. Overall system

As already alluded to before, the optimal results are achieved by implementing all three sorting technologies as can be seen in Fig. (7). Sieving (4.0 and 10.0 mm) was implemented as the first separation step, followed by the roll sorter where the middle size fraction is split into <4.0, 4.0 - 6.0 and >6.0 mm and the large ECs in <8.0, 8.0 - 17.0 and >17.0 mm. Lastly, the FMS split the ECs in ferromagnetic and nonmagnetic fractions.

In total 6 product categories were created of which an overview can be found in Table (III). Here it can be seen that for P1, P2 and P3 the majority of the weight is encompassed by the CRM containing components, 76.2, 71.4 and 66.5 G% respectively, while only capturing 21.09 wt% of the total EC weight of the sample. Additionally, for some EC types close to perfect recovery was achieved, such as 96.5 R% for *IC chips and transistors* or 100 R% for *Quartz resonators*.

These promising results also hold for the individual CRMs, as the majority can be found in the same 3 products (see Fig. (7)). Only three types of CRMs were lost in the other products: magnesium (*Heatsinks* in P4), titanium (*Inductors and transformers* in P5) and bismuth (*Golden connectors* in P4 and P6).

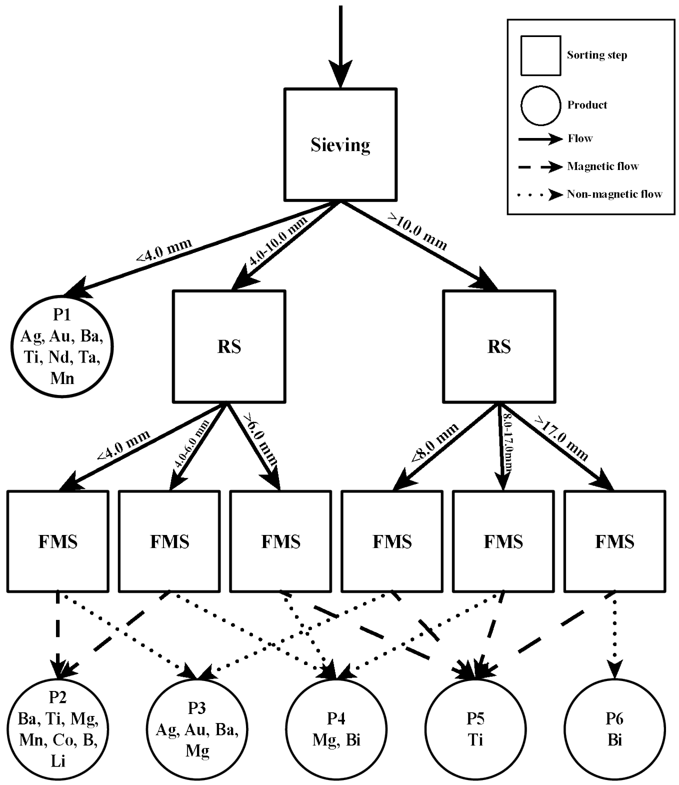

Fig. 7. A flowchart of the different sorting technologies and products to separate the electronic components.

TABLE III
THE DISTRIBUTION OF THE CRM CONTAINING COMPONENTS OVER THE DIFFERENT PRODUCTS IN GRAMS.

Component type	P1	P2	P3	P4	P5	P6
Central processing units (CPU)	-	-	34.35	-	-	-
IC chips and transistors	15.86	12.52	162.69	6.89	-	-
MLCCs + Ta capacitors	93.64	-	-	-	-	-
Golden connectors	-	-	-	30.25	14.82	29.75
Inductors and transformers	-	40.16	0.69	5.06	280.78	-
Blue capacitors	-	9.87	0.82	-	0.51	-
Resistors	0.90	5.10	1.91	5.00	-	-
Quartz resonators	-	25.32	-	-	-	-
Heatsinks	-	-	53.13	164.47	2.28	-
Other components	33.27	19.65	122.87	646.87	960.59	220.61

IV. CONCLUSIONS

Throughout this article we have seen that it is indeed possible to find and concentrate the critical raw materials in electronic components from discarded printed circuit boards using three simple mechanical separation methods: sieving, roll sorting and ferromagnetic separation.

Of these three separation technologies, size sieving (<4.0, 4.0 - 10.0 and >10.0 mm), was especially effective at sorting the small CRM rich *MLCCs + Ta capacitors*, while roll sorting (medium size: <4.0, 4.0 - 6.0, >6.0 mm and large size: <8.0, 8.0 - 17.0, >17.0 mm) separates thinner components, such as *IC chips and transistors*, from similarly sized ECs. On the other hand, the new type of ferromagnetic separator presents two methods of separation: traditional separation between ferromagnetic and nonmagnetic components; and differentiation between components with different ferromagnetic compositions.

By combining all three methodologies, a total of 6 different product categories can be distinguished. When combining three of these the majority of the CRMs and precious metals will be captured, while reducing the total mass to only 21.09 wt% of the original. This will in turn significantly increase the concentration of said materials, making it both cheaper and less energy intensive to metallurgically recover them.

However, additional separation technologies should still be explored as some ECs were still mixed together. For the nonmagnetic products two promising techniques are magnetic density sorting (MDS), previously successfully explored by the author [19], and eddy-current separation. If combined with improved shape separation and parameter optimisation, the FMS could also provide an even higher degree of separation for the magnetic products. Lastly, sensor-based sorting can provide additional flexibility for all types of ECs. Therefore, most of these methods will be explored in the coming years as a part of the Circular Circuits project [23] and ensure the circularity of the next generation of electronics.

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