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Chemical Characterization of an ARDUINO® Board and Its Surface Mount Devices for the Evaluation of Their Intrinsic Economic Value

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Abstract: The remarkable technological development observed in recent decades has led to an exponential increase in the production of electrical and electronic devices. Regardless of their field of application or the type of device, electronic boards are a common feature of all these devices. For this reason, electronic boards represent a constant in electrical and electronic equipment waste. Knowing their composition and intrinsic economic value is essential for identifying sustainable disposal and valorization processes. In the literature, several articles report typical compositions of electronic boards, but it is rare to find a component-by-component characterization. This procedure is important to determine the components that need to be removed to increase the recovery yields of materials or to identify components with high concentrations of hazardous substances. For this reason, in this scientific article, we propose to examine the chemical composition of all the components of the Arduino® electronic board using advanced chemical analysis techniques. Arduino is a popular electronic board mainly used to prototype electronic projects rapidly. The chemical composition of the Arduino board has yet to be entirely determined to date. The decision to use the Arduino board is due to the fact that this board is widespread globally and could represent a reference study.

Keywords: Arduino; surface mount devices; PCBs; chemical composition; intrinsic economic value; metals recovery; atomic emission spectroscopy

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1. Introduction

Technological development in recent decades has had a transformative impact on our lives, improving many aspects of our existence. Electronic devices such as tablets, smartphones, televisions, electro-domestic appliances, and numerous other devices underlie this development. Regardless of the field of application, electronic boards are a common feature of all these devices [1].

Electronic boards, also known as printed circuit boards (PCBs), are substrates, inflexible or flexible, consisting of an insulated panel of glass fibers and epoxy resin on which conductive lines are printed. These lines connect the different electronic components mounted on the board to form an electronic circuit. The electronic components assembled on the board are resistors, capacitors, transistors, microcontrollers, etc. [2]. These components, as well as the electronic board, contain several rare elements with high economic value. Some of these elements, due to their high supply risk and high economic importance, have been placed on the list of critical raw materials (CRMs) by the European Union (such as PGMs, Cobalt, Aluminum, Titanium, Copper, and Nickel) [3].

Depending on the type and application of PCBs, their composition varies. PCBs generally consist of about 28 wt.% metals, 22 wt.% plastics, and 50 wt.% ceramic and flame retardant (FR) materials [4,5].

The FR materials interfere with the chain of chemical reactions that occur during combustion, reduce the kinetics of the reaction, and decrease the amount of heat produced. FRs are often used to protect electronic components from any in-fires that short circuits or overloads might cause. The amount of flame retardancy on an electronic board depends on the type of material used and local or international fire safety regulations. Based on the type of FRs, four different types of electronic boards are classified: FR-1, FR-2, FR-3, and FR-4 PCBs. Table 1 shows the main characteristics of the above types [6].

Table 1. Materials and main characteristics of various FRs.

	FR-1	**FR-2**	**FR-3**	**FR-4**
Materials	Paper and phenol-formaldehyde resin.	Paper with a plasticized phenol formaldehyde resin.	Cotton linter/alpha cellulose paper with epoxy resin formulation.	Woven/Unwoven fiber-glass cloth with epoxy resin.
Glass Transition Temperature	130 °C	130 °C	130 °C	140–170 °C
Chemical resistance	Low	Low	Medium	High

In general, FR-4 flame-retardant electronic boards are the most popular. As can be seen from the table, it has a high glass transition temperature and chemical resistance. The chemical resistance of an electronic board flame retardant refers to the ability of the retardant to maintain its flame-retardant properties and resist chemical degradation when exposed to harsh chemicals or adverse environmental conditions. During regular operation or maintenance, electronic boards can be exposed to various chemical agents such as solvents, oils, acids, or bases. The chemical resistance of the flame retardant is important because it protects the electronic board from potential damage or malfunction caused by exposure to these chemicals [7].

Regarding the metal fraction, numerous scientific articles, reviews, and book chapters in the literature present the results of various chemical characterizations [4,5,8–13]. These papers analyze different types of electronic boards, from those in televisions to computers and smartphones. Among the most used characterization methods is Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), applied to the solution obtained by chemical digestion of the sample using acids. Table 2 shows the ranges of typical concentrations of the metals most commonly found in electronic boards.

Table 2. Base and precious metals range content in PCBs.

Base Metals Content (wt%)		**Precious Metals Content (ppm)**	
Cu	3–40	Au	250–2050
Al	0.2–14	Ag	110–4500
Sn	0.6–8.8	Pd	50–4000
Fe	1.2–8	Pt	5–30
Pb	1–4.2	Co	1–4000
Zn	0.04–6		
Ni	0–5.4		

Knowledge of the metal composition of PCBs is critical to correctly managing such materials when they come back from the market as waste printed circuit boards (WPCBs). Based on WPCB composition, these materials cannot be considered waste but should be considered a secondary source of important critical raw materials. In this regard, numerous studies are being conducted worldwide to develop increasingly economically and environmentally sustainable processes to recover the metals of most significant interest [14–19].

Generally, it is possible to identify three major categories of metallurgical processes: pyrometallurgical, hydrometallurgical, and bio-hydrometallurgical extraction processes. Of these three categories of raw material recovery processes, the hydrometallurgy route seems the most promising. Pyrometallurgy allows very high recoveries of raw materials but with a significant environmental impact (high emissions of toxic substances). At the other extreme, we find bio-hydrometallurgy, which, although it is the greenest way, still needs to be consolidated at an industrial level today due to a series of problems relating to extraction yields and the greater difficulty of management compared to the other two ways. At the center of these two extremes, we find hydrometallurgy. Hydrometallurgical processes produce high recovery yields with low environmental impacts [4,20]. Figure 1 qualitatively summarizes what has just been described.

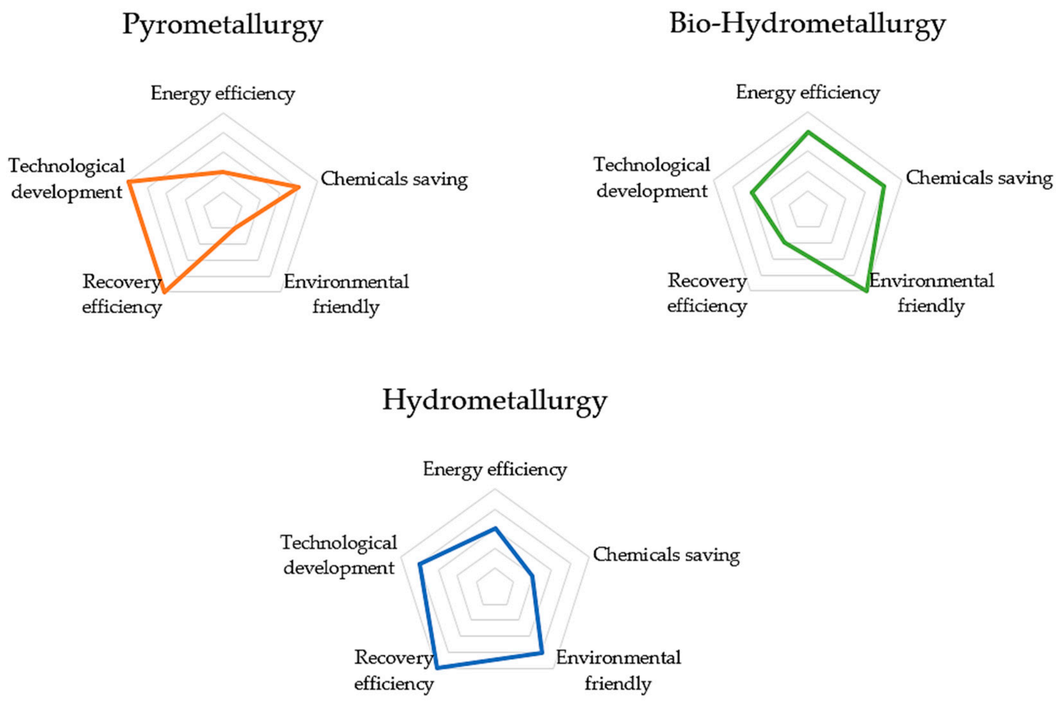


Figure 1. Qualitative comparison between the three major categories of metallurgical processes.

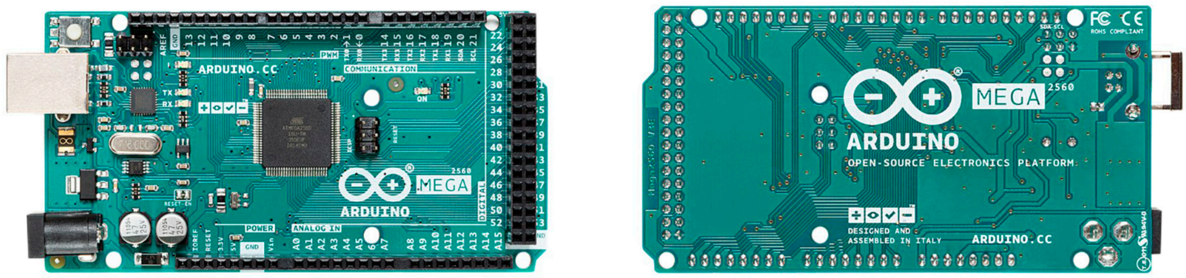
This hydrometallurgical route is very promising, with new solutions increasingly approaching the green concept of Minimum Liquid Discharge (MLD). Many countries without mineral resources are implementing strong investment policies for technological development in this sector. At the same time, increasingly stringent directives are being issued to support the proper management and subsequent treatment of this type of waste [21].

In order to maximize the recovery yields of the different metals present in WPCBs within a hydrometallurgical recovery process, it is appropriate, in some cases, to select the components to be treated. In addition, it is important to know the content of elements for each component treated in order to choose a reagent over another (optimizing the kinetics and thermodynamics of the process) [22,23]. For example, it has been seen that the presence of copper in the same leaching environment as gold results in a significant decrease in the recovery yield of the precious metal [24,25]. Based on these considerations, knowing each component's composition in detail is appropriate. As mentioned earlier, there are numerous present works in the literature that analyze the metal fraction of PCBs, while it is challenging to find works where this analysis is conducted separately for each component of the electronic board [26,27].

This paper aims to estimate the Arduino board's intrinsic economic value related to the metal fraction as it is a globally well-known electronic board. The method includes the disassembly of all the components of the board to perform an individual characterization of each component to detect all the metals. Further, metal characterization is performed on the residual board from which the components are removed. Arduino is a popular electronic board mainly used to prototype electronic projects rapidly. The chemical composition of the Arduino board has not yet been entirely determined and could help to understand in detail the chemical composition of traditional electronic components of a PCB. Furthermore, being a widespread electronic board, it could be considered as a standard reference sample for further studies.

2. Materials and Methods

The electronic board analyzed is the Arduino Mega 2560 Rev3 board. Figure 2 shows the photographic aspect of the board used [28].



(**a**) (**b**)

Figure 2. Photographic aspect front (**a**) and back (**b**) of the analyzed Arduino board.

In order to proceed with the characterization of each component, a preliminary step of disassembly of the various components was carried out using a hot air gun. The components removed from the board were weighed and subjected to chemical attack using different acid solutions. Table 3 identifies the different components and reports for each of the different methods used for metal dissolution.

Table 3. Components removed from the Arduino board and methods used for their leaching.

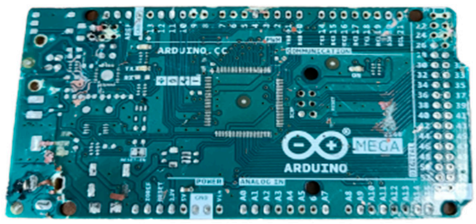
N.	Name	Image	Method
1	Board		Size reduction + AR
2	External pin		AR
3	USB-B port		AR

Table 3. *Cont.*

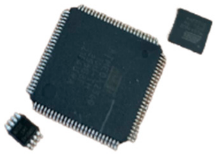
N.	Name	Image	Method
4	DC power jack		AR
5	Internal pin		AR
6	ICC [1]		Size reduction + AR
7	Capacitors		Size reduction + AR
8	Q.C. Oscillator		AR
9	Push button		AR
10	Voltage regulator		Size reduction + AR
11	M7 Diode		AR
12	Fuse		AR
13	Led		AR
14	MLCC		Size reduction, Calcination at 350 °C with KOH + DL
15	Transistor		AR

Table 3. *Cont.*

N.	Name	Image	Method
16	Plastic cover		-
17	Other [2]	-	AR

[1] ICC: integrated circuit chips, [2] Other: all unidentified residues of the disassembly process (unidentified components, welding residues, and detached parts of some components).

Aqua regia (AR) was used as the leaching solution for most of the components. This solution is a very aggressive mixture of HCl and HNO_3 in a 3:1 molar ratio. In order to effectuate the chemical attack, the material to be characterized was weighed using an analytical balance (for some of the components, a manual reduction in size has been foreseen).

The components were placed inside a flask, and 5 mL of the prepared AR was added. The flask was then placed on a heated plate to promote the dissolution of the metals in the solids (temperatures of about 80–90 °C favor the kinetics of dissolution). After this step, 20 mL of AR was added drop by drop (about 2 mL/min). During the early stages of the reaction, 5 mL of AR makeup was added to reduce the effect of nitric acid degradation. After 2 h from the first AR addition, once the reaction was finished, vacuum filtration was performed, and the leaching solution was recovered.

A different treatment was used for Multi-Layer Ceramic Capacitors (MLCCs). It is impossible to completely solubilize the metals present only by dissolution with acidic solutions. In this case, a thermal pretreatment of calcination in a muffle furnace with KOH at 350 °C was performed. After 1 h of thermal treatment, double leaching (DL) was performed with two different leaching agents: the first leaching was performed with water at a temperature of 90 °C to dissolve refractory elements, and the second step was performed with HNO_3.

ICP-OES (Agilent 5100) was used to analyze the leaching solutions obtained for each component. A qualitative analysis was first performed to identify the elements present in the analyzed sample; then, a single quantitative analysis was performed for each element identified.

Through Equation (1) (the combination of a material balance for the generic metal and the definition of the mass fraction), the composition of the metals of interest for each component was calculated.

$$\omega_{i,j} = \frac{c_{i,j} \cdot L_j}{m_j}, \quad (1)$$

where i refers to the analyzed element and j to the component. In this sense, $\omega_{i,j}$ is the mass fraction of element i for component j; $c_{i,j}$ is the concentration of metal i in the leaching solution of component j measured by ICP-OES (mg/L); L_j is the volume of the leaching solution of component j (L); and m_j is the mass of component j subjected to leaching (mg).

By knowing the weights of all components and their respective chemical composition, it was possible to determine the composition of the complete device. Once this result was obtained, it was possible to identify the electronic board's intrinsic economic value (IEV) by applying Equation (2).

$$\text{IEV} = \sum_{i=1}^{e} q_i \cdot m_i, \quad (2)$$

where q_i is the market quotation of the generic element i (EUR/kg) and m_i is the mass of the same element (kg). Market quotations are shown in Table 4 [29]. The IEV is not the board's real economic value (REV) but represents the economic value associated with the materials that compose it. IEV and REV differ in most cases. This is because the added value given by the manufacturing process and the performance that the device can offer are also considered in the REV of the device. In an end-of-life device, the REV is so close to the IEV that the latter can estimate the device's value.

Table 4. Market quotation of metals (2023).

Metal	*q* (EUR/kg)	Metal	*q* (EUR/kg)
Au	58,251.97 €	Si	9.00 €
Pd	43,196.81 €	Cu	8.29 €
Pt	29,940.00 €	Ti	7.53 €
Ag	712.51 €	Mg	2.82 €
Ga	535.43 €	Zn	2.68 €
Ba	347.28 €	Al	2.23 €
Co	27.34 €	Fe	0.23 €
Sn	23.84 €	Mn	0.004 €
Ni	21.76 €		

This type of analysis is conducted primarily as a preliminary analysis of a business plan for a hypothetical raw material recovery process. By associating the price of each raw material with the quantity on the board, it is possible to trace the intrinsic economic value of the device. This value will make it possible to identify the operating economic margin of any hydrometallurgical process.

3. Results and Discussions

The obtained solutions from the chemical attacks were analyzed by ICP-OES to determine the concentration of metals present. Before the quantitative analysis, a qualitative screening analysis was carried out for the solution of each component in order to identify the possible elements present. The results of the qualitative analysis are shown in Table 5.

Table 5. Results of qualitative analysis.

	Ag	Al	Au	Ba	Co	Cu	Fe	Ga	Mg	Mn	Ni	Pd	Pt	Si	Sn	Ti	Zn
Board	x		x	x		x	x		x	x	x	x		x	x	x	x
External pin	x		x			x					x	x			x		x
USB-B port	x		x			x					x	x			x		x
DC power jack	x		x			x	x			x	x	x	x		x		x
Internal pin	x		x			x					x	x			x		x
ICC	x		x		x	x	x				x	x			x		x
Capacitors	x	x	x			x	x					x	x		x		x
Q.C. Oscillator	x		x		x	x	x			x	x	x			x		x
Push button	x	x	x			x	x			x	x	x			x		x
V. Regulator	x		x		x	x	x					x	x		x		x
M7 Diode	x		x			x						x			x		x
Fuse	x	x	x			x					x	x			x		x
Led	x	x	x			x	x	x			x	x			x		x
MLCC	x			x		x	x			x	x	x		x	x	x	x
Transistor	x					x	x			x	x				x		x
Plastic cover																	
Other	x			x		x	x			x	x	x			x	x	x

The qualitative analysis also provides an estimation of the possible concentration of metals. Given the many elements identified through qualitative analysis, the main elements were selected based on the possible concentration linked with economic aspects.

Quantitative analysis was performed for these elements. The selected metals are those commonly present in similar PCBs [4,5,8–13] and also those whose content is low but have a high economic value. The results of the quantitative analysis are shown in Table 6.

Table 6. Results of quantitative analysis.

	Weight (g)	Plastic (g)	Base Metals (wt%)							Precious Metals (ppm)		
			Cu	Sn	Ni	Al	Zn	Fe	Ti	Ag	Au	Pd
Board	20.251	n.a.	15.09	3.36	-	-	0.36	-	-	350	2	15
External pin	7.929	5.505	56.95	9.56	1.00	-	25.84	-	-	642	107	45
USB-B port	3.406	1.531	63.11	4.82	0.07	-	25.81	-	-	403	5	50
DC power jack	1.329	0.685	48.57	7.03	0.24	-	25.53	19.07	-	811	-	45
Internal pin	0.800	0.190	58.40	12.41	1.02	-	28.99	-	-	975	63	59
ICC	0.629	-	28.75	3.19	-	-	0.17	1.67	-	639	191	34
Capacitors	0.541	-	0.41	0.27	-	37.76	0.01	59.50	-	59	-	-
Q. C. Oscillator	0.503	-	9.26	0.05	0.01	-	5.36	14.21	-	905	-	2
Push button	0.197	-	13.85	0.87	-	0.05	7.12	0.60	-	403	-	18
V. Regulator	0.129	-	42.80	2.96	-	-	0.29	0.02	-	3754	-	58
M7 Diode	0.065	-	33.95	4.26	-	-	0.21	-	-	1374	-	47
Fuse	0.028	-	38.41	9.38	0.67	0.49	0.24	-	-	2801	727	53
Led	0.003	-	24.47	8.08	4.97	2.11	0.34	0.19	-	2097	1774	161
CMC	0.164	-	9.63	6.07	-	-	0.40	-	15.72	13,335	104	162
Transistor	0.093	-	3.46	5.46	-	-	0.04	-	-	2032	581	-
Plastic cover	15.230	15.230	-	-	-	-	-	-	-	-	-	-
Other	0.115	-	3.42	8.31	-	-	0.05	-	0.48	1813	52	300

By considering the weight of each component and its metal fraction composition, it is possible to calculate the composition of the metal fraction of the Arduino Mega 2560 Rev3 board. Figure 3 shows the graph of the composition of Arduino's metal fraction.

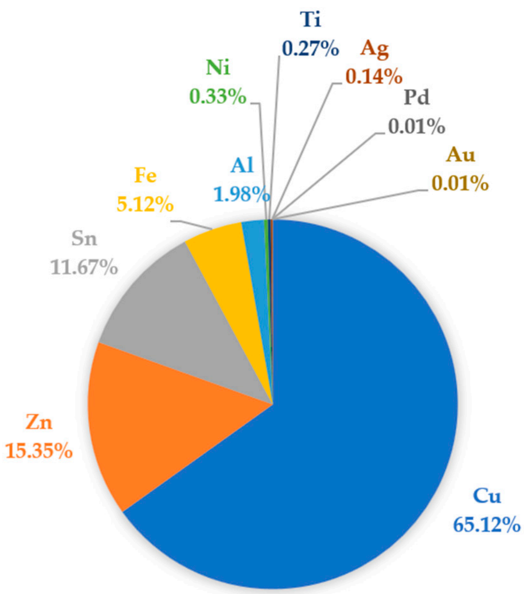


Figure 3. Metal fraction composition of Arduino Mega 2560 Rev3 board.

The determined composition considers the metals selected based on the criteria described above. However, it represents a good approximation of the metal fraction since the metals not considered in the calculation were in relatively low quantities.

The most present metal is copper (∼65%), followed by zinc (∼15%), tin (∼12%), and iron (∼5%). Aluminum, nickel, and titanium are present in relatively low percentages:

1.98%, 0.33%, and 0.27%, respectively. Regarding the precious metals, the most present is silver (0.14%), followed by palladium (0.01%) and gold (<0.01%).

Based on the detected metal fraction of the Arduino Mega 2560 Rev3 and the percentage of plastic, the chemical composition of the whole electronic board was calculated. The results of this analysis are shown in Figure 4.

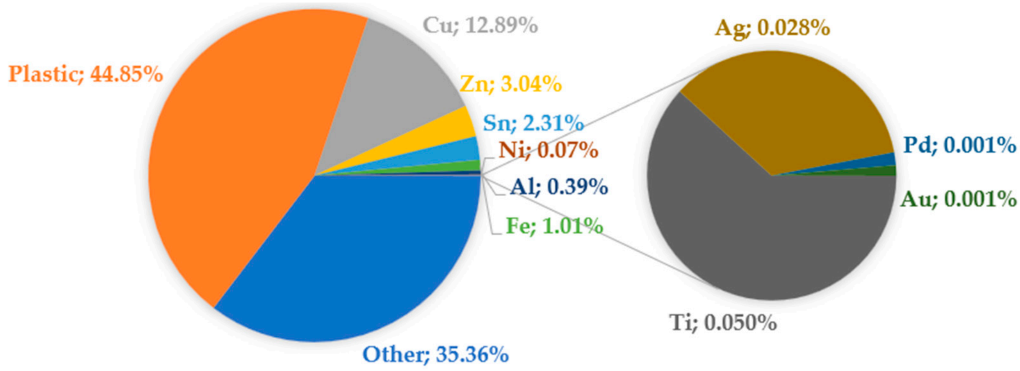


Figure 4. Overall composition of Arduino Mega 2560 Rev3 board.

In addition to the plastic and metal fraction, a fraction composed of different materials is not identified in detail (Other). This fraction includes fiberglass, epoxy resin, ceramic materials, brominated flame-retardant compounds of the board component, the metals not quantified, and the metal-bonded elements of the metal fraction (i.e., Oxygen). Indeed, by analyzing the leaching solutions by ICP-OES, it is possible to determine the concentration of the metal as an element but the chemical form cannot be defined. Some elements might be present not in their metallic form but as oxides or salts.

The concentrations obtained are consistent with those already found in the literature for analyzed samples similar to the one treated for this work. In Table 2, it is possible to see how the metals fall within the same ranges.

Given the chemical composition, an estimation of the IEV of the material can be determined. The estimate of this quantity is close to the real value of IEV that would be obtained if all the materials present in the device were considered. This result is because the estimate was made by selecting the materials that most affect this quantity (both in terms of quantity and economic value) and neglecting all those that have a very low significance instead. The results of this analysis are shown in Figure 5.

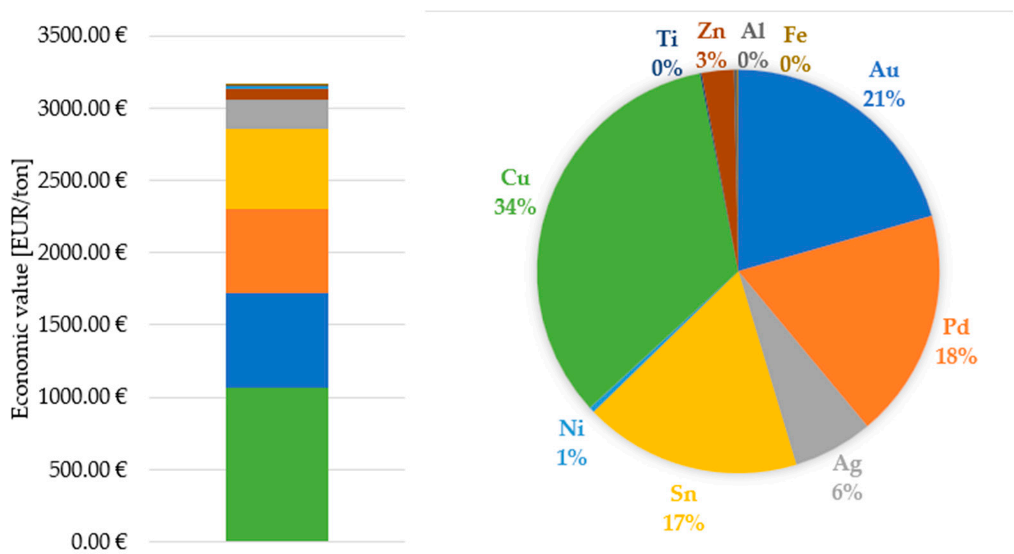


Figure 5. Estimated IEV of Arduino Mega 2560 Rev3 board.

The above figure shows that the estimated IEV of the Arduino Mega 2560 Rev3 is about 3165 €/ton, as well as the influence, expressed as a percentage, of the different metals on the total value. For example, copper accounts for about 34% of the IEV, a hydro-metallurgical process that recovers only this metal from this material will have a maximum operating economic margin of about 1.076 € per ton of material. Assuming that this process has a capacity of 1500 t/y and an overall recovery yield of 90%, it will have about 1.5 M€ of annual revenue from which Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) have to be subtracted for profit determination as well as for other economic performance indicators of the process such as the earnings before interests, taxes, depreciation, and amortization (EBITDA); the payback period (PBP); and the internal rate of return (IRR).

Another essential element is gold, which, although present in low concentrations due to its high economic value, accounts for around 21% of the IEV; it is followed by palladium and tin, contributing 18% and 17%, respectively. This type of analysis allows the identification of metals of most significant interest when a new recovery process is to be developed. From the obtained results, it is outright that a process aimed at recovering exclusively gold would leave 79% of the IEV in the solid residue. Developing a process that allows the selective recovery of copper, gold, palladium, tin, and silver is undoubtedly the most profitable route.

Assuming a process that recovers copper, gold, tin, palladium, and silver with recovery yields of 90% and a production capacity of about 1500 t/y, this process will have a maximum operating margin of about 2700 €/ton with an annual revenue of about 4.1 M€ from which CAPEX and OPEX have to be subtracted for profit determination.

4. Conclusions

A literature review showed that many studies on the chemical characterization of PCBs are carried out directly on the ground board without providing information on the composition of the specific components. This study clearly highlighted the components with the highest content of precious and base metals. In more detail, the chemical composition of all the different components on the Arduino board was determined. This information can be transferred globally to all other PCBs from various applications within a specific range of variability. By disassembling the different components, it was possible to carry out chemical attacks for each of them so that all the metals present could be solubilized.

By analyzing the concentrations in the leaching solutions, the composition of each component and the composition of the components and the board were used to estimate the composition of the whole Arduino board. The qualitative analysis determined the elements present with an approximate indication of their composition. Based on these results, a quantitative analysis was conducted on the metals most present or most influential from an economic point of view.

The gold content is mainly related to the pins and ICCs, while silver is detected in the MLCCs. Palladium is present in small amounts in all devices. Among the base metals, copper, tin, and zinc are found in all components, while iron and aluminum are found in high content in the capacitors.

In general, it was found that the overall board has the following mass fractions for base metals: 12.9% copper, 3.0% zinc, 2.3% tin, 1.0% iron, 0.4% aluminum, 0.1% nickel, and about 0.1% titanium. The concentrations of precious metals were determined: 285 ppm silver, 13 ppm palladium, and 11 ppm gold. The obtained results are comparable with those found in the literature for different electronic boards but with the analysis performed on the overall board grind.

Based on these values, the intrinsic economic value of the Arduino board is about 3165 €/ton. This value does not consider all the elements present, only those analyzed; however, precisely because of the criteria used in choosing the materials to be analyzed, this value represents an excellent approximation of the real value. The principal metals that contribute to this value are copper, with an incidence of about 35%; gold, with an incidence of 21%; and silver, with an incidence of about 18%. These results are essential to define the metals to be recovered during the development of a recycling process. This research makes it possible to understand which metals must be recovered if an economically sustainable process is desired. Furthermore, it is also possible to identify specific recycling paths for the different components based on their composition in order to reduce the environmental impact.

Author Contributions: Conceptualization, N.M.I. and P.R.; methodology, P.R. and F.V.; validation, N.M.I. and P.R.; investigation, P.R.; resources, F.V.; data curation, P.R. and N.M.I.; writing—original draft preparation, P.R.; writing—review and editing, N.M.I. and P.R.; visualization, N.M.I.; supervision N.M.I.; funding acquisition, F.V. All authors have read and agreed to the published version of the manuscript.

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