Environmental Sustainability of Printed Circuit Boards recycling practices: an Academic Literature Review

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Abstract: Printed Circuit Boards (PCBs) are crucial components, massively impacting several strategic industries. Nonetheless, in their production a significant amount of Critical Raw Materials and other strategic resources are involved. These kinds of materials and elements have been facing growing sustainability and availability issues in recent times. Therefore, it is of crucial importance to evaluate their recycling. However, the environmental impact of PCBs recycling practices is often overlooked. Usually, in these kinds of techniques environmentally impacting processes are involved. In this work, an Academic Literature Review is conducted, to investigate the studies performed about environmental sustainability of PCBs recycling practices.

Keywords: Printed Circuit Boards, Critical Raw Materials, Recycling, Environmental Sustainability, Life Cycle Assessment.

I. INTRODUCTION

Critical Raw Materials (CRMs) represent a hot topic for European Union countries, due to their cruciality for European economic growth, jobs and overall life-style and their concurrent supply issues (Bobba *et al.*, 2020). Currently, a list of thirty CRMs are identified by the European Commission, basing on their economic impact and supply risk for Europe (Blengini *et al.*, 2020). Besides the strategic cruciality for the European Countries, CRMs present significant environmental and social sustainability issues related to their extraction and processing phases (Hofmann *et al.*, 2018). Thus, it is of utmost importance to consider the implementation of circular practices for the recovery of CRMs (Charles *et al.*, 2020). CRMs are largely used in the production of Printed Circuit Boards (PCBs), which makes them an important potential recovery source (Gonzalez Baez *et al.*, 2022). Besides CRMs, PCBs production involves also massive amounts of other strategic and environmentally impacting raw materials like copper and gold, that can be recovered (Mueller *et al.*, 2015; Cucchiella *et al.*, 2016; Catinean *et al.*, 2021). Finally, e-plastics is another material whose recovery from PCBs is discussed (Kaya, 2017). Among the common techniques of recovery of materials from PCBs, procedures like pyrometallurgy and pyrolysis are included (Rosa and Terzi, 2016). These kinds of techniques, nonetheless, present typically non negligible environmental impacts, moreover related to energy consumption and hazardous gases release (Harvey *et al.*, 2022). Thus, the risk is that the recycling of CRMs from PCBs results as being particularly impacting and harmful for the environment. Given this strong issue, this work proposes a Systematic Academic Literature search and a narrative Literature Review related to the performed Life Cycle Assessment (LCA) studies about the recovery of materials from PCBs. The objective of the paper is to assess the level of environmental sustainability of recovery and recycling practices from PCBs compared to traditional linear practices. Therefore, according to this objective the paper is divided as follows: in Section 2 the methodology applied to perform the Literature Review is described. To guide the Literature Review, a research question is presented and responded through the critical analysis of academic publications related to the topic. The results of the critical analysis are presented and discussed in Section 3. Finally, in Section 4 major conclusions are drawn.

II. METHODOLOGY

Given the practical importance of the topic illustrated in paragraph I, the Literature review has been guided by a research question (RQ) which can be formulated as follows:

“Are the recovery and recycling practices from PCBs more environmentally friendly than traditional linear practices of PCBs manufacturing?”

Considering that research on this topic is still limited, in order to perform the systematic literature search and narrative literature review and respond the RQ, both Scopus and Web of Science databases have been used to allow gaining an overall perspective of all the LCA studies performed about the recycling from PCBs. To this aim, the following keywords and logical connectors have been used:

TITLE-ABS-KEY ((*"life cycle assessment"* OR *"lifecycle assessment"* OR *"environmental footprint"* OR *"life cycle analysis"* OR *"lifecycle analysis"* OR *"environmental sustainability"*) AND (*"electric"* OR *"electronic"* OR *" WEEE"* OR *"Waste electric and electronic equipment"*) AND (*"PCB?"* OR *"PCB? material?"* OR *"PCB? component?"* OR *"Printed Circuit board?"* OR *"Printed circuit board? material?"* OR *"Printed circuit board? component?"*) AND (*"recycled"* OR *"recycle"* OR *"recyclable"*))

The first section of the string aimed at including all the papers that discussed the quantification of environmental impact of the recycling process. It has been decided to not limit the search to the papers presenting only LCA methodology since the literature about the investigated topic is not vast. Therefore, also papers discussing environmental impact in a less structured and methodological way were deemed as interesting. The second section of the string aimed at considering only the articles focused on the waste of electronic equipment. In this way, the risk of inclusion of papers using the acronym of PCBs with a different meaning from Printed Circuit Boards has been avoided. Finally, the third and fourth sections of the string aimed at excluding those papers not discussing respectively PCBs and recycling processes.

The selected research string provided respectively 16 results on Scopus and 2 results on Web of Science. These results confirmed how few studies have been conducted in the academic Literature regarding the investigated topic. Among the resulting papers, one was a duplicate between Scopus and Web of Science, and another one was labelled as having an unknown author. The 16 left papers have been fully read and evaluated by their content. As inclusion criteria it was checked that papers:

- Considered an assessment or an evaluation of the environmental sustainability of the recycling process.
- Considered the recycling process of e-waste and, among the considered typologies of waste, included explicitly or exclusively PCBs.

These criteria led to the exclusion of 4 additional papers. In Figure 1, the adopted Literature Review process is illustrated.

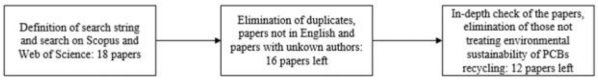

Figure 1. Process of the conducted Academic Literature Review

III. REVIEW AND DISCUSSION OF THE RESULTS

In order to guide the analysis of the twelve selected papers, few classification criteria have been considered:

- Scope of the proposed analysis.
- Level of consideration of PCBs: it has been assessed whether PCBs were the only recyclable considered element, if they were only one of the considered electronic elements or instead, they were considered indirectly.
- Environmental impact quantification methodology: the reliability of the results of the analysed works has been evaluated by assessing the adopted environmental impact quantification methodology of each paper.

- Assessment of the positive or negative environmental impact of the recycling activity compared to traditional sourcing.
- Type of implemented recycling practices.

The classification of the papers is synthetised in Table 1, while Table 2 summarizes the applied recycling practices in the analysed articles.

TABLE I. CLASSIFICATION OF THE ANALYZED WORKS ACCORDING TO THE DESCRIBED CRITERIA

Paper	**Scope of the Analysis**	**PCBs consideration level**	**Environmental impact quantification method**	**Environmental impact benchmark**
(Büyükbay *et al.*, 2010)	PCBs manufacturing plant in Turkey	Sole focus	Unstructured	Better than linear processes
(Bulach *et al.*, 2018)	Theoretical disassembly of automotive electronic components	Main considered electronic element but not the only one	LCA	Better than linear practices
(Pokhrel, Lin and Tsai, 2020)	Local recycling plants in Taiwan	Sole focus	LCA	Worse than linear practices
(Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016)	Management of computers discarded in Mexico in 2014	One of the considered elements	LCA	Better than linear practices
(Arain *et al.*, 2022)	Informal e-waste recycling community in Thailand	One of the considered elements	MFA & LCA	Better than linear practices
(La Rosa *et al.*, 2021)	Theoretical recovery process	One of the considered elements	LCA	Better than linear practices
(Soo and Doolan, 2014)	PCBs recycling in Malasyia and Australia	Sole focus	LCA	Benchmark not explicitly performed
(Bryan *et al.*, 2020)	Theoretical CEReS process	Sole focus	LCA	Better than linear practices
(Bastin *et al.*, 2020)	Lab scale process	Sole focus	LCA	Better than linear practices
(Kaya, 2019)	Theoretical context	One of the considered elements	Theoretical unstructured considerations	Better than linear practices
(Rao, 2014)	Overview of e-waste scenario in India	Not directly considered	Unstructured considerations	Mixed considerations
(Tantawi and Hua, 2021)	Theoretical context	One of the considered elements	Environmental implication score proposed by (Graedel *et al.*, 2015)	Mixed considerations

TABLE 2. APPLIED RECYCLING PRACTICES IN THE ANALYZED WORKS

Paper	**Recycling practices**
(Büyükbay *et al.*, 2010)	Micro etchant reuse and drag-out (defined as the amount of liquid involuntarily extracted with an electroplated part) recover by drain board application as on-site recycle of tin and copper.

(Bulach *et al.*, 2018)	Extraction of power electronic units, manual or mechanized dismantling, and refining and smelting of PCBs in other plants to recover copper, gold, silver, palladium and tin and chemical treatment with nitric agent and hydrochloric acid in combination with hydrogen peroxide to dissolve soldered connections to liberate tantalum.
(Pokhrel, Lin and Tsai, 2020)	Different cases, using mainly mechanical separation composed of six steps (1. Coarse crushing, 2. Screening, 3. Particles size meshing, 4. Wind separation, 5. Magnetic separation, 6. Eddy current separation) and purification by means of strong acids and other chemical substances
(Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016)	Generic, considering possible processes performed in Mexico Thus, practices were not precisely defined.
(Arain *et al.*, 2022)	"Informal" e-waste recycling with low technology methods and limited or no governmental regulation by four neighbourhoods inside a larger e-waste recycling community in Northeast Thailand. Thus, practices were not precisely defined.
(La Rosa *et al.*, 2021)	In order to recycle metal-powder from PCB, the metallic part of PCB has been manually separated from the plastic component and has been ground using a SPEX mill, 8000M series. This allowed obtaining metal-plastic powders.
(Soo and Doolan, 2014)	Generic processes of informal (low technology level, low legislative control) recycling in Malaysia and generic recycling in Australia. Thus, practices were not precisely defined.
(Bryan *et al.*, 2020)	Recycling in 5 steps: 1. PCBs are bled off from WEEE. 2. Pre-treatment is performed through a catalytic cracking resulting in a metal-rich char. 3. A bioreactor system is used to oxidise sulfidic minerals in the coal wastes, resulting in the production of a ferric iron-sulfuric acid lixiviant. 4. This is used to leach base and other soluble metals from the PCB char. 5. Valuable metals are recovered from the pregnant leach solution by a downstream process and the raffinate recycled to the coal waste bioleaching reactor.
(Bastin *et al.*, 2020)	Thermomechanical separation of PCB and surface mounted devices (SMD): pyrolysis to isolate metallic cores, which are further leached to obtain 92% pure tantalum oxide.
(Kaya, 2019)	Generic, theoretical
(Rao, 2014)	Generic, considering possible processes performed in India.
(Tantawi and Hua, 2021)	Generic, theoretical

Out of the twelve analysed papers, nine of them use a structured methodology to quantify the environmental impact of recycling practices. In eight cases, the exploited methodology includes LCA. The adoption of a so used and well-accepted methodology (Finnveden *et al.*, 2009) is beneficial to the reliability of the results.

A better sustainability of the recycling practices compared to the traditional ones is the result provided by most of the analysed works. Precisely, eight out of twelve papers highlight the improvement of sustainability practices. Specifically, the motivations explaining the better sustainability include:

- Reduction of toxicity (Bryan *et al.*, 2020).
- Reduction of eutrophication (Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016; Bulach *et al.*, 2018; Bryan *et al.*, 2020).
- Reduction of materials depletion (Büyükbay *et al.*, 2010; Bulach *et al.*, 2018; Bastin *et al.*, 2020; Bryan *et al.*, 2020; La Rosa *et al.*, 2021; Arain *et al.*, 2022).
- Reduction of global warming potential (Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016; Bulach *et al.*, 2018; Arain *et al.*, 2022).
- Reduction of acidification potential (Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016; Bulach *et al.*, 2018).

- Reduction of abiotic potential depletion of fossil fuels (Bulach *et al.*, 2018).
- Reduction of photochemical ozone creation potential (Bulach *et al.*, 2018).
- Reduction of freshwater aquatic ecotoxicity potential (Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016).
- Human health (Bastin *et al.*, 2020; Arain *et al.*, 2022).

Nonetheless, not all the analysed papers share the same opinion about the environmental sustainability of PCBs recycling practices. Most notable exception is (Pokhrel, Lin and Tsai, 2020), where recycling practices emerge as more impacting than linear practices. In this study, is claimed that the recovery from PCBs is more impacting than ores extraction process for all metals but gold. The major source of environmental impacts is stated to be coming from the purification phase of the recycling, due to the usage of strong acids and chemicals. Source of data for the study were local recyclers in Taiwan and Ecoinvent database. The exception is even more meaningful if it is considered that among the analysed works, this is the only one focusing exclusively on various kinds of PCBs taking data from real field cases. The other analysed case focusing exclusively on PCBs recycling that gets closest in terms of primary data sourcing is (Bastin *et al.*, 2020), where a Lab case is analysed. In this case, though, the process is focused on the recovery of tantalum, which is not among the metals considered by (Pokhrel, Lin and Tsai, 2020). It is possible that the difference in recycling objective leads to a difference in the recycling process and thus in the related environmental impact. Indeed, also in (Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016) is stated that human toxicity worsens with recycling practices, while it is stated to be improving in (Arain *et al.*, 2022) and (Bastin *et al.*, 2020). Once again, the scope of the analysis are different: (Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016) consider end of life (EoL) computers, (Arain *et al.*, 2022) and (Bastin *et al.*, 2020) consider respectively exclusively the recovery of plastics from household appliances and the recovery of tantalum from generic PCBs. This suggests how a first crucial variable is the typology of material to be recovered. This point is further enhanced by (Tantawi and Hua, 2021), where is stated that the cradle-to-gate environmental impact of recycling practices varies significantly over time due to the changes in elements concentration inside electronic items. Another important variable is the quantity of recycled materials in absolute terms. Indeed, from (Alcántara-Concepción, Gavilán-García and Gavilán-García, 2016), emerges that for impact categories like global warming potential, acidification potential and eutrophication potential a 10% increase of the recycled quantity compared to the as-is situation would be more beneficial than a 35% increase. Some possible reasons behind appear to be the increase in the consumption of fossil fuels and transportations and related emissions for the recycling processes. A major role appears to be played also by how the recycling process is performed and controlled. In six of the analysed papers the specific implemented recycling practices are described (Büyükbay *et al.*, 2010; Bulach *et al.*, 2018; Bastin *et al.*, 2020; Bryan *et al.*, 2020; Pokhrel, Lin and Tsai, 2020; La Rosa *et al.*, 2021), with various levels of detail. All these papers, where the recycling process was theoretical (Bulach *et al.*, 2018; Bryan *et al.*, 2020; La Rosa *et al.*, 2021), performed in a lab (Bastin *et al.*, 2020; Pokhrel, Lin and Tsai, 2020), or in an industrial controlled environment (Büyükbay *et al.*, 2010), where the process could be improved and optimized. On the other hand, the cases where the recycling practices are not deemed as more sustainable than linear practices, refers to uncontrolled cases of average PCBs recycling practices performed in Malaysia (Soo and Doolan, 2014), India (Rao, 2014) and Taiwan (Pokhrel, Lin and Tsai, 2020). This is a further indication that the recycling practices implemented are massively important to determine the environmental sustainability of the recycling process compared to linear practices.

As an example, (Bryan *et al.*, 2020) underlines how the used energy sources are crucial in influencing the environmental performance of PCBs recycling. A confirmation of this concept is provided by (Rao, 2014), which underlines that to ensure the sustainability of e-waste recycling practices, it is crucial to keep them under control and institutions play a crucial role in this sense

IV. CONCLUSIONS

From the conducted review, it clearly appears how unstructured is the Literature related to the investigated topic. This probably occurs because usually e-waste recycling is treated as a whole, without explicit distinction among different e-waste components like PCBs. Nonetheless, given the growing relevance and criticality of CRMs and other strategic materials used in technological products, their recycling is becoming a more and more important activity (Fishman et al., 2018; Nassar et al., 2015; Reuter et al., 2013). Thus, it would be useful if the Academic Literature focused more on the environmental assessment of PCBs recycling practices, in order to provide indications to practitioners and institutions about this topic.

From the Academic Literature, it emerges that recycling of PCBs can be a practice more sustainable than traditional extraction processes, moreover if the avoided resources depletion is considered. Nonetheless, this is not a guaranteed result, and it seems to be strongly dependent on both kind of materials recovered and on how much attention is paid to sustainability in designing and controlling the PCBs recycling process and practices. Indeed, (Rao, 2014) underlines how it is crucial to keep the recycling processes under control to ensure the acceptability of their sustainability level. Generally speaking, recycling practices of PCBs bear a significant environmental impact, and it is important to improve and optimise them in order to improve their sustainability (Soo and Doolan, 2014). In conclusion, according to the academic Literature, the sustainability of PCBs recycling can be better than the linear practices of PCBs manufacturing. In this sense, a larger contribution of the Academic Literature about sustainability assessment of PCBs recycling practices compared to the current poor contribution may be helpful in providing practitioners and institutions guidelines to optimize the sustainability of the recycling practices.

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