

Paper-based PCB – Cellulosic fibres and functional ink separation towards recycling

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Short abstract

Millions of tonnes of electronic waste are generated annually in the European Union, creating significant environmental challenges. The E.U. project CircEl-Paper proposes a novel approach to electronic design by developing multilayer printed circuit boards (PCBs) based on circular economy principles. These PCBs are made primarily from paper, a material with strong recycling potential, and incorporate sustainable bio-based resources and environmentally friendly materials. This study investigates how conventional paper and board recycling processes can be adapted to recycle a simple paper-based electronic device developed in the project: an RFID antenna printed with silver-based ink. Three typical recycling operations—pulping, centrifugal cleaning, and flotation—were first tested separately at laboratory scale. Results showed that the paper-based PCB easily breaks down during standard pulping, causing the silver tracks to detach from the paper and fragment into particles between 10 and 100 µm in size. Due to silver high density, centrifugal cleaning efficiently concentrates Ag particles in one stream with 60% separation yield from the cellulosic fibers. Although silver is not naturally hydrophobic and therefore not ideal for flotation, its small and porous particles are nevertheless removed with about 70% efficiency due to entrainment in bubble trails. Finally, when the three processes were combined in a complete recycling line, fibers and silver were efficiently separated into two streams, achieving over 90% fiber recovery and more than 80% silver recovery. This demonstrates that conventional paper recycling processes can successfully treat simple paper-based electronic devices.

Keywords: paper-based PCB, recycling, separation, cellulosic fibres, silver ink particles

1. Introduction and background

In an increasingly connected and digital world, printed electronics offers many opportunities. As it can be developed on various types of substrates to provide a wide range of functionalities, a crucial challenge consists in designing more sustainable devices. In this framework, CircEl-Paper European project (<https://circelpaper.eu/>) is heading towards multilayer PCB (Printed Circuit Board) made from paper, using circular economy principles, bio-based resources and ecofriendly materials. Using paper as main constituent of electronics enables to upscale processing by R2R manufacturing, and constitutes a major advantage for PCB end-of-life since paper-based PCB recycling could be envisaged using conventional paper and board recycling processes. Adapting these processes to paper-based PCB is the objective. The first step consisted in studying a simple model, a RFID antenna printed by flexography with Ag-based ink on a coated paper.

Classical recycling processes have already been investigated in our lab (Khiari et al. 2025; Conceição et al. 2026) on same models. Recycling was simulated at lab-scale. It started by pulping the antenna in water in order to defibrate the paper substrate and detach the functional materials, i.e. the ink, from the cellulosic material; then centrifugal cleaning and flotation, two well-known unit separation operations, have been selected to separate the fibers and the silver-based ink into two streams of recoverable materials. These operations were conducted using standard operating conditions for printed graphic paper recycling. If the potential of fiber and ink separation was

already demonstrated, no clear mechanism was given to explain the Ag separation. This study deepens understanding by varying pulping conditions that influence the separation.

2. Materials and methods

2.1. Material and Methods

The studied PCB is an industrial printed RFID antenna (Figure 1a) printed by Fedrigoni by the flexographic process on an 86 g/m² white coated office type paper, using a silver ink made of Ag-nanoparticles. After printing, the device is exposed to a near-infrared irradiation to improve the electrical conductivity of the printed tracks. The paper contains 29 w% of mineral fillers. Fillers are present in the paper bulk and in the coat to improve printability (Figure 1b). The Ag content per antenna is 4.62 ($\pm$ 0.03) mg. Detailed characterizations are given in (Khiari et al. 2025).

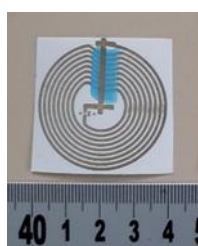


Figure 1a: RFID antenna

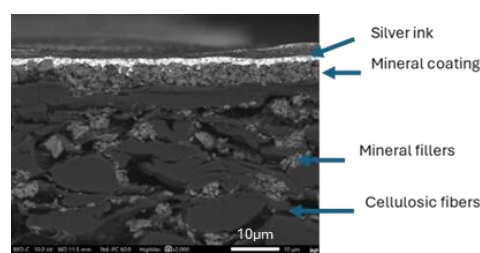


Figure 1b: SEM image of the cross section of the RFID antenna

2.2. Methods

Pulping was carried out in water in a lab-scale pulper of 36 L capacity, equipped with a helicoidal impeller (described in Khiari et al. 2025). 1 kg of material (unprinted or printed substrate) was pulped at medium consistency (10%) to favor fibers/fibers and fiber aggregates/fibers friction. Sodium hydroxide was added to swell fibers, improving disintegration and ink detachment. For the unprinted substrate, NaOH doses and pulping time were varying in classical ranges (Göttsching and Pakarinen, 2000), i.e. from 0 to 2% NaOH (w NaOH/w device) and 5 to 20 min for the time. For the printed substrate, the pulping time varied from 10 to 120 min while other pulping parameters were kept constant (65°C, 0.5% NaOH).

The **fiber floc content**, according to Vilaseca et al., 2011, characterizes the paper disintegration efficiency. A pulp sampling is passed through a 150 μm slots screen during 10 min with water. The individualized fibers pass through the screen, while the fiber aggregates (the rejects) remain on the screen. The floc content is the dry mass of rejects divided by the dry mass of the initial sample.

Ink fragmentation was tracked using image analysis on pulp handsheets to sort ink fragments by their respective size classes. Results are expressed in occupied area (OA=surface occupied by a class of fragments relative to the total surface of the ink on the handsheet).

Cleaning was investigated using a home-made cleaner running in batch mode (described in Khiari et al. 2025). The cleaner is fed with approximately 50 g (dry matter) of antenna suspension obtained after 10, 30 and 60 min of pulping. The pulp is diluted with water up to 0.5% consistency (typical cleaning condition) at the inlet of the cleaner. After 10 min operation, Ag separation rate (mass of Ag in the reject fraction divided by the mass of Ag in the inlet) is determined.

Flotation was carried out in the Voith Lab-flotation cell of 23 L capacity (described in Khiari et al. 2025), using 230 g (dry matter) of antenna suspension, obtained after 20 or 60 min of pulping. The pulp consistency was adjusted to 1% with water for optimal efficiency, and 0.2 % Brij₁₀₀ surfactant was added. During the 8 min flotation, the air load applied was 200%. When flotation is combined with cleaning, flotation is carried out before cleaning because it runs at a higher consistency than cleaning (1% compared to 0.5%).

Mass balance is made by gravimetry. The considered sample is dehydrated on a sand bath, dried at 105°C in an oven and then calcinated at 900 °C for 2 h. The mineral fraction corresponds to the calcination residue and the organic matter to the calcined fraction.

Ag quantification is performed according to (Conceição et al. 2023) by leaching the mineral fraction containing Ag in 40 mL of 3.1 mol/L HNO₃ at 25 °C for 24 h. The obtained leachate is analyzed by Atomic Absorption Spectroscopy (AAS) at 328.07 nm wavelength.

3. Results and discussion

3.1. Pulping stage

Paper recycling starts with pulping, that aims at individualizing the fibers and detaching the contaminants from the fibers (Marlin and Carré, 2016). A side effect is the fragmentation of the contaminants that are removed in the subsequent separation operations. To separately study the effect of pulping on the paper substrate and on ink detachment/fragmentation, pulping was first investigated on the unprinted device. The paper disintegration efficiency is presented in Figure 2.

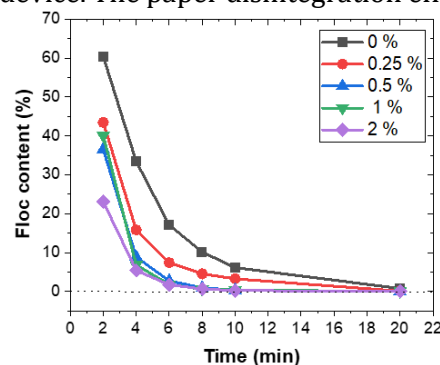


Figure 2: Effect of pulping time and NaOH content on the pulping efficiency of the paper substrate

Figure 2 shows that the paper exhibits a very good pulping ability, as classical graphic papers, since the floc content rapidly decreases with pulping time, whatever the NaOH dose applied. In the absence of NaOH, pulping is efficient but extended time is required to fully disintegrate the paper. The NaOH dose of 0.5% was fixed for the next trials since with higher quantities (1 and 2% NaOH) no more improvement is observed.

During pulping, the conductive circuits (silver tracks) are also subjected to mechanical forces such as shearing, compression, or direct impacts with the pulper impeller. The mechanical stresses weaken the printed tracks until they fracture, causing ink fragmentation that impacts the efficiency of later separation steps. Ink fragmentation during pulping is presented in Figure 3. After 5 minutes of disintegration, four classes of ink particles dominate: [0.01-0.04], [0.04-0.15], [0.15-0.4] and [0.4-1] mm² classes. Ink particles already exhibit very small sizes meaning that ink detachment and silver track fragmentation is rapid and easy under the tested pulping conditions. After 5 minutes, a gradual change is observed in the < 0.01 mm² classes. In classes > 0.01 mm², the most pronounced changes appeared between 5 and 20 minutes. After 10 to 20 minutes, the predominant population is the [0.01- 0.04] mm² class with more than 40% of the total ink particles. This illustrates that biggest size particle are progressively replaced by smaller particles by fragmentation. Given the dimensions of the printed tracks (2 µm thick), its sudden impact with the impeller probably generates a large quantity of fragments. This causes the ink to either fragment at the same time as the paper substrate or to detach from the substrate, which in both cases leads to the fragmentation of the tracks.

After pulping, the next step is to separate the functional ink in one stream and the cellulosic fibers in another one for further valorization. Based on the work of Khiari et al., 2025, centrifugal cleaning and flotation are retained as efficient processes for Ag separation. These operations are first studied individually in batch mode before the proposal of a complete recycling line.

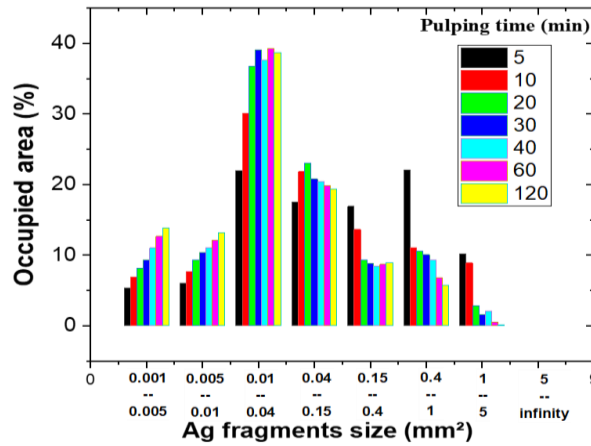


Figure 3: Ink fragment population obtained during the RFID antenna pulping

3.2. Centrifugal cleaning

Centrifugal cleaning separates particles based on their density. Due to centrifugal forces induced in the cleaner, the inlet pulp is separated into two streams. Light materials with thin shape, high specific surface area, and small size generally end up in the accept fraction with the cellulosic fibers. Meanwhile, heavier materials with thick shape, small specific surface area, and large size go in the reject fraction (Marlin and Carré, 2016). In the paper recycling industry, materials that fall into the latter category include sand, metal or glass debris, and small pieces of wood. For the antenna, the ink contains high-density Ag particles (10.49 g/cm^3); therefore, centrifugal cleaning may separate silver from fibers, provided the particle size is appropriate. Ag separation rates, after varying pulping time, are presented in Table 1.

Table 1. Ag separation rate after centrifugal cleaning – effect of pulping time

Pulping time, min	10	30	60
Ag separation rate, %	57.2	60.8	54.7

The pulping time does not affect the Ag separation rate which is slightly below 60 % in average. This was expected, as the ink particle size remains constant during pulping (Figure 3). If centrifugal cleaning is promising, the Ag separation is still far from 100%. Despite the high density of the metal, some Ag fragments floated on the pulp surface during dilution, suggesting hydrophobic behavior. The floatability of the Ag particles may be due to high porosity that traps air or a poor wettability property. As a result, some fragments may be difficult to centrifuge. The composition of both fractions was analyzed. Ideally, fibers would be fully recovered in the accept stream and Ag in the reject stream. Ashes (mineral fraction), also present in the paper substrate, contaminate both streams. Mass balances are thus performed on the different streams to quantify organic matter, inorganic matter, and Ag content. Since the pulping time does not significantly impact the mass balance, only one example is given in Table 2 (cleaning after 60 min pulping).

Table 2: Mass balance on the inlet and outlet fractions of the cleaner (after 60 min pulping)

(C_p =pulp consistency; m_{org} = mass of organic matter; m_{inorg} = mass of inorganic matter; m_{Ag} = mass of silver)

Fraction	Inlet	Accept	Reject
C_p (%)	0.5	0.46	0.8
$m_{dry\ pulp}$ (g) [%]	52.20 [100 %]	46.77 [89.6 %]	2.49 [4.77 %]
m_{org} (g) [%]	36.66 ± 0.21 [100 %]	32.37 ± 0.1 [88.3 %]	1.35 ± 0.19 [3.7 %]
m_{inorg} (g) [%]	15.54 ± 0.21 [100 %]	14.40 ± 0.04 [92.7 %]	1.16 ± 0.19 [7.5 %]
m_{Ag} (mg) [%]	642.20 ± 11.20 [100 %]	190.27 ± 23.77 [29.6 %]	351.08 [54.7 %]

Mass balance analysis may not always close: if output mass is lower than input, part of the material remained in the device and is considered lost; if higher, the discrepancy is attributed to non-representative sampling. Different fractions are thus considered when performing the mass balance. For Ag quantification, the Ag richest stream, i.e. the reject fraction and the inlet fraction are considered as the most reliable. This means that 351 mg of Ag is recovered in the reject from the 642 mg at the inlet, leading to a Ag separation of 54.7%. Concerning the fiber recovery, the accept and inlet fractions, richer in organic matter are taken as reliable fractions. In calculation, the organic matter is assumed to be cellulosic fibers, the rest of the matter, the inorganics, is mineral fillers present in the bulk of the paper or in the coat. With these hypotheses, 32.37 g of fibers are concentrated in the accept fraction compared to 36.66 g at the inlet, giving a high fiber recovery rate of 88.3%, in the range of what is expected in paper recycling. Inorganic matter concentrates in the accept fraction with 92.7% initial ashes but the 7.5% going in the rejects are richer in Ag. Hence fibers and mineral fillers mainly go in the accept fraction whereas Ag concentrates in the reject one. Finally, efficient fibers/Ag separation is obtained with the cleaner.

3.3. Flotation

In the paper industry, flotation is used to remove hydrophobic elements from paper pulp, such as oil-based inks commonly used in graphic paper printing. Flotation uses air bubbles stabilized by a surfactant to collect hydrophobic elements and to transport them on the surface of the flotation cell in the resulting foam which is removed from the pulp. One side effect, commonly referred as de-ashing, is the dragging of fine elements such as non-hydrophobic elements. De-ashing occurs when air bubbles rise to the surface, bubbles creating lines of flow in which fine particles can be trapped and carried to the surface. This effect has been already observed in previous study, where almost 30% initial Ag could have been recovered by flotation (Khiari et al. 2025). In the present study, sodium silicate usually added to limit the dragging effect (Bajpai, 2024) is suppressed to favor Ag extraction. Flotations, performed after 20 or 60 min pulping, show similar efficiencies (result not presented): pulping time does not significantly influence the ink removal by flotation since ink particles are sufficiently fragmented. In the following Table 3, only one example of mass balance and Ag separation efficiency and fiber recovery is presented (flotation after 60 min pulping).

Table 3: Mass balance on the inlet and outlet fractions of the flotation (after 60 min pulping)

<i>(Cp=pulp consistency; m_{org}= mass of organic matter; m_{inorg}= mass of inorganic matter; m_{Ag}= mass of silver)</i>			
Fractions	Inlet	Accept	Reject
Cp (%)	1.0	0.91	1.41
m _{dry pulp} (g) [%]	232.46 ± 1.77 [100 %]	203.22 ± 0.0 [87.42 %]	29.78 ± 0.29 [12.81 %]
m _{org} (g) [%]	162.65 ± 1.71 [100 %]	147.89 ± 0.59 [90.93 %]	12.29 ± 0.02 [7.56 %]
m _{inorg} (g) [%]	69.81 ± 0.73 [100 %]	55.33 ± 0.33 [79.26 %]	17.49 ± 0.03 [25.05 %]
m _{Ag} (mg) [%]	2.85 [100 %]	0.54 ± 0.01 [18.95 %]	2.05 ± 0.05 [71.93 %]

The mass balance shows that the organic matter, i.e. fiber recovery, is close to 91 % in the accept fraction, whereas only 7.5% go in the reject fraction. Looking at inorganic matter, 79.3 % is accounted in the accept fraction. Some inorganics are dragged in the reject foam. Regarding Ag, silver is mainly recovered in the reject fraction with 71.9% of the initial Ag. The Ag separation rate in the reject fraction is remarkable since it is higher than that obtained with centrifugal cleaning. SEM images (not shown) made on the dehydrated foam. This confirms that the flotation rejects are rich in Ag particles, with characteristic size of about 100 µm for the largest fragments and 10 µm for the smallest one. Although Ag fragments are not intrinsically hydrophobic, Ag particles exhibit sizes that allow them to be entrained in the bubble trail during flotation.

3.4. Complete recycling line

A complete recycling line combining flotation and centrifugal cleaning using the same operating conditions as before has been conducted at lab-scale varying pulping time (Figure 4). For this experiment, the inlet of each unit operation was the accept fraction of the previous operation.

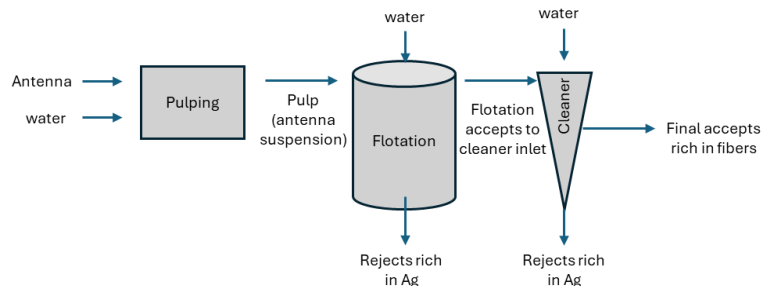


Figure 4: Recycling line for the flexography-printed RFID antenna recycling

After 10 to 60 min pulping, flotation concentrated 45 to 65% of initial Ag in the reject fraction. Centrifugal cleaning, applied on the flotation accept stream still containing Ag, further extracted residual Ag. In total, 81 to 86% Ag is recovered in the flotation and cleaning rejects. Considering the organic matter, more than 90% of the fibres are recovered in the final accept fraction.

4. Conclusions

This study shows that a full conventional recycling line improves the separation of fibres and silver ink for simple paper-based electronic devices: more than 80% Ag and 90% fibres are recovered. 10 to 20 min pulping (classical conditions in paper industry) is sufficient to get suitable ink fragmentation for Ag removal by flotation and centrifugal cleaning. Extended pulping time has no benefit. Flotation and centrifugal cleaning are complementary: centrifugal cleaning removes the largest dense Ag fragments whereas the finest ones are dragged in the flotation foam. Finally, recycled fibres are suitable for papermaking despite they still contain Ag traces. Silver impact in the paper has not yet been tested, and recovered Ag valorisation is currently being studied.

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References

- Bajpai, P. 2024. Recycling and Deinking of Recovered Paper, Elsevier
- Conceição, J.H.F., Party, M., Curtil, D., Svecova, L., Marlin, N., Reverdy-Bruas, N. 2023. Investigation of methods to quantify silver screen-printed onto cellulosic substrate: Towards recycling of printed electronics. *Flex. Print. Electron.*, 8 035014
- Conceição, J.H.F., Curtil, D., Eude, L., Abboud, P., Reverdy-Bruas, N., Svecova, L., Marlin, N. 2026. Applicability of paper deinking process for silver separation and concentration from a paper-based printed electronics prototype, *RSC Adv.*, 16(3):2743-2753
- Göttsching, L. and Pakarinen, H. 2000. *Recycled fiber and deinking*. Helsinki: Fapet Oy

Khiari, R., Marlin, N., Curtil, D., Aourousseau, M., Svecová, L. and Reverdy-Bruas, N. 2025. Separation of Silver and Cellulosic Fibers for Recycling and Reuse of Printed Electronic Devices Components, *Recycling*, 10(6), 201

Marlin, N. and Carré, B. 2016. *Chapter 4: Recycled Fibers*, in Lignocellulosics fibers and wood handbook: renewable materials for today's environment. Belgacem N. and Pizzi A, Wiley-Scrivener

Vilaseca, F., Puig, J., Pèlach, M. À., El Mansouri, N.-E., Alcalà, M., Roux, J.-C., and Mutjé, P. 2011. Study and modeling of the disintegration kinetics of coated paper, *BioRes.*, 6(2), 1659-1669