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# Transforming printed electronic paper waste into eco-friendly adsorbents for gas effluents purification

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Due to the integration of more sustainable technologies, printed electronic devices have been emerging in markets such as packaging, magazines, and labels. These devices offer an eco-friendly alternative to traditional electronics by using less harmful materials such as paper and textiles, and conductive inks, primarily composed of silver. Nevertheless, as the production of such devices grows, concerns about their end-of-life, recyclability, and environmental impact emerge. As a result, the project which aligns with the European Green Deal and circular economy principles, aims to convert printed electronic paper residues into porous materials employing hydrothermal carbonization (HTC). The HTC process was optimized by adjusting paper-to-water ratios, temperature, and retention time. Besides that, ICP-OES analysis confirmed the effective immobilization of the metal within the carbon matrix, highlighting its potential for resource recovery. Hydrochars produced were activated with KOH to improve their sorptive properties and further studies will be done to determine the material's potential for gas purification.

## 1. Introduction

Printed electronic devices were developed to reduce the environmental impact traditional electronics. These new devices use more efficient and less harmful materials, application include printing circuits on substrates such as paper, textiles and plastic using conductive inks, typically based on silver [1]. However, the increasing production of these devices raises concerns about their recyclability.

Recycling residues of the material contains carbon (cellulose fibers) and metals, which can be transformed into porous materials through different processes of thermo-conversion. Two processes gained notoriety in production of higher energy density chars, slow pyrolysis and hydrothermal carbonization (HTC) [2,3]. In the work scope of the research, we are limited to the HTC process. The optimal conditions for cellulose carbonization range from 220 to 240°C, with synthesis times varying from a few minutes to several days [4]. Due to hydrochar's low surface area and porosity, its direct application

is limited. Activation is required to enhance its properties, which can be achieved through two methods: physical activation using CO<sub>2</sub> or steam at high temperatures (>800 °C) and chemical activation, where hydrochar is impregnated with chemical agents like KOH, H<sub>3</sub>PO<sub>4</sub>, or ZnCl<sub>2</sub> before high-temperature treatment (450-650 °C) [5].

This activation process can enhance the sorptive properties of hydrochar, making it a promising alternative for high-performance adsorption applications, such as biogas purification.

## **2. Purpose and Approach**

The purpose of this research work is to study and optimize the thermo-conversion of printed electronic waste, into a bio-sorbent suited for the remediation of gas effluents. The overall goal of the research is to progress paper end-of-life solutions for electronic devices with a focus on resource recovery, sustainability, and environmental responsibility.

A series of experiments were carried out under different conditions to select suitable conditions for the hydrothermal carbonization (HTC) of electronic printed paper residues. The studies were conducted in 5 mL batch reactors, with modifications in the mass ratio of paper to water (0.1 to 0.3), temperature (220 to 240°C), and reaction time (1 to 6 hours).

Following this study, a single condition for HTC was selected and subsequently activated as follows: 10wt% of paper in deionized water was placed in a 500 ml stainless steel autoclave, then sealed and heated to 240 °C for two hours, after completing the process the autoclave was cooled down naturally to room temperature. The HTC carbon recovered was separated by filtration and dried overnight at 105 °C.

The hydrochars produced were then activated through the following protocol. Hydrochar was mixed with potassium hydroxide (KOH) at two different mass ratios: 1:1 and 1:0.5 (hydrochar to KOH). The mixture was stirred for 20 minutes, and the resulting slurry was dried overnight at 105 °C. The dried KOH-hydrochar mixture was subsequently activated in a tube furnace at 500 °C for 1 hour under N<sub>2</sub> gas flowing. Following activation, the samples were washed with deionized water to remove any excess activating agent. The washed samples were then dried overnight at 105 °C and the activated hydrochar (AH) was stored. The AHs were labeled AH T-X-Y, where T denotes the activation temperature, X refers to the impregnation ratio (KOH/hydrochar mass ratio) and Y represents the activation duration (in hours).

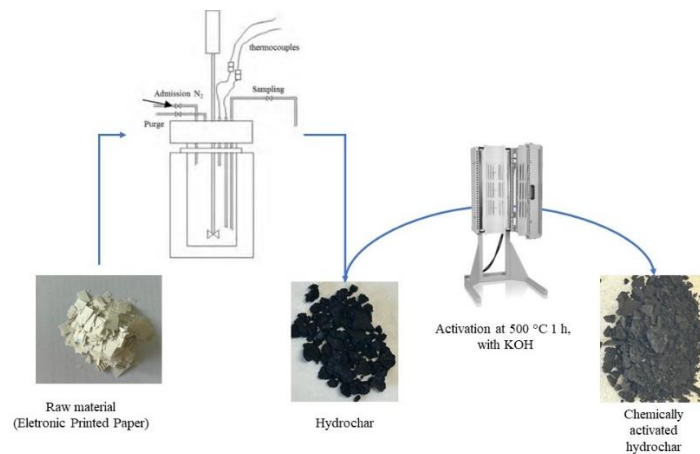


Fig. 1: Graphical methodology

### 3. Scientific innovation and Relevance

The project tackles environmental challenges within the paper industry by converting waste fractions into fresh hydrochar, thereby contributing to the reduction of greenhouse gas emissions. Furthermore, the presence of valuable metals such as silver in the carbon material creates a unique opportunity to improve adsorption efficiency for certain contaminants. This dual-purpose approach leverages both the carbon and metallic components of the waste, optimizing resource recovery.

Although limited data is available on the quantities of printed e-devices produced, their output are expected to rise with technological advancements and the development of more complex materials. In this context, the relevance of this research work becomes evident, as it offers a novel solution for converting this unexploited waste into valuable feedstock for new processes.

### 4. Results and Conclusion

In the HTC process screening, the paper-to-water mass ratio did not significantly impact the carbon content or the yield of the hydrochar. Similarly, changes in retention time and temperature resulted in negligible variations in the elemental composition (Table 1). However, the yield was notably affected by the severity of the process. Therefore, for adsorbents production, optimizing conditions to enhance carbon content and porosity could be more advantageous, even if it results in lower solid yields.

Table 1. Elemental composition of hydrochars and yield under different conditions

Temperature (°C)	Retention time (h)	C(wt%)	H(wt%)	O* (wt%)	Ag (wt%)	Yield (%)
280	1	34.25 ± 1.00	3.51 ± 0.06	28.88	0.76 ± 0.08	32.5
280	6	36.23 ± 0.37	3.40 ± 0.29	27.37	0.81 ± 0.02	26.7
240	2	34.72 ± 0.39	3.27 ± 0.04	24.54	0.99 ± 0.01	33.8
220	1	34.87 ± 1.24	4.44 ± 0.32	42.52	0.31 ± 0.07	83.0 <sup>#</sup>
220	6	37.02 ± 0.20	3.90 ± 0.07	30.68	0.73 ± 0.09	37.8

O\* = calculated by difference; # = significant portion of the original material's mass remains in the product

Moreover, inductively coupled plasma optical emission spectrometry (ICP-OES) analysis using the Jobin Yvon Ultima revealed enhanced concentration of silver (Ag) in the hydrochars produced compared to the raw material (Ag.wt% = 0.28), confirming the effective immobilization of the metal within the carbon matrix

Table 2. Main characteristics of samples (dry basis)

Sample	Feedstock	Hydrochar	Activated hydrochar		
	Paper	H 240-2	AH 500-0-1	AH 500-0.5-1	AH 500-1-1
Chemical composition (wt.%)					
C	34.63 ± 0.08	34.72 ± 0.39	31.37 ± 0,5	39.14 ± 1,95	31.75 ± 0.32
H	4.47 ± 0.1	3.27 ± 0.04	1.80 ± 0,12	2.17 ± 0,03	1.75 ± 0.13
N	nd	nd	Nd	nd	Nd
O*	33.8	24.54	19.125	8.51	18.58
Ash	27.1	37.47	47.7	50.18	47.92
O/C	0.73	0.53	0.41	0.18	0.40
H/C	1.55	1.13	0.69	0.67	0.66
Yield Production (%)	-	31-33	76.4	61.4	61.82

nd= not detected O\* = calculated by difference

According to the Van Krevelen classification, activated hydrochar AH500-0.5-1 is the most similar to charcoal. This similarity indicates that the hydrochar underwent considerable structural transformation during the activation process, making it a potential material for adsorption applications. More research is needed to validate our hypothesis, including an assessment of specific surface area and pore volume, as well as the efficiency of activated hydrochar as an adsorbent. These further studies will help us better understand the material's adsorption capacity and performance, giving vital data to assess its potential for gas purification.

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