

# Influence of Carbon Ink Type on the Sensitivity of Screen-Printed Humidity Sensors

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## Short abstract

Flexible and low-cost humidity sensors are increasingly required for environmental, agricultural, and industrial monitoring. In this work, flexible resistive humidity sensors were fabricated by screen printing using four carbon-based conductive ink formulations: two water-based inks (carbon nanoparticles and graphene) and two solvent-based carbon nanoparticle formulations using different polymer binders (PEI and acrylic). The sensors were characterized under controlled humidity cycles ranging from 30 to 90 %RH.

The results reveal a strong influence of ink formulation on sensor sensitivity. Water-based inks exhibit significantly higher sensitivities than solvent-based inks, with a maximum sensitivity of approximately 0.6 %/%RH obtained for the graphene ink. The effect of the graphene layer thickness was also investigated, highlighting the influence of film structure on the hygrometric response. These results demonstrate the potential of water-based graphene inks for the fabrication of low-cost flexible humidity sensors with scalable printed electronics technologies.

**Keywords :** Screen-Printing, Humidity Sensors, Carbon based Ink

## 1. Introduction and Background

Humidity measurement represents a key challenge in many scientific, industrial, and environmental fields. The level of relative humidity directly influences human comfort, material preservation, industrial process stability, and air quality. In agriculture, it affects crop growth and soil management, while in the electronics and food industries, it can impact device reliability and product durability. This wide range of applications has led to the development of humidity sensors based on different detection principles, particularly capacitive and resistive sensing, and relying on a broad variety of sensitive materials. Among these approaches, resistive sensors based on carbon-based materials and graphene printed by screen printing have recently demonstrated promising performance in terms of sensitivity and ease of fabrication (Beniwal et al., 2023).

Despite these advances, several limitations remain. Conventional technologies may require complex, energy-intensive, or costly fabrication processes, as well as rigid substrates that limit their integration onto flexible or non-planar surfaces. In the context of the transition toward more sustainable and accessible electronics, the development of additive manufacturing processes such as screen printing offers new opportunities, especially in the field of sensing (Selmi et al., 2025), (Le Borgne et al., 2019), (Selmi et al., 2023). The use of carbon-based conductive inks enables the fabrication of sensitive structures on thin polymer substrates with low material consumption and compatibility with various supports. These approaches promote the development of lightweight, flexible sensors with a reduced environmental footprint while maintaining electrical performances suitable for hygrometric detection. Moreover, it has been shown that the integration of hydrophilic materials in bilayer architectures, where a sensitive layer is deposited on top of a conductive carbon layer, can amplify resistance variation under relative humidity (Intaro and Netsuwan, 2025). However, the hygrometric response of these devices strongly depends on the nature of the conductive ink used, particularly the type of conductive material, the polymer matrix, and the dispersion medium of the ink (aqueous or solvent-based), which can influence the adsorption and diffusion of water molecules within the sensitive layer.

Although resistive carbon-based sensors have shown promising sensitivity, there is currently a lack of systematic studies evaluating how the formulation of carbon-based inks affects reproducibility, flexibility, and overall sensor performance under controlled humidity conditions. In this work, we investigate the influence of carbon-based conductive inks formulations on the

sensitivity of humidity sensors fabricated by screen printing. A comparative study is carried out using different commercial inks, including aqueous and solvent-based formulations, in order to evaluate their behavior under controlled relative humidity conditions. The objective is to better understand the role of the overall characteristics of these inks in the hygrometric response and to identify solutions compatible with flexible, reproducible, and low-cost fabrication for environmental monitoring applications. These characteristics make the proposed sensors particularly suitable for low-cost, flexible, and large-area humidity monitoring applications, such as soil moisture monitoring in agriculture, environmental sensing for air and soil quality.

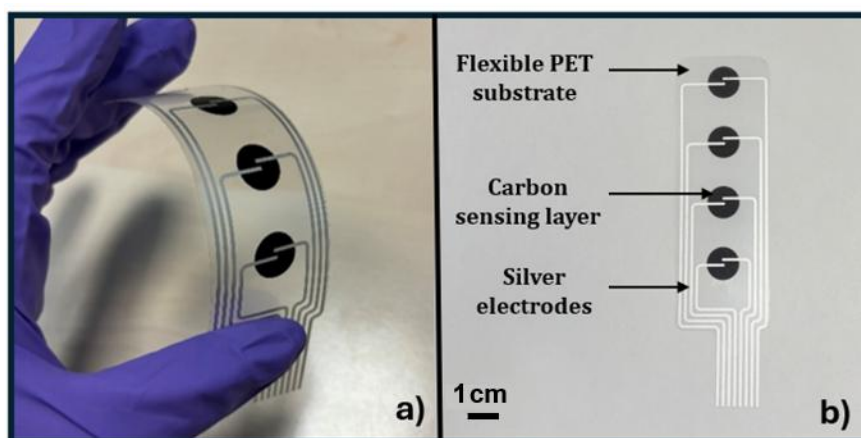
## 2. Materials and Methods

### 2.1. Materials

In this study, the electrodes were fabricated using a silver conductive ink. Each sensor consists of two conductive electrodes positioned on top of the carbon-based resistive active layer, which has a diameter of 12 mm. The face-to-face area of the electrodes defines the geometry of the sensor, with a distance of 1 mm between the two electrodes.

For the screen-printing of the conductive layers, four carbon-based inks were evaluated. Two water-based inks were first investigated : a carbon nanoparticle-based resistive ink and a graphene-based resistive ink. Devices were fabricated on a PET film with a thickness ranging from 120 to 125  $\mu\text{m}$ . The exact chemical compositions of the inks were not disclosed by the manufacturers.

For comparison purposes, two non-aqueous carbon-based inks were also studied: a carbon nanoparticles conductive ink using a PEI (polyetherimide) polymer binder in a solvent-based formulation, and a carbon nanoparticles conductive ink with an acrylic polymer binder, also in a solvent-based formulation.



*Figure 1. Flexible screen-printed humidity sensor fabricated on a PET substrate: (a) fabricated flexible device and (b) annotated image indicating the PET substrate, sensing layer, and electrodes.*

### 2.2. Screen-Printing

Humidity sensors were fabricated by screen printing using an ATMAOE MF44 equipment (Figure 2a). The devices were printed on a flexible PET substrate. The screen-printing process employed a DCF 1-22 capillary film applied to a nylon screen (example in figure 2b) with a mesh count of 90 for carbon inks and 120 for silver ink.

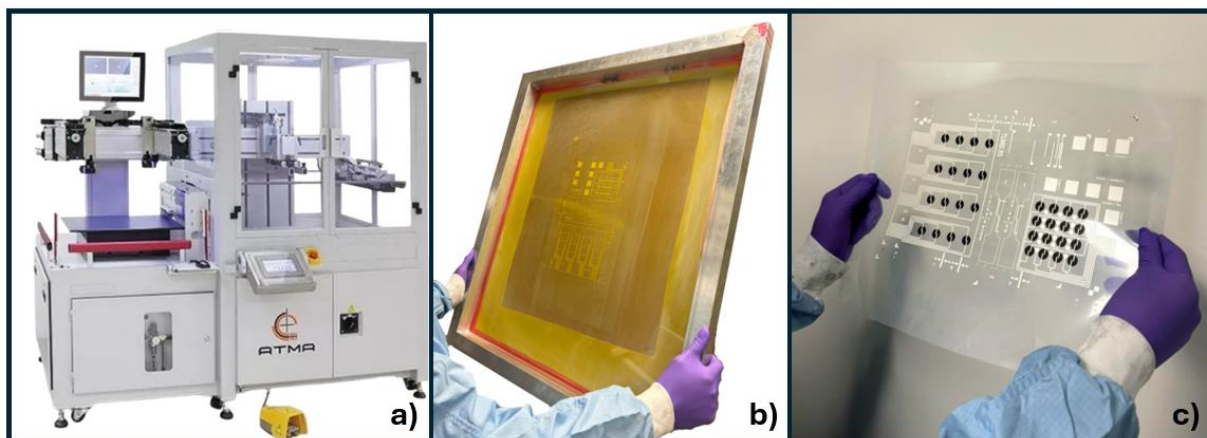


Figure 2. Screen-printing process used for the fabrication of the sensors : (a) ATMAOE MF44 screen-printing machine, (b) patterned screen used for printing the silver electrodes, and (c) flexible PET substrate containing the screen-printed humidity sensors.

The deposition was carried out using a polyurethane squeegee with a hardness of 75 Shore, inclined at  $20^\circ$  relative to the normal to the screen. The printing speed was set to  $100 \text{ mm}\cdot\text{s}^{-1}$  for the carbon inks and  $150 \text{ mm}\cdot\text{s}^{-1}$  for the silver ink, using a single printing pass. During the printing process, the patterns are printed onto the PET substrate, resulting in the screen-printed humidity sensors shown in Figure 2c.

For aqueous inks, a single printing pass produced a thickness of about  $7 \text{ }\mu\text{m}$  for carbon nanoparticle ink and  $2 \text{ }\mu\text{m}$  for graphene ink. To investigate the influence of the deposited layer thickness on sensor performance, a second screen-printing pass was performed for the graphene ink, resulting in a deposited thickness of approximately  $4 \text{ }\mu\text{m}$ .

The carbon-based conductive layers were printed first and cured at  $60^\circ\text{C}$  for 20 minutes. The silver electrodes were subsequently screen-printed and subjected to the same thermal treatment. For the solvent-based carbon nanoparticles inks containing either a PEI or an acrylic polymer binder, the same screen-printing parameters were used. The resulting layer thickness was approximately  $10 \text{ }\mu\text{m}$ . After printing, the samples were left to dry for 24 h at room temperature, followed by thermal curing at  $70^\circ\text{C}$  for 5 minutes for the silver ink and 10 minutes for the carbon inks.

### 2.3. Humidity Characterization

Humidity tests were carried out using a Binder climatic chamber (model MKF 115). The measurements were performed at room temperature ( $25^\circ\text{C}$ ).

All the devices were subjected to a humidity cycle starting at 30 % relative humidity (RH). The humidity level was then increased in 10 % RH increments up to 90 % RH, with each step maintained for 10 minutes. A descending phase was subsequently applied following the same procedure, from 90 % RH to 30 % RH, with 10 % RH steps, each lasting 10 minutes.

## 3. Results and discussion

### 3.1. Influence of Silver Electrodes

Before analyzing the hygrometric response of the sensors, the potential contribution of the metallic electrodes was evaluated. The resistance of the screen-printed silver tracks was measured under the same humidity conditions applied to the sensing layers. Relative humidity increased from 40 %RH to 90 %RH in successive 20-minute steps, and measurements were performed at  $25^\circ\text{C}$  and  $40^\circ\text{C}$ .

The results, shown in Figure 3, indicate that the resistance of the silver electrodes remains nearly constant throughout the entire humidity cycle, with minor variations considered negligible with respect to the humidity-induced effects analyzed in the following sections.

This stability is consistent with the intrinsic electrical properties of noble metals. Silver exhibits high electrical conductivity and minimal interaction with water molecules under ambient conditions, resulting in a resistance that is largely independent of relative humidity. In the case of nanoparticle-based silver inks, slight variations may occur due to incomplete sintering, porosity, or surface effects; however, in the present study these effects are minimal, indicating a high-quality conductive silver layer.

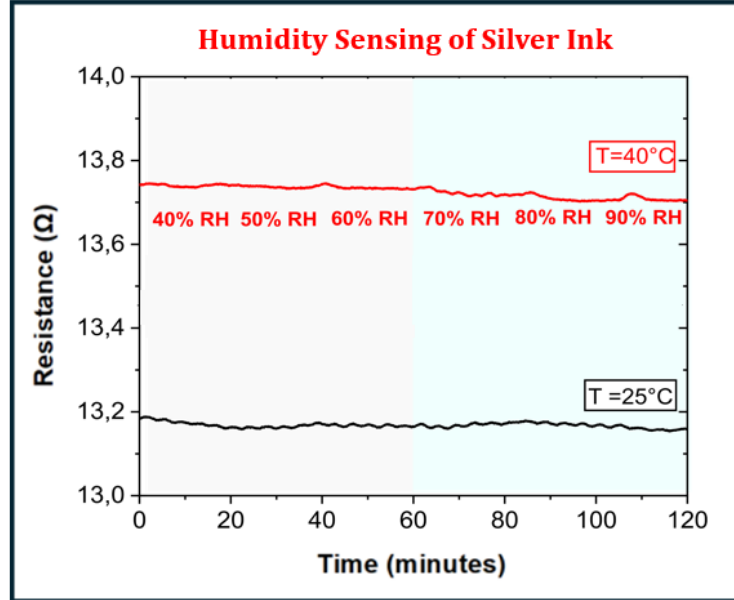


Figure 3. Resistance stability of screen-printed silver electrodes under humidity cycling.

These results confirm that the metallic electrodes function as stable conductive contacts. So, the humidity-sensitive layer deposited between the electrodes governs the electrical response, while the electrodes provide reliable electrical connections (Farahani et al., 2014).

### 3.2. Comparison of the Sensitivities of Aqueous and Solvent-Based Inks

Figure 4 presents the sensitivities obtained for sensors fabricated using the four inks investigated. The relative resistance variation was calculated as :

$$\Delta R / R_0 = (R - R_0) / R_0,$$

where  $R_0$  is the resistance at 30 %RH. For each humidity step, the resistance  $R$  corresponds to the average resistance measured during the humidity plateau, which was used to determine the sensor sensitivity. As shown in figure 4, the two aqueous inks exhibit significantly higher sensitivities than the solvent-based carbon nanoparticle inks. The highest sensitivity is obtained with the aqueous graphene ink, with a value of approximately 0.6 %/%RH, whereas the aqueous carbon nanoparticle ink shows a sensitivity of about 0.22 %/%RH. In comparison, the solvent-based inks display much lower sensitivities, with values of approximately 0.037 %/%RH for the carbon nanoparticle ink with a PEI binder and 0.034 %/%RH for the ink with an acrylic binder. Thus, the sensitivity of the aqueous graphene ink is approximately one order of magnitude higher than that of the solvent-based inks, highlighting the strong influence of ink formulation on the hygrometric performance of the sensors.

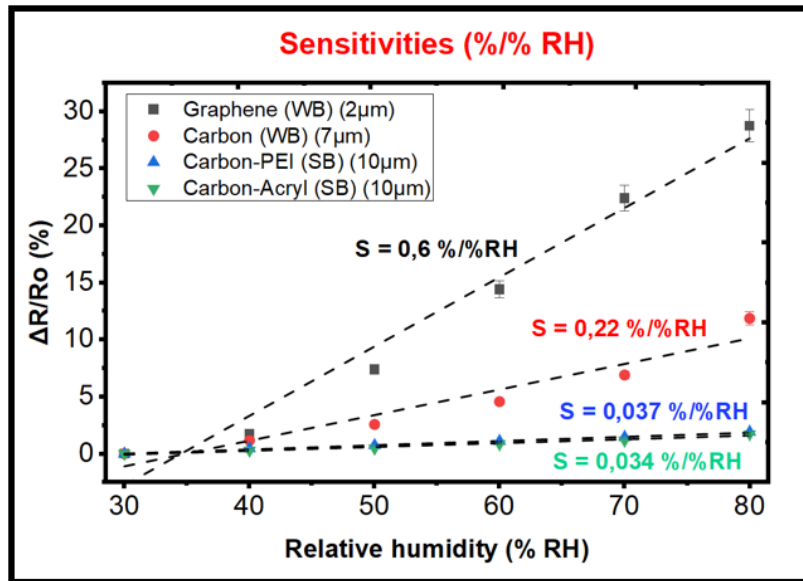


Figure 4. Sensitivity comparison of humidity sensors using different carbon-based inks.

This difference can largely be explained by the nature of the polymer matrix and the dispersion medium. Aqueous inks generally provide a more hydrophilic environment, which promotes the adsorption and diffusion of water molecules within the sensing layer. The presence of water in the conductive network can therefore modify the electrical conduction pathways, leading to larger variations in the sensor resistance.

In contrast, the solvent-based inks rely on polymer matrices with lower affinity for water molecules. One formulation uses an acrylic polymer binder, while the other is based on a PEI (polyetherimide) polymer. Acrylic polymers are widely used in conductive inks because of their good film-forming properties and mechanical stability, but their relatively hydrophobic nature can limit moisture adsorption within the sensing layer. PEI, on the other hand, is a high-performance thermoplastic polymer known for its high thermal and chemical stability. Molecular-scale studies of PEI–water interactions have shown that the polymer structure can restrict the incorporation and mobility of water molecules within the matrix (De Nicola et al., 2017). This limited interaction with water may reduce the influence of ambient humidity on the conductive network formed by the carbon nanoparticles.

Thus, the polymer matrix acts as a partial barrier to moisture penetration, which results in lower sensitivities. In contrast, aqueous inks favor the presence and diffusion of water within the sensing layer, thereby amplifying the effect of humidity.

The importance of water molecule adsorption within the sensing layer for resistive humidity sensors has been widely discussed in the literature. Hygrometric performance notably depends on the ability of the sensing material to adsorb and diffuse water, which is strongly influenced by the physicochemical properties and the hydrophilic nature of the matrix (Farahani et al., 2014).

### 3.3. Influence of the Nature of the Conductive Material

Beyond the ink formulation, the nature of the conductive material also significantly influences the hygrometric response of the sensors. The results show that the graphene-based ink exhibits a higher sensitivity than the aqueous ink based on carbon nanoparticles.

This difference can be attributed to the structural properties of graphene-based materials as these materials possess a very high specific surface area due to their two-dimensional structure. This large active surface provides numerous adsorption sites for water molecules, which can enhance the interaction between ambient humidity and the sensing layer.

In addition, previous studies on graphene-based humidity sensors have shown that the adsorption of water molecules can modify the electrical conduction within the material, notably by affecting

charge transport between conductive sheets and altering the overall resistance of the sensing layer (Borini et al., 2013).

### 3.4. Influence of the Graphene Layer Thickness

The influence of the sensing layer thickness was investigated using the aqueous graphene ink by comparing sensors fabricated with a single screen-printing pass and with two successive passes. Results are presented in Figure 5. Increasing the number of screen-printing passes leads to an increase in the deposited layer thickness, from approximately 2  $\mu\text{m}$  for a single pass to about 4  $\mu\text{m}$  for two passes.

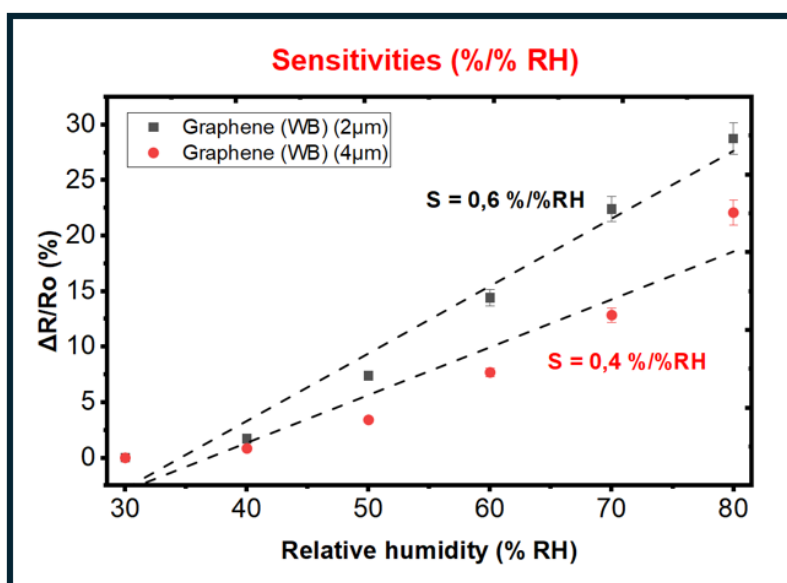


Figure 5. Effect of graphene layer thickness on humidity sensor sensitivity.

The results suggest that the thickness of the graphene layer may influence the hygrometric response of the sensor. Increasing the film thickness could modify the organization of the conductive network as well as the interactions between the sensing layer and the water molecules. A thicker layer contains a larger amount of active material, which could increase the number of potential water adsorption sites and thus amplify the resistance variation.

However, the thickness of the conductive film may also influence the diffusion of humidity through the layer. In thicker films, the penetration of water molecules could be slower or may not involve the entire film thickness, which could limit the interaction between ambient humidity and the conductive network. The sensor response may therefore result from a balance between the amount of active material and the accessibility of adsorption sites within the printed layer.

In graphene-based conductive films, the microstructure and thickness of the film play an important role in the formation of the conductive network and in the electronic transport properties. The thickness can therefore influence both the accessibility of adsorption sites and the diffusion of water molecules within the film. Consequently, variations in film thickness may lead to changes in the sensitivity of graphene-based humidity sensors. Similar mechanisms related to adsorption phenomena and charge transport in graphene-based materials have been discussed in previous studies (Borini et al., 2013), (Beniwal et al., 2023).

Further work will be necessary to better understand these mechanisms and could explore a wider range of conductive layer thicknesses to evaluate the influence of this parameter on humidity diffusion and on the electrical response of the sensors.

### 3.5. Sensor Reversibility

The reversibility of the sensors was evaluated through successive humidity cycles. The measurements show that the resistance of the devices returns to a value close to the initial resistance after each cycle, indicating that the interaction between water molecules and the sensing layer is largely reversible. These results confirm the proper functioning of the sensors and their ability to respond reproducibly to variations in relative humidity.

## 4. Conclusion

In this work, flexible resistive humidity sensors were fabricated by screen printing using different carbon-based conductive inks, and a comparative study was carried out to evaluate the influence of ink type on sensor sensitivity. The results showed that aqueous inks exhibit significantly higher sensitivities than solvent-based inks, with the highest sensitivity of approximately 0.6 %/%RH obtained for the graphene ink. This improvement can be attributed to stronger interactions between water molecules and the sensing layer, promoted by the hydrophilic nature of the aqueous medium and the structural properties of graphene.

The study also suggests that the thickness of the conductive layer may influence the hygrometric response of the sensors, indicating a potential role in water adsorption and diffusion within the sensing film.

Overall, these results highlight the potential of aqueous graphene-based inks for the development of flexible, printable, and low-cost humidity sensors. Future work will focus on systematically investigating the influence of the sensitive layer thickness, as well as the stability and reproducibility of the sensors over an extended humidity cycles and longer operating periods.

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