REVIEW

Ink-based disposable electrodes: Versatile analytical platforms for point-of-need applications

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Abstract

Ink-based disposable electrodes are emerging as promising technologies in analytical chemistry, driven by the increasing demand for on-site analysis in medical, food, and environmental sectors. Their widespread adoption is attributed to their low cost and easy fabrication. Additionally, such devices can provide fast and reliable results, making them valuable analytical tools for unprivileged communities and remote areas. This review focuses specifically on the fabrication of disposable electrodes using ink-based techniques, including stencil/screen printing and inkjet printing. It begins with an overview of ink formulation, highlighting the role of raw materials and the importance of their control in electrode fabrication processing. Subsequently, the principles, advantages, and limitations of each printing technique are discussed, demonstrating the potential and versatility of the resulting sensors in diverse analytical applications. Therefore, this work provides comprehensive insights into the fabrication of ink-based electrodes, aiming not only to consolidate the state of the art but also to encourage new approaches and technological advances in the development of accessible, versatile, and effective electrochemical sensors.

Keywords: Conductive inks, disposable electrodes, inkjet printing, point-of-need, screen-printing, electrochemical sensors.

Introduction

Disposable analytical devices have garnered significant attention due to the substantial demand for point-of-need analysis, primarily in medical, food, and environmental applications. Such popularity is attributed to their ability to provide rapid and reliable results, especially for underprivileged communities and remote locations (Pradela-Filho, et al., 2023a). Depending on the fabrication approach, disposable devices can be produced on a large scale within minutes, resulting in low-cost units (Manjushree & Adarakatti, 2023). Additionally, these devices typically yield consistent responses from batch to batch, ensuring their reliability. Consequently, disposable devices are typically designed for single-use analysis, eliminating the need for a conditioning step before use (Berkel & Özbek, 2024). Also, this minimizes the potential risk of contamination during sequential analysis. Moreover, disposable devices typically require low sample volumes, which is advantageous for biological analysis. Common examples of commercial disposable devices include pregnancy and glucose tests (Killard, 2017), which provide medical information without the need for time-consuming procedures, specialized training, and sophisticated instrumentation. Although a limited number of commercial platforms are available, their importance was reinforced by the global outbreak of COVID-19 in 2020 (de Matos Morawski et al., 2023; Rasmi et al., 2021). During the pandemic, disposable devices were crucial tools for early disease diagnosis, helping to reduce the spread by enabling timely diagnosis.

Besides medical importance, disposable electrochemical sensors have also emerged as a necessity for quantifying environmental pollutants, including pesticides, pharmaceutical compounds, and heavy metals. For example, pharmaceutical compounds are regularly discharged into residential plumbing systems, contaminating aquatic environments, such as rivers, groundwater, and lakes. These pollutants have harmful effects on human health, and increase the risk of the proliferation of drug-resistant microorganisms (Silva et al., 2024). Given the widespread use of pesticides and fertilizers in agriculture, disposable devices also serve as valuable tools for food analysis (Camargo et al., 2024). Such applicability has also been extended to the analysis of food additives, such as nitrite and sulfite (Araújo et al., 2021; Wang et al., 2017), which are substances added to food to ensure longer preservation. Another application involves evaluating the differentiation or authenticity of alcoholic beverages, such as beers, wines, and whiskey (Novakowski et al., 2011). Besides food quality control, disposable devices are attractive platforms for the quantification of illegal substances (e.g., cocaine), serving as a rapid screening test for investigative police to apprehend suspicious individuals, thereby combating criminal organizations (Cardoso et al., 2019; da Silva et al., 2018; Novais et al., 2024). In general, the development of disposable devices is closely tied to the ongoing effort to find practical, accessible, and rapid analytical solutions for real-world applications.

For point-of-need diagnostic tests, the World Health Organization (WHO) established the ASSURED criteria, which require that they be affordable, sensitive, specific, user-friendly, rapid and robust, equipment-free, and deliverable to end users (Smith et al., 2018). Despite serving as a reference for developing diagnostic tools, no current assay fully satisfies all components, with achieving an optimal combination between sensitivity and specificity posing the main challenge. In this context, research laboratories have extensively worked in this innovative field, especially developing disposable electrochemical devices. Such devices are normally operated using voltammetric, amperometric, potentiometric, and impedimetric techniques, which typically provide information (e.g., current, potential, or charge transfer resistance) related to either a redox process or a local equilibrium occurring at the

electrode surface. The resulting electrochemical signals are correlated to the analyte concentration levels, enabling the acquisition of quantitative data (Stradiotto et al., 2003).

To further document the number of publications, a search was conducted on the Web of Science database using the keyword “disposable electrodes”, and the results (Figure 1) reveal a growing number of publications from 2000 to 2024. The popularity of disposable electrochemical sensors is typically associated with the possibility of fabricating miniaturized analytical platforms through accessible alternatives (Adkins et al., 2015; Ataide et al., 2020; Dungchai et al., 2009; Nie et al., 2010; Noviana et al., 2020; Ozer & Henry, 2021). Additionally, affordable and portable instrumentation is commercially available (de Lima et al., 2025), allowing out-of-lab analysis with lab-made disposable electrochemical devices. Considering the broad field, this review article will focus exclusively on the electrode fabrication using ink-based techniques, such as stencil/screen printing and inkjet printing. First, insights into ink preparation will be discussed, highlighting the influence of raw materials and the need for controlling the processing parameters. Then, it will discuss the fundamental aspects of each technique, raising their main features, discussing their challenges, and exemplifying some analytical applications to demonstrate the versatility of the resulting sensors. Therefore, this review article will serve as valuable guidance to inspire future research and innovation in the field of electroanalysis.

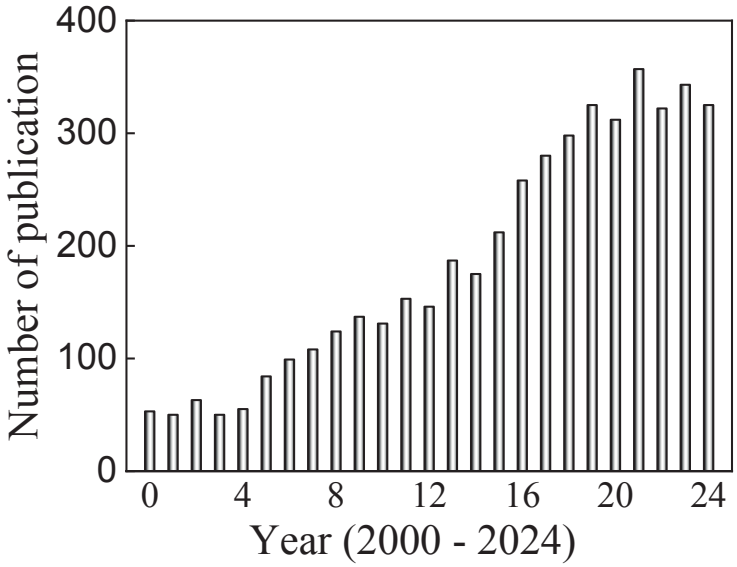


Figure 1. Graph showing the number of publications per year. The results were obtained from the Web of Science database using the keyword “disposable electrodes”.

Ink formulation overview

Formulating conductive inks typically involves dispersing conductive materials in an appropriate solvent. This solvent not only serves as the medium for dispersion but also plays a critical role in determining viscosity, flow properties, and ink storage stability (Saidina et al., 2019). To ensure adequate dispersion and good chemical stability, additional components are often incorporated into the formulation, including stabilizer agents, surfactants, and binders. One of the main concerns during the formulation step is to ensure that the final product remains cost-effective, chemically stable, and

exhibits adequate viscosity, while also providing strong adhesion to a variety of substrates. Achieving reliable adhesion is fundamental for the mechanical robustness and electrical performance of the printed materials, especially when the devices are intended for use in flexible or disposable electronic applications (Carvalho et al., 2023; Leite et al., 2025).

Conductive sources for inks

Conductive material is the main active component of the ink and determines the electrical and electrochemical properties of the electrode. Key considerations for the conductive material selection include the chemical stability of the material, the availability of a large electroactive surface area, compatibility with biomolecule immobilization or functionalization strategies, a broad operation potential window in the most aqueous solutions, and, fundamentally, the ability to ensure high electrical conductivity (Bi et al., 2019). According to the literature (Camargo et al., 2021), graphite is the most common conductive source used for ink-based electrode fabrication, as it presents lower cost, high availability, stability, low toxicity, and purity (Pradela-Filho et al., 2017, 2020). Other carbon sources include carbon nanotubes (Akindoyo et al., 2021; Bouzidi et al., 2022), carbon black (Barich et al., 2024), and carbon nanofibers (Hatala et al., 2019; Warren et al., 2013). Barich et al. investigated how variations in the composition of three commercial carbon-based conductive inks could influence the sensitivity of electrochemical sensors (Barich et al., 2024). The authors reported that a smoother electrode surface, often correlated with higher binder content and lower concentration of carbon black particles, generally leads to reduced electrochemical surface area (ECSA) and slower electron transfer kinetics. This effect is attributed to the binder's encapsulation of carbon black particles, which blocks active sites and impedes efficient electron transfer. Overall, the composition of the ink critically governs the surface roughness and morphology of the electrodes, which in turn substantially influences ECSA values. Surfaces exhibiting appropriate roughness and porosity typically provide a larger active area, thereby enhancing sensitivity and improving overall electroanalytical performance.

In the case of metal-based ink, the primary components are typically noble metal nanoparticles, such as silver, copper, and gold. Among these, copper has been the most frequently reported in the literature (Li et al., 2020; Na et al., 2019). Optimization of the metal precursor is a critical step toward obtaining inks suitable for printing patterns with high electrical conductivity. Metal precursors may be provided either as dispersions of metal nanoparticles in water, organic solvents, or water/solvent mixtures, or in the form of nanopowders (Nayak et al., 2019). Specifically, the formulation of Cu inks requires particular attention, as copper can be easily oxidized at room temperature, affecting the ink stability.

Conversely, copper is a cost-effective metal with excellent electrical conductivity, making it a promising candidate for metal-based ink formulations. Li and Chen demonstrated this potential by synthesizing a copper nanoparticle ink composed of spherical particles with an average size of 2.5 nm (Li & Chen, 2014). The enhanced particle packing density and resulting high conductivity were attributed to the small particle size and improved air stability. However, copper's tendency to oxidize remains a significant limitation, as it compromises both conductivity and long-term stability. To overcome this issue, Zhang et al. recently developed a copper-based ink with improved oxidation resistance for use in flexible printed devices (Zhang et al., 2025). Their formulation featured nanoparticles with a controlled size of 8.5 nm and demonstrated excellent antioxidant properties, representing a significant step forward in stabilizing copper-based inks for practical applications. Another metal source widely explored for ink preparation is silver particles. However, it also presents some limitations related to the pH of the medium and storage stability. In contrast, gold offers greater biocompatibility and corrosion resistance, which are highly desirable features for point-of-need applications (Camargo et al., 2021).

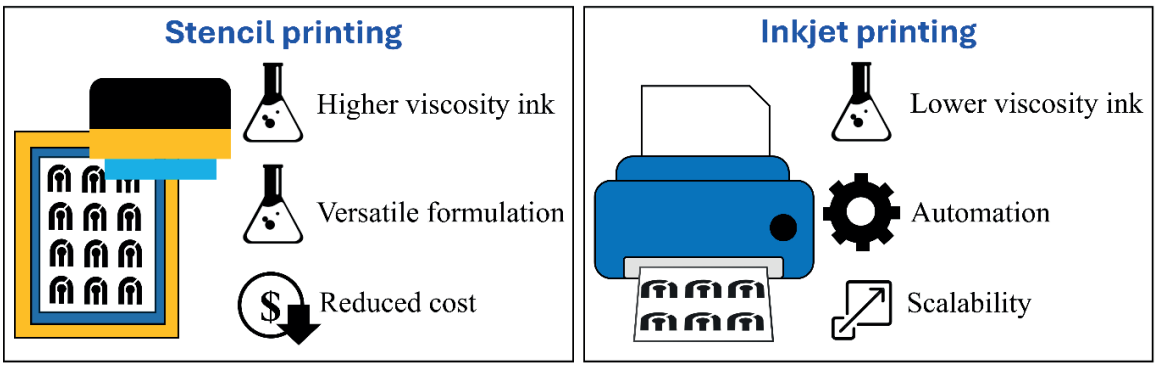
Selecting solvents and binders for conductive inks

In addition to the conductive component, selecting an appropriate solvent is an important step in ink formulation. The solvent imparts ink fluidity and significantly influences its viscosity, drying behavior, and interaction with the substrate used for electrode fabrication (Boumegnane et al., 2022). A critical factor in this process is the compatibility between the solvent and the binder, which ensures proper dispersion of the conductive material within the composite. Since most binders are based on polymers, organic solvents are commonly used to control ink viscosity. However, aqueous solvents have gained increasing attention due to their lower toxicity, greater environmental compatibility, and improved suitability for inks involving biological components (Jia et al., 2020).

For biosensing applications, the preservation of biological activity must also be considered during the ink formulation. The presence of biocompatible solvents and mild processing conditions is essential to maintain the functionality of enzymes, antibodies, or other recognition elements. Furthermore, the surface of the printed electrode should allow effective post-printing functionalization, enabling selective immobilization of biomolecules without compromising the sensor response.

Additives play a pivotal role in tuning the physicochemical properties of conductive inks and ensuring performance during processing. Thickeners also control viscosity and prevent particle sedimentation, while surfactants and dispersants enhance colloidal stability and uniform distribution of conductive materials. Binders improve adhesion and film integrity and influence layer porosity, directly affecting theelectrochemical response. Careful selection and optimization of additive type and concentration are essential, as they can impact electrical properties and sensor functionality, particularly in biosensors reliant on direct interactions between the electrode surface and immobilized biocomponents (Saquib et al., 2025).

High-viscosity inks are more suitable for techniques like screen and stencil printing (Figure 2), where pressure is applied to push the ink through a mesh or opening (Ataide et al., 2023). In these methods, higher viscosity helps define the printed pattern more clearly, prevents the ink from spreading too much, and ensures good coverage of the target area. Thicker inks also tend to form more robust and conductive films, which can be useful when durability or higher conductivity is needed (Fernandes et al., 2020). On the other hand, inkjet printing requires low-viscosity ink to allow smooth droplet formation and avoid clogging the nozzles. These lower-viscosity inks make it easier to print fine, high-resolution features. Still, if the ink is too fluid, it can lead to issues like uneven film thickness or pattern distortion. Because of this, ink formulation needs to be carefully balanced to match the printing technique specifications and avoid problems during or after deposition (Zhang & Sun, 2024).



| **Figure 2.** Examples of printing processes and comparison of their main features.

The mechanical adhesion of conductive inks to the substrate and their long-term stability are strongly influenced by the drying process. Parameters such as temperature and drying time must be optimized to enable efficient solvent evaporation and film formation without degrading the ink or substrate. Drying methods may include thermal treatment or UV light exposure, depending on the formulation and substrate characteristics (Facure et al., 2022). Particular care is required when working with heat-sensitive materials, such as flexible polymers. Substrate properties such as surface energy, wettability, and roughness significantly affect ink spreading, anchoring, and the resolution of printed features (Zhu et al., 2023). Inadequate compatibility may result in reduced print quality and lower electrochemical performance, which can negatively affect the sensitivity of the analytical method.

Despite advances in conductive inks for electrochemical sensing, some challenges remain. Sustainability is a major concern, requiring the replacement of toxic organic solvents with water-based alternatives and the use of biodegradable or recyclable materials. The development of biocompatible and “green” inks that meet regulatory standards is also critical, alongside demand for formulations compatible with portable, flexible, and disposable devices for point-of-care and wearable applications. In this sense, the literature reports numerous works looking for green alternatives to make conductive inks (Bi et al., 2023; de Freitas et al., 2023, 2026; Camargo et al., 2025; Wang et al., 2016). Advances in functional inks with antifouling, self-healing, or stimuli-responsive features also promise to improve sensor robustness, multifunctionality, and adaptability for several analytical applications.

Screen/Stencil printing

Screen printing is an advanced silkscreen printing technique that allows the transfer of a pattern to a flat surface using a mesh screen, usually made of silk or nylon. It is a low-cost, highly scalable technique that enables the use of conductive inks of different viscosities and/or characteristics (Li et al., 2022). Screen-printed electrodes (SPEs) have gained prominence due to the versatility of the screen-printing process, which is compatible with a wide range of substrates, including paper (Verma et al., 2024), textiles (Costa et al., 2025), polymers, and others (Cagnani et al., 2020). This adaptability enables the development of devices for multiple applications (Costa et al., 2025).

Stencil printing (Figure 2), a variant of screen printing, represents a simpler and cheaper approach that does not require sophisticated serigraphic equipment (Ferreira et al., 2024; Kongkaew et al., 2022). In this method, conductive inks are applied directly onto the substrate through open masks, which can be produced from a variety of low-cost materials such as adhesive films or transparency sheets. These masks define the geometry of the electrodes and fluidic structures, and their simplicity renders them inexpensive and easily adaptable for new layouts or device configurations. However, their applicability is limited by ink requirements, as higher viscosity formulations are necessary to achieve consistent and well-defined patterning and prevent spreading (Anushka et al., 2023; Ataide et al., 2020). Table 1 presents a comparison of the screen and stencil printing techniques.

Table 1. Comparative analysis of screen and stencil printing techniques, highlighting their principles, substrates, resolution, advantages, and disadvantages (Ataide et al., 2020).

Method	Screen printing	Stencil printing
Principle	Ink pressed through a stencil mask attached to a mesh/frame onto paper.	Ink applied directly through cut-out holes in a stencil.
Mask/Template	Requires dedicated mesh for each design (vinyl, films, emulsions)	Masks are easy and cheap to make (adhesive tape, transparency film)
Resolution	Higher precision; channels down to ~380 um	Lower precision; resolution limited by stencil quality and ink viscosity.
Advantages	- Wide ink variety. - Multiple fabrication is possible. - Durable electrodes when cured. - Scalable for mass production.	- Low-cost method. - Simple and fast fabrication. - No specialized equipment is needed. - Compatible with flexible/3D substrates. - Easy mask preparation.
Disadvantages	- Each new design needs a new mask. - Screen masks are expensive. - Curing adds time and complexity. - Controlled ink formulation (viscosity, adhesion). - Less practical for rapid prototyping.	- Lower resolution. - Reduced electrode durability. - Ink must have high viscosity. - Risk of non-uniform coverage. - Less reproducible results. - Shorter lifetime in aqueous media. - No ideal for complex or high-density electrode patterns.

Although stencil printing offers an accessible and low-cost alternative, its limitations in reproducibility and ink compatibility must be considered. In contrast, screen printing offers a more controlled and versatile approach, enabling higher resolution and improved durability of the fabricated devices (Stefano et al., 2022). These differences highlight the relevance of understanding the operational principles of both methods, since screen printing, despite requiring more elaborate equipment, ensures precise deposition of conductive inks and supports the scalable fabrication of point-of-need analytical devices.

The screen-printing process is divided into three distinct stages. First, the flooding stage, where the ink is spread across the mesh, filling the open areas and establishing a uniform starting volume for subsequent transfer. In the second stage, the mesh contacts the substrate through the application of downward force with the help of a squeegee. At this point, the balance of the interfacial free energies governs the ink adhesion to the mesh and the substrate and determines the initial ink distribution between both surfaces. Finally, in the third stage, the mesh is vertically lifted, inducing the ink to form filamentous structures. These filaments extend, flow, and eventually rupture once cohesive forces are overcome, resulting in partial ink deposition on the substrate while some material remains within the mesh pores (Islam et al., 2025). The screen-printing approach enables the transition from prototyping to large-scale production, as the process can be automated (Gomez-Gijon et al., 2025).

Moreover, SPEs can be functionalized with metallic or organic nanomaterials, such as enzymes, which enhance biocompatibility and enable the immobilization of biomolecules, an approach widely applied in immunosensor fabrication (Hemdan et al., 2025). In terms of application, SPEs are available in various geometries and electrode configurations, with the three-electrode system (working, reference, and auxiliary electrodes) being the most common. Their inherent versatility enables analyses with minimal sample volumes, immersion in electrolyte solutions, and the development of flexible, biocompatible, and wearable technologies (Pattan-Siddappa et al., 2025). Furthermore, SPEs are compatible with flow-batch and microfluidic systems, supporting applications in environmental, pharmaceutical, and clinical fields (Keshavarz et al., 2025).

Despite the advantages of SPEs, the fabrication process can also face some challenges because small variations in ink composition, substrate properties, or printing conditions lead to inconsistencies in sensor performance (Qi et al., 2025). Integrating multiple ink layers is technically challenging, demanding precise alignment to prevent defects such as misalignment or ink bleeding. Additionally, environmental factors such as humidity and temperature strongly influence ink viscosity, drying behavior, adhesion, and ultimately conductivity, making process control a critical parameter for achieving reliable performance (Campos-Arias et al., 2024). Besides, both equipment and operational costs may pose limitations to the widespread adoption of the technique. The process relies on the use of a mesh to define the electrochemical area of the sensor. However, the mesh could stretch with intensive use, and a new screen must be manufactured, since the deformation changes the working electrode dimensions, contributing to variability between batches and affecting the thickness and uniformity of the conductive layer. Another challenge is the risk of contamination of the working electrode by the ink used for the reference electrode, which requires thorough cleaning between steps. Environmental factors are often overlooked in reports on screen-printed electrodes. Their fabrication generates waste through the use of solvents, screens, and other materials, and their disposable nature further exacerbates concerns regarding environmental sustainability (Crapnell & Banks, 2024).

The use of specialized equipment and the incorporation of modifiers (e.g., molecularly imprinted polymers or metallic particles) have been employed to increase the reproducibility and applicability of the electrodes, although these strategies inevitably increase both cost and process complexity (Asif et al., 2025). The choice of substrate is equally critical: it must exhibit chemical and physical resistance, as its interaction with conductive inks directly influences the arrangement of conductive particles and, consequently, sensor performance. Substrate selection is also a key factor in the device's environmental sustainability. Ideally, substrates should be chemically inert, present controlled surface roughness, ensure strong ink adhesion, and, when necessary, offer flexibility (Miglione et al., 2022). Current research aims to address the limitations of resolution and material compatibility using nanoinks, hybrid printing techniques, and flexible substrates for wearable devices (Nageib et al., 2023). Other promising directions include the integration of sensors with digital platforms for real-time monitoring and sensitivity enhancement via molecular imprinting and biorecognition elements (Silveri et al., 2025).

To better exemplify the applicability of screen/stencil-printed electrodes, Table 2 summarizes recent advances in their electroanalytical applications, highlighting the predominance of carbon inks as the electrode material and their compatibility with diverse substrates. The resulting electrodes are versatile, with applicability in biological, food, and environmental applications. Additionally, such devices have been explored with different electrochemical techniques, such as chronoamperometry, DPV, impedance spectroscopy, and potentiometry.

Table 2. Screen/stencil-printed devices, used inks, substrates, detection methods and target analytes.

Sensor	Ink	Substrate	Analyte	Technique	Reference
Carbon/PVP/chitosan	CCB	Polyester	Tryptophan	DPV	(Camargo et al., 2025)
Carbon	CCGP	Glass	Escherichia Coli, Bacillus Subtilis	impedance spectroscopy	(Gopalakrishnan et al., 2025)
Carbon	CC	Polyester	alkaline phosphatase	DPV	(Kalligosfyri et al., 2025)
Carbon/PtNPS/rGO	CG	PVC	fluoride	DPV	(Verma et al., 2025)
Carbon	CC	Paper	phosphorus (phosphomolybdate)	SWV	(Seddaoui et al., 2025)
Carbon/MWCNTs	CCGP	Polyimide	pH	Potentiometry	(Milic et al., 2025)
Carbon	CGE	PVC	capsaicin	DPV	(Ferreira et al., 2024)
Carbon/AuNPs/rGO	LC	Paper	HPV 18	DPV	(Wang et al., 2025)
AuNPs/rGO/biosensor	CC	PET	IL-6, TNF-α	Chronoamperometry	(Hosseini et al., 2025)
Carbon/CuNPs	CG	Polyester	Criatinine	DPV	(Senturk et al., 2025)

CCB: Commercial Carbon Black; CCGP: Commercial Carbon graphene paste; CC: Commercial Carbon; CG: Commercial graphite; CGE: Commercial graphene; LC: Lab-made carbon.

Seddaoui et al. reported the development of an integrated paper-based electrochemical sensor, fabricated by screen-printing technique on office paper, for the determination of phosphorus in Antarctic lacustrine sediments (Seddaoui et al., 2025) (Figure 3A). Phosphorus is an essential nutrient for life that cannot be supplied through biochemical fixation and must be applied via alternative means such as commercial fertilizers. However, during this process, most of the phosphorus remains unavailable to plants, and its excess can be transported to aquatic ecosystems, leading to eutrophication. In that work, a three-electrode system was printed using commercial conductive carbon ink and modified with carbon black nanoparticles to enhance sensitivity. Phosphorus extraction from the sediment was carried out with a lab-made portable 3D-printed cartridge specifically designed for this purpose. Since phosphorus is not electroactive, the extracted analyte was passed through a filter pad preloaded with acidic ammonium molybdate to form the electroactive complex phosphomolybdate. This complex then diffuses to the electrodes, where it is oxidized and quantitatively detected using square wave voltammetry (SWV). This innovative platform demonstrated selectivity, reproducibility, and portability, highlighting the potential of screen printing on the fabrication of a sustainable point-of-need device for environmental monitoring in extreme conditions such as the Antarctic region.

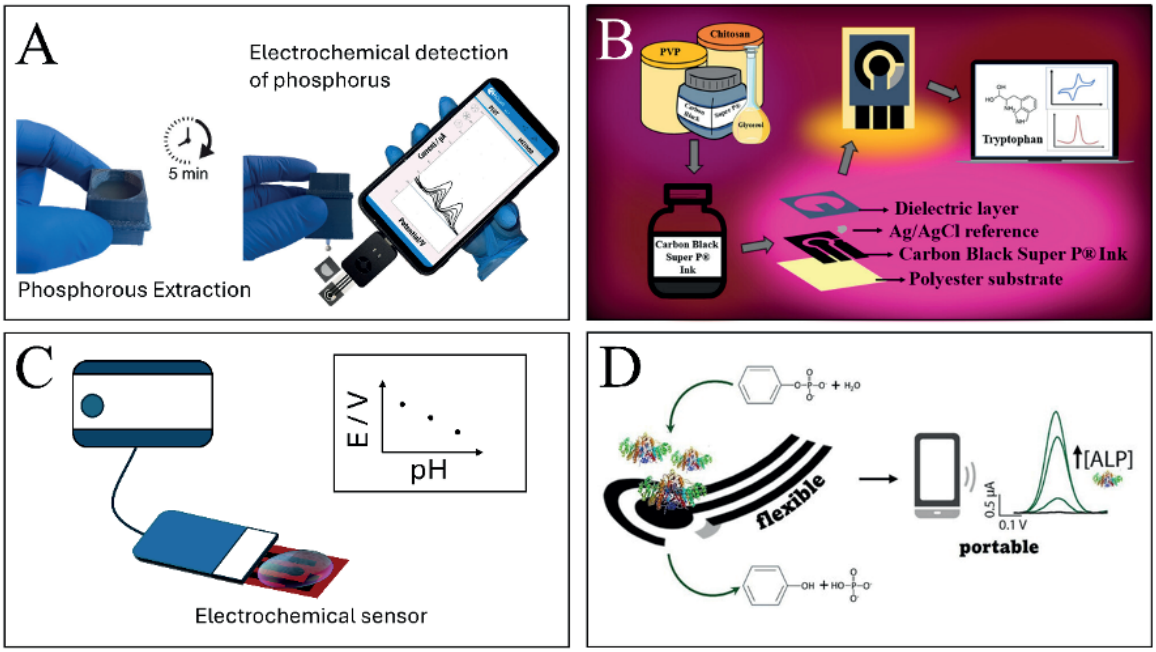


Figure 3. Applications of stencil/screen-printed electrodes; A) Integrated paper-based electrochemical sensor, fabricated by screen-printing technique on office paper, for the determination of phosphorus in Antarctic lacustrine sediments; Reproduced from (Seddaoui et al., 2025), licensed under Creative Commons CC BY 4.0. B) Screen-printed electrode system fabricated with a novel water-based conductive ink for tryptophan detection; Adapted from (Camargo et al., 2025), licensed under Creative Commons CC BY 4.0. C) Flexible screen-printed carbon-based electrode functionalized with carboxylated multiwall carbon nanotubes for portable pH environmental and biomedical monitoring; Adapted from (Milic et al., 2025), licensed under Creative Commons CC BY 4.0. D) Flexible screen-printed electrochemical sensor for alkaline phosphatase detection in biological fluids. Reproduced from (Kalligosfyri et al., 2025), licensed under Creative Commons CC BY 4.0.

Tryptophan was successfully detected by using SPE, as reported by Camargo et al. (Camargo et al., 2025). This molecule is an essential amino acid involved in several physiological processes, including neurotransmitter synthesis, regulation of mood, appetite, and sleep. The authors developed a screen-printed electrode system fabricated with a novel water-based conductive ink (Figure 3B). The ink formulation combined carbon black, poly(vinylpyrrolidone), and chitosan, yielding a homogeneous conductive layer with improved reproducibility and adhesion while eliminating the use of toxic organic solvents. The proposed electrochemical method represents a rapid and cost-effective alternative to conventional methods such as HPLC. The proposed sensor exhibits a wide linear range (0.5 – 300 µmol L^{-1}), a low detection limit of 0.0018 µmol L^{-1}, and minimal interference from common coexisting species such as ascorbic and uric acids. Validation with pharmaceutical and beverage samples resulted in recovery rates between 86.2% and 114%, confirming its applicability in real matrices.

In another study, Milic et al. reported the development of a flexible screen-printed carbon-based electrode functionalized with carboxylated multiwall carbon nanotubes for portable pH environmental and biomedical monitoring (Milic et al., 2025) (Figure 3C). More recently, Kalligosfyri et al. (Kalligosfyri et al., 2025) introduced a flexible screen-printed electrochemical sensor for alkaline phosphatase de-

tection in biological fluids (Figure 3D), achieving detection limits as low as 0.03 U/L in buffer and 0.08 U/L in serum, with reproducibility below 10%. This minimalistic design enabled real-time and point-of-care diagnostics without relying on complex surface modifications or labeling strategies (Kalligosfyri et al., 2025).

Together, these advances illustrate how stencil/screen-printing, combined with sustainable and simplified architecture, can deliver reliable, low-cost, and portable sensing platforms. Therefore, stencil/screen-printed electrodes represent highly promising platforms for electrochemical sensing, offering low cost, rapid prototyping, and versatile design (Coltro & Janegitz, 2025).

Inkjet printing

Inkjet printing has emerged as a versatile and scalable technique for electrode fabrication (Pradela-Filho et al., 2023b). This technique involves precisely depositing droplets of a conductive ink over a substrate surface to produce high-quality conductive layers. The ink deposition is digitally controlled, dispensing the need for a mask and eliminating sensor marker dependency (Shen et al., 2021; Zea et al., 2022), which is advantageous compared to stencil printing techniques. Inkjet printers normally rely on piezoelectric and thermal technologies (Pradela-Filho et al., 2023a; Sandry et al., 2023). In piezoelectric inkjet technology, an electric potential is applied to piezoelectric crystals attached to the ink chambers in the printhead. Under the influence of this potential, the crystals deform (either expand or contract), compressing the ink chamber and increasing internal pressure. This pressure forces the ink through the nozzle, ejecting droplets onto the desired substrate (Wijshoff, 2010). Thermal technology relies on a resistor to heat the ink inside the nozzle. The heat creates small bubbles of vapor, which increase pressure and eject the droplet of conductive ink. Thermal printers can reach high temperatures (~300 °C) inside the nozzles, which may compromise the integrity of sensitive biological or synthetic components in conductive inks (Setti et al., 2005). Therefore, piezoelectric inkjet technology is often chosen for heat-sensitive inks.

Conductive inks must meet specific criteria to ensure a reliable printing process. The properties include storage stability, viscosity, particle size, and surface tension (Pradela-Filho et al., 2023b). Even though the inks can be formulated using various carbon allotropes or metallic particles (Camargo et al., 2021), suspensions containing larger particles are prone to clogging the nozzles, which is a common problem encountered with the inkjet printing technique. The acceptable particle size depends on the cartridge specifications and must be carefully verified before ink production. Low-viscosity inks reduce clogging risks, facilitating the ink ejection through the nozzles (Calvert, 2001). High surface tension is essential to keep ink droplets stable in the nozzle and prevent unwanted dripping. Depending on the composition, the ink dries or precipitates over long storage periods, also leading to clogging issues. Therefore, using stable inks with optimized physical properties avoids clogging and ensures a reliable ink deposition (Van Osch et al., 2008).

Inkjet printing allows rapid prototyping of disposable electrodes. Additionally, this technique is compatible with accessible substrates, such as paper and plastic materials. Table 3 presents examples of electrochemical sensors fabricated by inkjet printing, highlighting the ink composition, substrate, analyte, and corresponding analytical technique. Table 3 shows the possibility of acquiring commercial conductive ink for electrode fabrication. Unlike lab-made inks, the commercial materials present a high cost. However, they normally offer physical properties suitable for the printing process. Among the substrates, plastic materials are widely explored, since they do not absorb the ink, eliminating

the need for depositing multiple ink layers. Table 3 also shows that the analytical applicability of the resulting devices is normally evaluated with diverse electrochemical techniques, including voltammetry, amperometry, potentiometry, and electrochemical impedance spectroscopy (EIS).

Table 3. Electrochemical sensors fabricated by inkjet printing.

Electrode	Ink	Substrate	Analyte	Technique	Reference
Ag	Commercial Silver	chromatographic paper	Paraquat	SWV	(Deroco et al., 2021)
Ag and GOD/Ag	Commercial Silver	PVC	H_2O_2, Picric acid, Glucose	LSV	(Pradela-Filho et al., 2023b)
IrOx/Pt	Lab-made Platinum	Polyethylene naphthalate	pH	Potentiometry	(Zea et al., 2019)
Au	Lab-made Gold	PET	amyloid-β42	DPV	(Sui et al., 2019)
PdAg-N-hrnGO	Lab-made PdAg-N-hrnGO	PET	H_2O_2 and Glucose	Amperometry	(Ceylan et al., 2025)
LOx/PB	Commercial Graphene	polyimide	Lactate	Amperometry	(Boček et al., 2025)
CoS	Lab-made Graphene	polyimide	Glucose	Amperometry	(Akiiga et al., 2025)
Aptamer/Ag	Commercial Silver	PET	NGAL	EIS	(Rosati et al., 2022)
DNA-functionalized	Commercial AuNPs and AgNP	PET	SARS-CoV-2	SWV	(Rossetti et al., 2024)
DNA-functionalized	Commercial AuNPs	PET	hnRNP H1	DPV	(Dai et al., 2019)

GOD: glucose oxidase; PVC: Polyvinyl chloride; IrOx: Iridium Oxide; PdAg-N-hrnGO: palladium and silver-decorated, N-doped holey graphene and nano graphene; PET: polyethylene terephthalate. MWCNTs: multi-walled carbon nanotubes; LOx/PB: lactate oxidase/ Prussian Blue; CoS: Cobalt sulfide; NGAL: neutrophil gelatinase-associated lipocalin; EIS: Electrochemical Impedance Spectroscopy; AuNPs: gold nanoparticles; AgNP: silver nanoparticles; SWV: Square wave voltammetry; DPV: Differential pulse voltammetry; hnRNP H1: heterogeneous nuclear ribonucleoprotein H1.

Deroco et al. fabricated an inkjet-printed electrochemical system (Figure 4A) for quantifying the pesticide paraquat (Deroco et al., 2021). Despite its importance in agriculture, paraquat is a highly toxic and water-soluble substance, considered a potential contaminant of aquatic systems and posing a risk to human and animal health. Such aspects highlight the need for easy-to-use and sensitive systems to quantify the paraquat concentration levels. In that work, the three-electrode electrochemical system was produced using commercial silver ink, chromatographic paper, and a piezoelectric Dimatix Materials Printer. To obtain a conductive film on the chromatographic paper substrate, four layers of ink were necessary during the printing process. After depositing each layer, the electrodes were subjected to a thermal treatment at 120 °C for 20 minutes to cure the silver ink. Hydrophobic barriers were then created on paper using wax printing, delimiting the area of the

three-electrode electrochemical system. The proposed system provided a linear range from 3.0 to 100 mol L^{-1} paraquat, with fabrication reproducibility of 7.1% for five different sensors. Additionally, the sensors showed selectivity to paraquat, enabling its quantification in human blood serum, orange juice, and water samples.

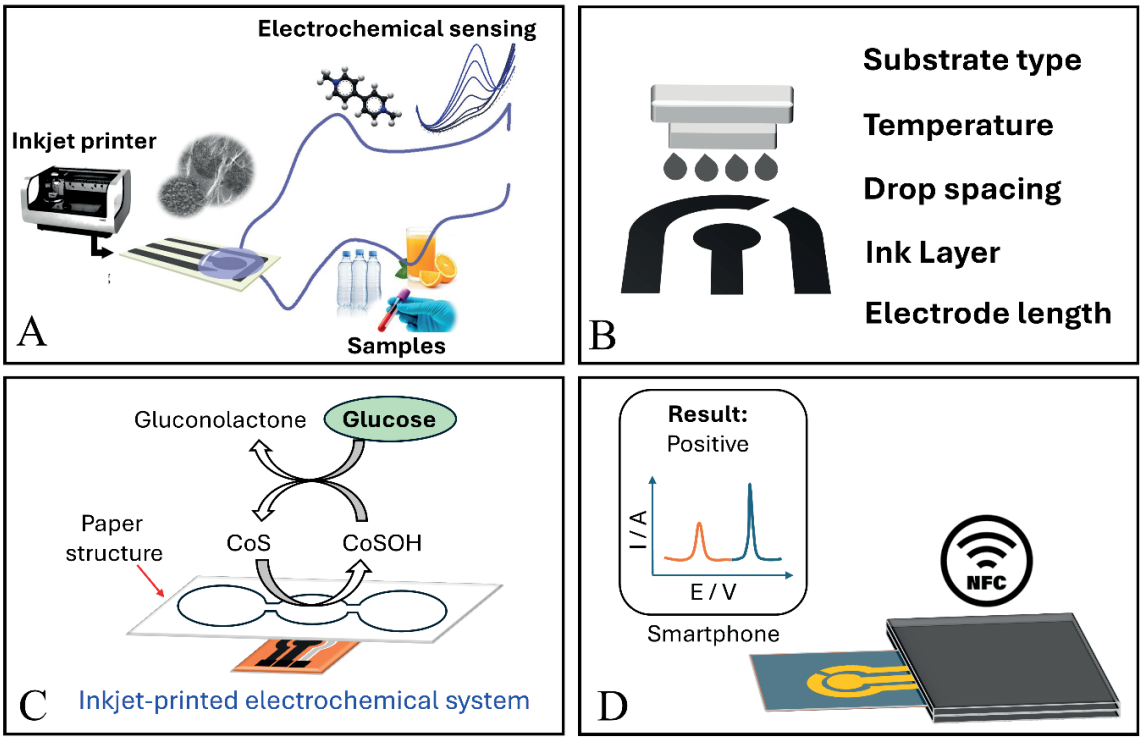


Figure 4. Examples of inkjet-printed electrochemical sensors designed for (bio) sensing applications. A) Electrochemical sensors used for the quantification of the pesticide paraquat. Reproduced with permission from Deroco et al. (Deroco et al., 2021), Chemosensors; published by MDPI, 2025. B) Controlling the inkjet printing process to fabricate electrochemical sensors for picric acid, hydrogen peroxide, and glucose quantification. Adapted from Pradela-Filho et al. (Pradela-Filho et al., 2023b), Advanced Materials Technologies, with permission of John Wiley and Sons, 2025. C) Integrating an inkjet-printed electrochemical system into a paper structure to create a microfluidic device. Figure C exemplifies the work reported by Akiiga et al. (Akiiga et al., 2025). D) Combining an inkjet-printed electrochemical sensor with an NFC potentiostat for the DNA-based multiplexed detection of SARS-CoV-2 genes. Figure D exemplifies the work reported by Rossetti et al. (Rossetti et al., 2024).

Besides the possibility of using diverse substrates (Table 3) for electrode production, another advantage of inkjet printing is the ability to control the inkjet printing process to produce electrochemical (bio) sensors. Pradela-Filho et al. (Pradela-Filho et al., 2023b) showed the influence of the printing parameters on the electrical properties of the sensing devices (Figure 4B). Initially, the printing process was evaluated with different substrates, including paper, polyimide, and polyvinyl chloride (PVC) tapes. Polyimide and PVC offered more continuous ink lines, providing better electrical conductivity to the resulting sensors. Next, the effect of the printing parameters was evaluated with PVC. The parameters included ink deposition temperature, ink drop spacing, electrode length, and

the number of ink layers. The authors observed that increasing the temperature of the printing tray makes the substrate surface flatter and facilitates the solvent evaporation, leading to narrow conductive ink lines. The decrease in the ink drop spacing enhanced film conductivity by generating more continuous ink lines. Although the number of printed layers increases the film thickness, a single ink layer was sufficient to provide suitable electrical conductivity to the resulting materials. The electrical conductivity of the conductive lines was enhanced upon decreasing the electrode length, which provided better electrochemical responses to the sensors. Under optimized conditions, three-electrode electrochemical systems showed batch-to-batch reproducibility (RSD = 3%). The analytical performance of the sensors was further evaluated for picric acid and hydrogen peroxide. In addition, the sensors were next functionalized with glucose oxidase, with their analytical applicability assessed for glucose quantification. The authors highlight that these species were selected as analytes because of their relevance in forensic and biological applications.

Considering the influence of the inkjet printing parameters, some studies also show the possibility of using the Design of Experiments (DoE) methodology to enhance the printing quality of an electrical circuit (Bucciarelli et al., 2021; Testa et al., 2025). The authors highlight that such a statistical method improves ink deposition uniformity and reduces production costs. Inkjet-printed electrodes can also be integrated with paper devices for microfluidic analysis (Figure 4C), extending their analytical applicability. Akiiga et al. (Akiiga et al., 2025) report on the combination of such systems. Initially, the authors fabricated a conductive ink by combining liquid-phase exfoliated graphene (LPEG) and cobalt sulfide (CoS). Then, the resulting ink was used to print the electrodes on flexible polyimide (Kapton) substrates. The photoresist Cytop was then applied to the electrodes as a passivation layer, enhancing the system's durability. After fabrication, a paper structure was attached to the electrochemical system, generating a microfluidic system for non-enzymatic glucose quantification. To create hydrophobic barriers on the chromatography paper, this substrate was soaked in octadecyl trichlorosilane (OTS) solution. After modification, the paper substrate was exposed to UV light using an acrylic mask, creating the desired pattern. To conduct electrochemical measurements, a 10 µL solution of NaOH (pH 13) was initially added to the paper microchannel, followed by sequential addition of artificial sweat onto the sample inlet. The injection of the analyte solution generates a signal in a stair format using amperometry. The integrated system was tested for glucose quantification, exhibiting competitive analytical parameters compared to other previously reported systems. Additionally, the proposed device exhibits high selectivity for glucose, with potential applications in glucose monitoring of biological samples. This approach highlights the versatility of inkjet-printed electrodes.

Besides offering versatility, inkjet-printed gold electrodes have also been integrated into a near-field communication (NFC) portable potentiostat (Figure 4D) for clinical diagnosis. Using this approach, Rossetti et al. (Rossetti et al., 2024) proposed an electrochemical system for the simultaneous quantification of two SARS-CoV-2 genes, the ORF1ab and the N gene. SARS-CoV-2, the coronavirus responsible for the COVID-19 pandemic, emerged in late 2019, sparking global public concern (Aliyeva et al., 2025; Murvanidze et al., 2025). The quantification strategy involved simultaneously binding a pair of antisense oligonucleotides for each gene (viral ORF1ab and the N gene). ORF1ab and N gene capture probes were first immobilized on the gold electrode. Then, redox-labeled ORF1ab and N genes act as a signal probe. In the presence of the target RNA sequences, the formation of RNA-DNA duplexes brings the attached redox probe close to the electrode surface, generating two distinct electrochemical peaks. Methylene blue and ferrocene were used as redox probes for this system, providing simultaneous results without interference. The electrochemical measurements were re-

corded using an NFC portable potentiostat connected to a smartphone, providing rapid responses (5 min) without multiprocessing steps. Additionally, the NFC potentiostat enabled electrochemical measurements with a current and voltage scale of ± 20 μA and ±0.8 V, respectively. Besides offering reliable responses, electrochemical sensors were produced at the minute scale, highlighting the ability to scale electrode fabrication using the inkjet printing technique. Therefore, this approach highlights the importance of inkjet-printed sensors in medical applications, as they could serve as rapid and cost-effective tools to assist medical specialists in decision-making.

Conclusions

Ink-based disposable electrodes represent an attractive and innovative approach for sensing purposes in a wide range of analyses. The characteristics of emerging techniques employed for their fabrication, such as screen/stencil printing and inkjet printing, including cost-effectiveness, versatility, and compatibility with various substrates, enable them to meet the requirements of point-of-need applications. In this review, we focused on stencil/screen-printed and inkjet-printed devices, discussing the fundamental aspects of the techniques, their advantages and drawbacks, innovative point-of-need applications, as well as prospective insights into strategies for ink preparation and the characteristics of raw materials.

Screen/stencil printing techniques can be used for the deposition of conductive films onto a wide range of substrates, including polymers and paper, producing chips where electrochemical measurements can be performed using small sample volumes. Furthermore, advances in the development of conductive inks, which can incorporate nanomaterials such as graphene, carbon nanotubes, metal nanoparticles, and hybrid composites, have enhanced the electrochemical performance of these devices. All these benefits, associated with the scalable potential, low-cost materials, and affordable equipment of these manufacturing techniques, have enabled electroanalysis to transition from the laboratory to on-site and point-of-need testing. Nevertheless, significant challenges still exist. For instance, screen printing still struggles to produce structures with features lower than 200 μm, and stencil printing also falls short of this, which constrains the manufacturing of miniaturized devices.

Besides being compatible with a wide range of conductive inks, including carbon, graphene, and metal nanoparticles, and suitable for various substrates such as paper, plastics, and flexible materials, inkjet printing offers the further advantages of being mask-free and precise droplet placement. Its approach enables the creation of digital pattern designs, which are hugely helpful for small batches of custom devices. The absence of mask use, provided by digitally controlled droplet placement, significantly reduces ink wastage, as it uses only the required ink volume to cover the electrode design. This also impacts the spatial printing resolution, enabling the technique to reach resolutions as fine as 10 μm. Despite these advantages, inkjet printing presents some limitations. Nozzle clogging is a common problem reported for this technique, especially when using high concentrations of dispersed particles and high-viscosity components. Additionally, printing on porous substrates, such as certain types of paper, can result in poor resolution and uneven deposition, which in turn affects conductivity.

The success of using either stencil/screen printing or inkjet printing in the fabrication of functional electrochemical devices indeed lies in the strategic formulation of conductive inks. For screen printing, focusing on the development of water-based systems, biodegradable binders, and nanomaterials derived from natural sources is key to creating safe, long-lasting, and eco-friendly biomedical

and wearable devices. Recent developments of carbon nanotubes and graphene-based inks have resulted in products with additional properties, such as viscoelastic recovery and thixotropy. It has been achieved by tailoring the combination of cellulose-based binders and solvents, such as water and terpineol.

A similar approach has recently been adopted in the development of customized inks for inkjet-printed electrodes to enhance sustainability, electrochemical performance, and printability. A significant increase in conductivity has been achieved by using the biopolymer chitosan in carbon-based inks, along with enhanced wettability and sensitivity. Improved printability was achieved by incorporating humectants into the formulation of silver nanoparticle-based inks, which demonstrated strong adhesion to smooth substrates, such as PET, and prevented clogging issues. All these advancements highlight the trend toward more eco-friendly, reliable, and high electrochemical performance inkjet-printed electrodes.

Looking even further ahead, future trends will focus on the integration of both printing technologies in order to combine their particular advantages. For instance, using stencil/screen printing for bulk electrode structures while inkjet printing can be used for fine-patterned functionalization and localized biomolecule immobilization. In addition, promising approaches are expected in the direction of the development of calibration-free devices, ratiometric detection strategies, and wireless data acquisition modules to enable fully autonomous, user-friendly point-of-care devices. As manufacturing protocols become standardized and compliant with required regulations, these printed electrodes will be fundamental to the next generation of portable diagnostic systems, enabling rapid, multiplexed, and cost-effective healthcare solutions.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

The authors declare that the data supporting the findings of this study are available within the paper.

Ethics committee approval

Ethics committee approval is not required for this study.

Authors' contribution statement

The authors acknowledge their contributions to this paper as follows: **Study conception and design**: GJSJ, RMR, WBV, LAPF, TRLCP; **Manuscript draft preparation**: GJSJ, RMR, WBV, LAPF, TRLCP; **Final manuscript revision:** LAPF, TRLCP. All authors reviewed the manuscript and approved the final version of the manuscript.

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