

# Role of Metal Oxide Nanoparticles in Improving Carbon Paste Electrodes for Organic Compound Analysis

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**Abstract:** Metal oxide nanoparticles have emerged as promising modifiers for improving the analytical performance of carbon paste electrodes in the electrochemical determination of organic compounds. Conventional carbon paste electrodes offer advantages such as low cost, simple fabrication, renewable surfaces, and compatibility with different modifiers; however, their sensitivity and selectivity may be limited when analyzing compounds present at low concentrations or in complex sample matrices. Incorporating metal oxide nanoparticles, including iron oxide ( $Fe_3O_4$ ), zinc oxide (ZnO), titanium dioxide ( $TiO_2$ ), nickel oxide (NiO), and copper oxide (CuO), can improve electrode surface properties, electrocatalytic activity, and electron-transfer behavior.

**Keywords:** Metal Oxide Nanoparticles, Carbon Paste Electrode, Electrochemical Analysis, Organic Compounds, Voltammetry.

## I. INTRODUCTION

Electrochemical analytical methods play an important role in pharmaceutical quality control, food analysis, environmental monitoring, and chemical research. The detection of organic compounds is particularly significant because many substances, including phenols, aromatic amines, antioxidants, pharmaceutical ingredients, and pesticide residues, can affect human health, food quality, and environmental safety. Conventional analytical techniques such as high-performance liquid chromatography, gas chromatography, and spectrophotometry provide valuable analytical information, but they may require expensive instrumentation, extensive sample preparation, and specialized operating procedures. Electrochemical techniques offer an alternative by enabling rapid measurements with relatively simple equipment and the potential for portable analysis.

Carbon paste electrodes are widely investigated because they are prepared by mixing conductive carbon powder with a suitable binder, commonly a nonconductive oil. Their surface can be renewed by removing and replacing the paste, making them convenient for repeated experiments. Moreover, the composition of the paste can be adjusted by incorporating nanomaterials, polymers, ionic liquids, or other functional modifiers. A comprehensive review of nanomaterial-based carbon paste electrodes describes their applications across pharmaceutical analysis, biological compounds, and environmental monitoring.

Metal oxide nanoparticles are particularly useful because their physicochemical properties depend on particle size, morphology, surface chemistry, and composition. When appropriately incorporated into carbon paste, these materials can provide additional electroactive sites, influence adsorption of target molecules, and promote electron-transfer reactions. Their effectiveness, however, depends on the analyte, electrode formulation, electrolyte, and experimental conditions. Consequently, selecting an appropriate metal oxide modifier is essential for developing a reliable analytical method.

### **METAL OXIDE NANOPARTICLES AND THEIR ROLE IN ELECTRODE MODIFICATION**

Metal oxide nanoparticles are nanoscale materials composed of metal cations and oxygen anions. Common examples used in electrochemical sensing include  $\text{Fe}_3\text{O}_4$ ,  $\text{ZnO}$ ,  $\text{TiO}_2$ ,  $\text{NiO}$ ,  $\text{CuO}$ , and manganese oxides. Their value in electrode modification arises from their surface activity, chemical stability, adsorption characteristics, and, in some cases, catalytic or semiconducting properties.

Iron oxide nanoparticles, particularly  $\text{Fe}_3\text{O}_4$ , can improve the electrochemical response of selected organic compounds by facilitating interfacial electron transfer and providing active surface sites. In a study published in *Micromachines*, Pwavodi et al., (2021) developed an  $\text{Fe}_3\text{O}_4$  nanoparticle-modified carbon paste electrode for determining sinapic acid, syringic acid, and rutin. The study reported detection limits of  $(2.2 \times 10^{-7})$  M,  $(2.6 \times 10^{-7})$  M, and  $(0.8 \times 10^{-7})$  M, respectively, using differential pulse voltammetry.

Zinc oxide nanoparticles are attractive because of their surface properties and compatibility with composite materials. When combined with conductive carbon materials,  $\text{ZnO}$  can contribute to the recognition and electrochemical determination of selected organic molecules. Titanium dioxide nanoparticles may offer chemical stability and surface adsorption properties, although their electrical conductivity is generally limited and may require combination with conductive components. Nickel oxide and copper oxide can exhibit useful redox and catalytic behavior, making them potential modifiers for compounds whose electrochemical oxidation is otherwise slow or poorly resolved.

The effectiveness of each material depends on its dispersion and interaction with the carbon matrix. Excessive nanoparticle loading can increase aggregation, block conductive pathways, and reduce the accessible electrode surface. Therefore, nanoparticle concentration and paste composition must be optimized rather than assuming that a greater amount of modifier will always improve analytical performance.

### **MECHANISMS OF PERFORMANCE IMPROVEMENT**

Metal oxide nanoparticles can improve the analytical response of carbon paste electrodes through several interconnected mechanisms.

**Enhanced electron transfer:** Certain metal oxides promote interfacial charge transfer or facilitate redox reactions involving organic analytes. This may increase peak current and improve the visibility of electrochemical signals. The magnitude of improvement depends on the electrical properties of the oxide, its contact with carbon particles, and the electrochemical reaction being studied.

**Increased active surface area:** Nanoparticles may introduce additional electrochemically accessible sites. A larger accessible surface can increase analyte interaction and improve signal intensity, provided that the particles remain well dispersed within the paste.

**Improved adsorption and preconcentration:** Surface hydroxyl groups, defects, and other chemical functionalities can influence the adsorption of organic molecules. This can be particularly useful for phenolic compounds and other analytes that interact with oxide surfaces. However, excessive adsorption may cause electrode fouling or incomplete recovery between measurements.

**Catalytic activity:** Some metal oxides facilitate the oxidation or reduction of target compounds, potentially lowering the required overpotential and improving peak separation. This property can help distinguish compounds with similar electrochemical behavior, although selectivity must be experimentally verified.

**Improved analytical selectivity:** Combining metal oxide nanoparticles with carbon nanomaterials, polymers, or molecularly imprinted materials can modify the electrode's chemical affinity for particular analytes. Such composite electrodes may offer better discrimination in mixtures than an unmodified electrode, but selectivity depends on the complete electrode formulation rather than the metal oxide alone.

These mechanisms are commonly evaluated using cyclic voltammetry, differential pulse voltammetry, and electrochemical impedance spectroscopy. CV helps characterize redox behavior, DPV supports sensitive quantitative measurements, and EIS provides information about interfacial charge-transfer resistance. The combined use of these techniques can help establish whether the modifier produces a genuine analytical improvement.

## APPLICATIONS IN ORGANIC COMPOUND ANALYSIS

### 1. Phenolic compounds and antioxidants

Phenolic compounds occur in foods, beverages, plant extracts, industrial wastewater, and pharmaceutical preparations. Their electrochemical behavior makes them suitable targets for modified electrode analysis.  $\text{Fe}_3\text{O}_4$  nanoparticle-modified carbon paste electrodes have been investigated for the simultaneous or individual determination of phenol derivatives and natural antioxidants. In particular, Pwavodi et al. (2021) demonstrated the determination of sinapic acid, syringic acid, and rutin in wine samples using DPV. This application illustrates the potential of modified electrodes for food analysis and antioxidant measurement.

### 2. Pharmaceutical compounds

Many pharmaceutical compounds contain electroactive functional groups that can be detected through oxidation or reduction reactions. Modified carbon paste electrodes have been applied to the analysis of compounds such as levodopa, tyrosine, and other pharmaceutical or biologically relevant substances. A broad review of nanomaterial-based carbon paste electrodes documents applications involving pharmaceutical compounds and describes the use of several electrochemical techniques.

Metal oxide modifiers may improve sensitivity in suitable systems, but the performance of each specific metal oxide must be confirmed experimentally for the pharmaceutical compound under investigation.

### 3. Environmental organic pollutants

Phenol derivatives, including catechol and hydroquinone, are important environmental analytes because they may occur in industrial effluents and contaminated water. A 2025 publication in Microchemical Journal investigated a  $\text{NiO}$  nanoparticle-modified carbon paste electrode for the voltammetric simultaneous determination of catechol and hydroquinone. The reported work highlights the continuing interest in nanoparticle-modified electrodes for resolving closely related organic pollutants.

## FOOD AND BEVERAGE QUALITY ASSESSMENT

Modified carbon paste electrodes can provide a practical approach to screening electroactive compounds in wine, beverages, and other food matrices. Their potential advantages include relatively simple preparation, small sample requirements, and compatibility with portable electrochemical instruments. Nevertheless, matrix components may interfere with measurements, so recovery experiments, standard-addition procedures, and comparison with validated reference methods are important before routine application.

## COMPARATIVE REVIEW OF METAL OXIDE NANOPARTICLES

Table 1 summarizes representative metal oxide modifiers, their expected contributions to electrode performance, and potential applications. The mechanisms listed for  $\text{ZnO}$ ,  $\text{TiO}_2$ ,  $\text{NiO}$ , and  $\text{CuO}$  are general material-based expectations; they should not be interpreted as identical experimental outcomes for every carbon paste formulation.

Table 1. Metal oxide nanoparticles used or investigated for improving carbon paste electrodes

| Metal oxide modifier                   | Potential contribution                                                             | Suitable organic analytes or applications                    | Important consideration                           |
|----------------------------------------|------------------------------------------------------------------------------------|--------------------------------------------------------------|---------------------------------------------------|
| Iron oxide ( $\text{Fe}_3\text{O}_4$ ) | Interfacial electron transfer, surface interactions, and improved current response | Phenolic compounds, rutin, sinapic acid, syringic acid       | Particle dispersion and oxidation-state stability |
| Zinc oxide ( $\text{ZnO}$ )            | Surface adsorption and modification of electrochemical response                    | Selected phenolic compounds and pharmaceutical analytes      | Conductivity and compatibility with carbon        |
| Titanium dioxide ( $\text{TiO}_2$ )    | Chemical stability and surface interaction with analytes                           | Selected pharmaceuticals and electroactive organic compounds | Often benefits from a conductive composite        |
| Nickel oxide                           | Redox activity and improved                                                        | Catechol, hydroquinone, and                                  | Background current and                            |

|                    |                                                                |                                                     |                                                  |
|--------------------|----------------------------------------------------------------|-----------------------------------------------------|--------------------------------------------------|
| (NiO)              | voltammetric discrimination in suitable systems                | related phenolic pollutants                         | electrode fouling                                |
| Copper oxide (CuO) | Potential electrocatalytic activity and surface redox behavior | Selected electroactive organic compounds            | Chemical stability and possible interference     |
| Manganese oxides   | Surface redox activity and adsorption-dependent responses      | Selected phenolic and other electroactive compounds | Strong dependence on oxide phase and electrolyte |

Source basis: George et al., (2018), the carbon paste electrode review by Nguyen et al., (2020), Pwavodi et al., (2021), and the NiO-modified electrode study published in 2025. The table synthesizes material properties and reported application areas rather than presenting a head-to-head experimental comparison.

**Table 2. Representative experimental findings from published studies**

| Study                             | Electrode modifier or approach                                              | Target compounds                                                  | Analytical method or key finding                                                                                               |
|-----------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|
| George et al. (2018)              | Review of metal oxide nanoparticles and composites                          | Chemical and biochemical species                                  | Reviewed nanoparticle properties and electrochemical sensing applications                                                      |
| Nguyen et al. (2020)              | Review of nanomaterial-based carbon paste electrodes                        | Pharmaceuticals, biological compounds, and environmental analytes | Summarized sensor materials, methods, and analytical applications                                                              |
| Dang et al. (2020)                | Fe <sub>3</sub> O <sub>4</sub> -modified carbon paste electrode             | Phenol, nitrophenols, and chlorinated phenols                     | DPV combined with partial least-squares calibration for simultaneous determination of six phenolic compounds                   |
| Pwavodi et al. (2021)             | Fe <sub>3</sub> O <sub>4</sub> nanoparticle-modified carbon paste electrode | Sinapic acid, syringic acid, and rutin                            | DPV; reported detection limits of $(2.2 \times 10^{-7})$ , $(2.6 \times 10^{-7})$ , and $(0.8 \times 10^{-7})$ M, respectively |
| Achache et al. (2025 publication) | NiO nanoparticle-modified carbon paste electrode                            | Catechol and hydroquinone                                         | Investigated simultaneous voltammetric detection in environmental samples                                                      |

The comparison indicates that Fe<sub>3</sub>O<sub>4</sub>-modified carbon paste electrodes have demonstrated applications in both natural phenolic compounds and mixtures of environmental pollutants. The reported work by Dang et al. (2020) is particularly relevant because combining DPV with multivariate calibration can help distinguish overlapping signals in complex mixtures.

The studies should not be interpreted as proving that one metal oxide is universally superior; meaningful comparisons require consistent experimental conditions and the same target analytes.

## II. CONCLUSION

Metal oxide nanoparticles offer a promising approach to improving carbon paste electrodes for the electrochemical analysis of organic compounds. Their contributions may include enhanced electron-transfer behavior, additional active surface sites, improved adsorption, and catalytic effects. Fe<sub>3</sub>O<sub>4</sub>-modified carbon paste electrodes have demonstrated practical applications in the determination of natural phenolic compounds and environmental phenol derivatives, while NiO-modified electrodes have been investigated for the simultaneous determination of catechol and hydroquinone. However, analytical performance depends on the specific metal oxide, its concentration and dispersion, the carbon paste composition, and the chemical properties of the analyte. Challenges related to reproducibility, electrode fouling, selectivity, and real-sample interference must be addressed before widespread routine use. Future advances in hybrid

nanomaterials, chemometric analysis, standardized fabrication, and portable instrumentation could strengthen the role of these electrodes in food quality assessment, pharmaceutical analysis, and environmental monitoring.

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