

Full Paper

Electrochemical Behavior of Glucose in Neutral Medium: Effect of TiO₂ Modified Carbon Paste Electrodes and Metal Ion Additives for Table Sugar Production

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Abstract- This study investigates the electrochemical behavior of glucose in a neutral medium (1 M NaCl) using modified carbon paste electrodes (CPE) containing different percentages of titanium dioxide (TiO₂). The influence of metal ion additives (1% Mg²⁺ and 1% Cr²⁺) on the redox behavior of glucose was also examined to explore potential formulations for novel table sugar products. Electrochemical techniques, including cyclic voltammetry (CV), polarization curves, and electrochemical impedance spectroscopy (EIS) were employed. Results show that the incorporation of TiO₂ into the carbon paste electrodes significantly enhances the electrochemical response toward glucose oxidation, with the CPE 50% TiO₂/50% carbon paste composition showing optimal performance. The addition of Mg²⁺ and Cr²⁺ ions further modified the electrochemical behavior, with Cr²⁺ demonstrating the most substantial enhancement in current density and reduced charge transfer resistance. These findings provide valuable insights for developing modified electrodes for glucose sensing and suggest potential pathways for creating enhanced table sugar formulations with improved electrochemical properties.

Keywords- Glucose electrochemistry; Carbon paste electrode; Titanium dioxide; Metal ion additives; Electrochemical impedance spectroscopy; Cyclic voltammetry; Table sugar formulation

1. INTRODUCTION

Glucose is one of the most abundant and important carbohydrates, serving as a primary energy source in biological systems and finding widespread applications in food industries, particularly in table sugar production [1]. Understanding the electrochemical behavior of glucose provides valuable insights for developing glucose sensors, energy conversion systems, and potentially novel food formulations [2,3]. Traditional carbon electrodes have been widely used for glucose detection; however, their sensitivity and selectivity are often limited [4].

Modification of carbon electrodes with metal oxides has emerged as an effective strategy to enhance electrochemical performance [5,6]. Among various metal oxides, titanium dioxide (TiO_2) has attracted significant attention due to its excellent catalytic properties, chemical stability, biocompatibility, and environmental friendliness [7,8]. TiO_2 can facilitate electron transfer processes and provide more active sites for glucose oxidation, potentially improving the sensitivity and performance of glucose detection systems [9].

Furthermore, the addition of metal ions such as Mg^{2+} and Cr^{2+} to glucose solutions can potentially alter the electrochemical behavior of glucose by influencing its interaction with electrode surfaces or by participating in the electron transfer processes [10,11]. This could have implications for both sensing applications and the development of modified sugar formulations with enhanced properties for table sugar production.

This study aims to investigate the electrochemical behavior of glucose in a neutral medium (1 M NaCl) using carbon paste electrodes modified with different percentages of TiO_2 . Additionally, the effect of adding 1% Mg^{2+} and 1% Cr^{2+} on the electrochemical response of glucose is examined to explore potential applications in developing novel table sugar formulations. Various electrochemical techniques, including cyclic voltammetry, polarization curves, and electrochemical impedance spectroscopy, were employed to comprehensively characterize the electrochemical behavior under different conditions.

2. EXPERIMENTAL SECTION

2.1. Reagents and materials

The chemicals used in this work were of analytical grade. Graphite (99%, Merck), Glucose ($\text{C}_6\text{H}_{12}\text{O}_6$, 99%, Merck), titanium dioxide (TiO_2 , 99%, Merck), and sodium chloride (NaCl, 99%, Merck) were purchased and used without further purification. Magnesium and chromium salts (analytical grade, 99%, Merck) were used as sources of Mg^{2+} and Cr^{2+} ions, respectively. All solutions were prepared using distilled water.

2.2. Apparatus

A thermostatically controlled three-electrode cell was used for all electrochemical measurements. The cell was equipped with an Ag/AgCl reference electrode, an auxiliary

electrode using a 1 cm² platinum plate, and the prepared carbon paste electrode (CPE) or TiO₂-modified CPE as the working electrode. Electrochemical measurements, including cyclic voltammetry (CV), polarization curves, and electrochemical impedance spectroscopy (EIS), were carried out at room temperature using a Voltalab potentiostat (PGZ 100).

2.3. Preparation of modified carbon paste electrodes

Four different compositions of carbon paste electrodes were prepared:

1. CPE 100% (pure carbon paste)
2. CPE 75%/TiO₂ 25% (75% carbon paste, 25% TiO₂)
3. CPE 50%/TiO₂ 50% (50% carbon paste, 50% TiO₂)
4. CPE 25%/TiO₂ 75% (25% carbon paste, 75% TiO₂)

For each composition, the appropriate amounts of carbon powder and TiO₂ were thoroughly mixed to form a homogeneous paste. The resulting paste was packed into a cylindrical plastic cavity and attached to a carbon graphite rod to ensure electrical contact. Prior to measurements, the electrode was rinsed with double-distilled water and then immersed in the electrolytic solution.

2.4. Electrochemical measurements

All electrochemical measurements were performed in a 1 M NaCl solution (neutral medium) at room temperature. Cyclic voltammetry was conducted at a scan rate of 100 mV/s within a potential window of -1.5 V to +1.5 V vs. Ag/AgCl. For glucose measurements, 0.08 M glucose was added to the electrolyte solution. The effects of metal ion additives were studied by adding 1% Mg²⁺ or 1% Cr²⁺ to the glucose-containing electrolyte.

Polarization curves were recorded to determine the corrosion parameters. Electrochemical impedance spectroscopy (EIS) measurements were performed in the frequency range of 100 kHz to 10 mHz with an amplitude of 10 mV at the open circuit potential (OCP).

3. RESULTS AND DISCUSSION

3.1. Electrochemical characterization of TiO₂-modified CPEs

3.1.1. Cyclic voltammetry

Figure 1 shows the cyclic voltammograms of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1 M NaCl solution. The unmodified CPE (100%) exhibited minimal electrochemical activity within the studied potential range, with a small anodic current observed at potentials above 1.0 V.

The introduction of TiO₂ into the carbon paste significantly enhanced the electrochemical response. The CPE 75%/TiO₂ 25% electrode showed increased current densities in both anodic

and cathodic regions compared to the unmodified electrode. As the TiO₂ content increased to 50%, the current response further improved, particularly in the anodic region around 1.0 V, suggesting enhanced electron transfer capabilities. However, when the TiO₂ content was increased to 75%, a slight decrease in current density was observed, indicating that an excessive amount of TiO₂ might hinder electron transfer due to the semi-conductive nature of TiO₂.

The enhancement in electrochemical activity with TiO₂ modification can be attributed to the following factors:

1. Increased active surface area provided by TiO₂ nanoparticles
2. Catalytic properties of TiO₂ for electrochemical reactions
3. Improved electron transfer kinetics at the electrode/electrolyte interface

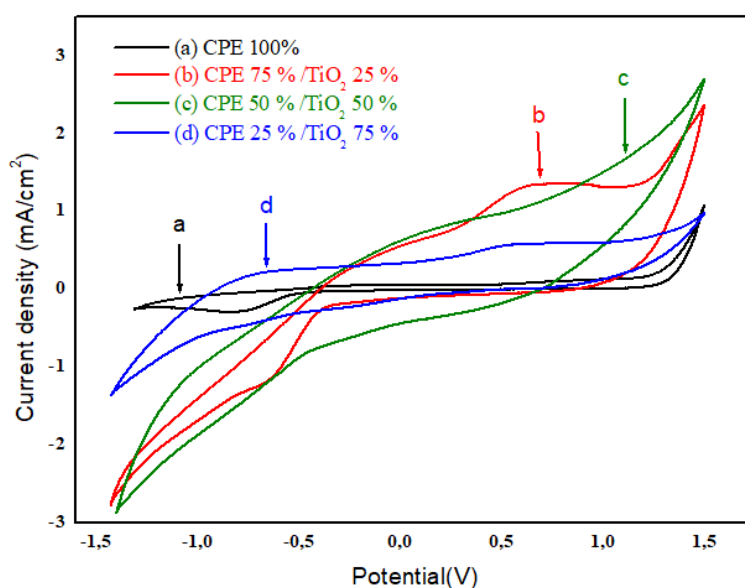


Figure 1. Cyclic voltammograms of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1 M NaCl solution

3.1.2. Polarization curves

The polarization curves (Figure 2) provide insights into the corrosion behavior of the different electrode compositions. The unmodified CPE showed a relatively narrow potential range with moderate current densities. With increasing TiO₂ content, the electrodes exhibited broader potential ranges and higher current densities, suggesting enhanced electrochemical activity. The CPE 50%/TiO₂ 50% electrode demonstrated an optimal combination of corrosion resistance and electrochemical activity, as evidenced by its well-defined polarization curve and moderate corrosion potential.

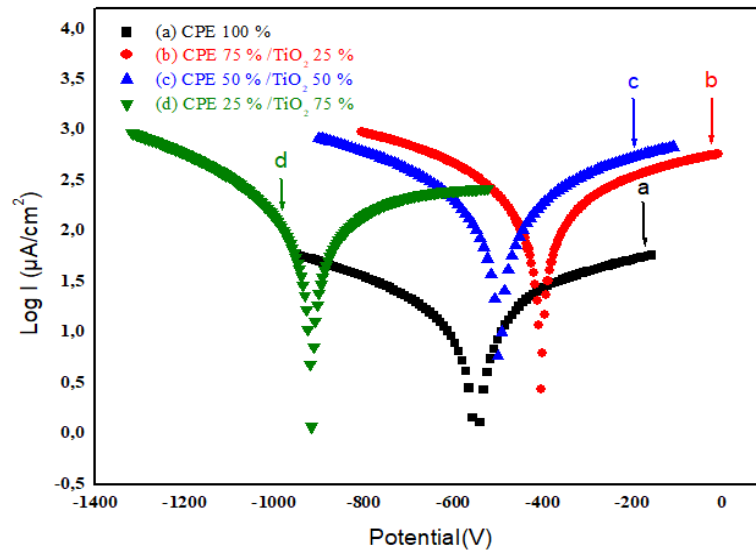


Figure 2. Tafel plots of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1M NaCl solution

3.1.3. Electrochemical impedance spectroscopy

EIS measurements (Figure 3) revealed significant differences in the impedance characteristics of the various electrode compositions. The Nyquist plots showed decreasing semicircle diameters with increasing TiO₂ content, indicating reduced charge transfer resistance. The CPE 50%/TiO₂ 50% and CPE 25%/TiO₂ 75% electrodes exhibited the lowest charge transfer resistances, confirming their enhanced electron transfer capabilities. The improved conductivity with TiO₂ modification can be attributed to the formation of conductive pathways within the carbon paste matrix, facilitating electron movement through the electrode material.

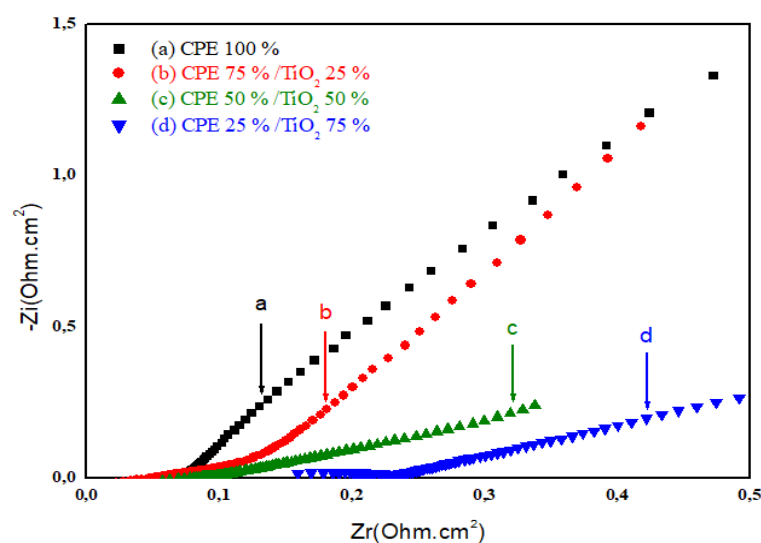


Figure 3. EIS diagrams of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1 M NaCl solution

3.2. Electrochemical behavior of glucose

3.2.1. Cyclic voltammetry of glucose on different electrodes

Figure 4 presents the cyclic voltammograms of 0.08 M glucose in 1M NaCl solution on the different electrode compositions. The unmodified CPE showed minimal response to glucose, with only a slight increase in anodic current at potentials above 1.0 V, indicating poor glucose oxidation kinetics.

The TiO₂-modified electrodes exhibited significantly enhanced responses to glucose. The CPE 75%/TiO₂ 25% electrode showed distinct redox peaks associated with glucose oxidation/reduction processes. The CPE 50%/TiO₂ 50% electrode demonstrated the highest current densities for glucose oxidation, with well-defined anodic peaks around 1.0 V. The CPE 25%/TiO₂ 75% electrode showed moderate activity, confirming that an optimal TiO₂ content is necessary for maximizing glucose detection performance.

The enhanced glucose oxidation on TiO₂-modified electrodes can be explained by:

1. Increased adsorption of glucose molecules on the TiO₂ surface
2. Catalytic effect of TiO₂ on glucose oxidation
3. Formation of surface complexes that facilitate electron transfer

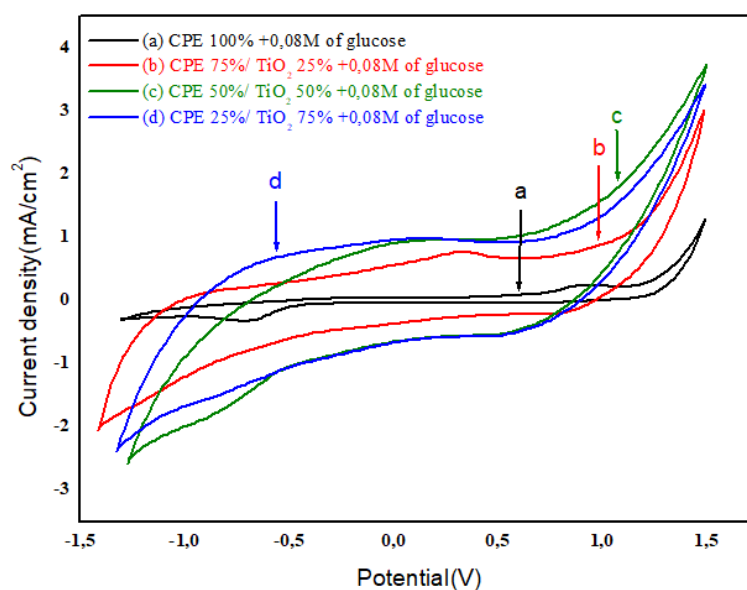


Figure 4. Cyclic voltammograms of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1M NaCl solution containing 0.08M of glucose

3.2.2. Polarization behavior in glucose solution

The polarization curves in glucose-containing electrolyte (Figure 5) showed distinct differences compared to the base electrolyte. The presence of glucose led to changes in

corrosion potentials and current densities for all electrode compositions. The TiO₂-modified electrodes exhibited more pronounced shifts in corrosion potentials, indicating stronger interactions with glucose molecules. The CPE 50%/TiO₂ 50% electrode showed the most favorable polarization behavior, with a well-defined transition from cathodic to anodic regions and moderate corrosion current.

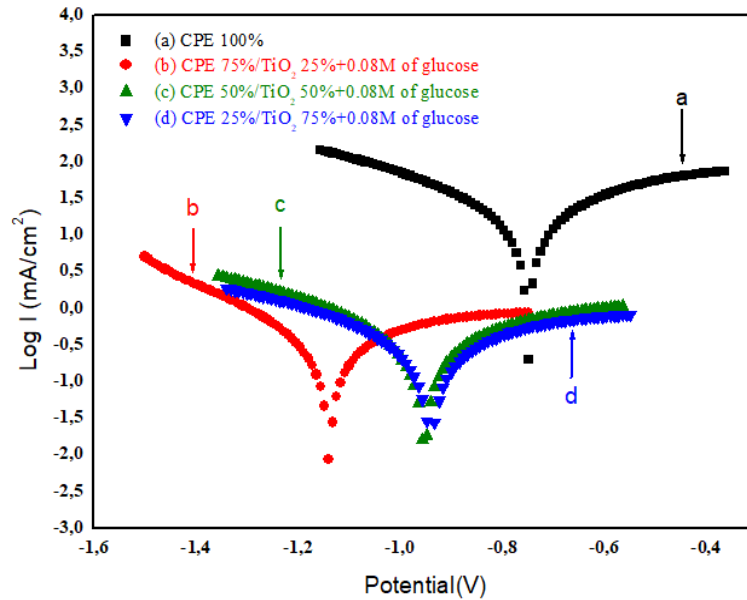


Figure 5. Tafel plots of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1M NaCl solution containing 0.08M of glucose

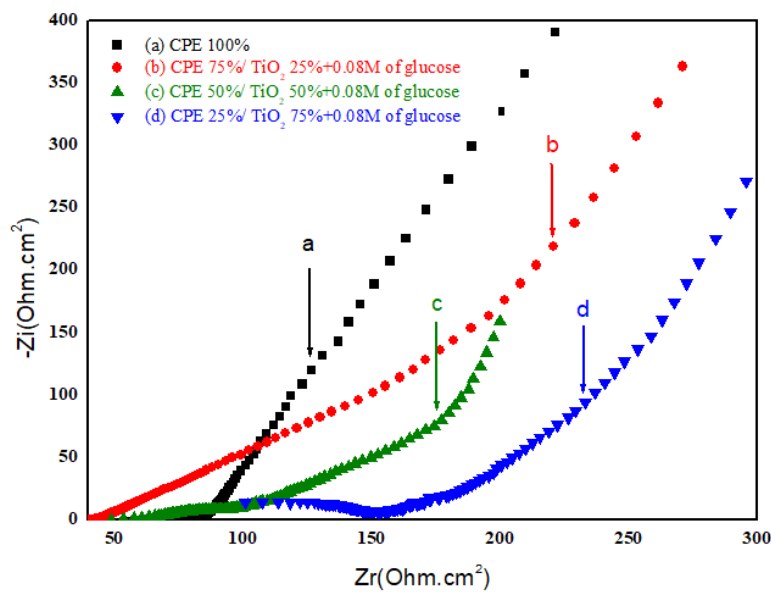


Figure 6. EIS diagrams of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1M NaCl solution containing 0.08M of glucose

3.2.3. Impedance characteristics in glucose solution

The EIS measurements in glucose solution (Figure 6) revealed significant changes in impedance characteristics compared to the base electrolyte. The charge transfer resistances decreased for all electrode compositions in the presence of glucose, indicating facilitated electron transfer processes. The CPE 75%/TiO₂ 25% and CPE 50%/TiO₂ 50% electrodes showed the most pronounced decreases in charge transfer resistance, suggesting optimal interaction with glucose molecules. The observed changes in Nyquist plots confirm the electrocatalytic activity of TiO₂-modified electrodes toward glucose oxidation.

3.3. Effect of metal ion additives on glucose electrochemistry

3.3.1. Influence of Mg²⁺ addition

The addition of 1% Mg²⁺ to the glucose solution resulted in notable changes in the electrochemical behavior (Figure 7). The cyclic voltammograms showed increased current densities for all electrode compositions, with the CPE 75%/TiO₂ 25% electrode exhibiting the most pronounced enhancement. The anodic peak corresponding to glucose oxidation shifted to slightly lower potentials, suggesting facilitated oxidation kinetics in the presence of Mg²⁺.

The EIS measurements (Figure 8) confirmed the positive influence of Mg²⁺ on glucose electrochemistry. The charge transfer resistances decreased significantly for all electrodes, particularly for the CPE 75%/TiO₂ 25% and CPE 50%/TiO₂ 50% compositions. This suggests that Mg²⁺ ions may mediate electron transfer between glucose molecules and the electrode surface, possibly by forming complexes with glucose that are more electroactive.

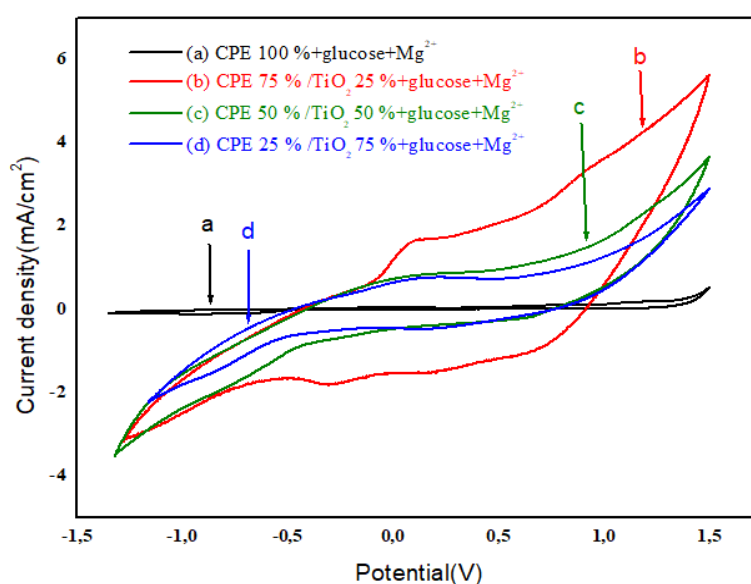


Figure 7. Cyclic voltammograms of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1M NaCl solution containing 0.08M of glucose and 1% Mg²⁺

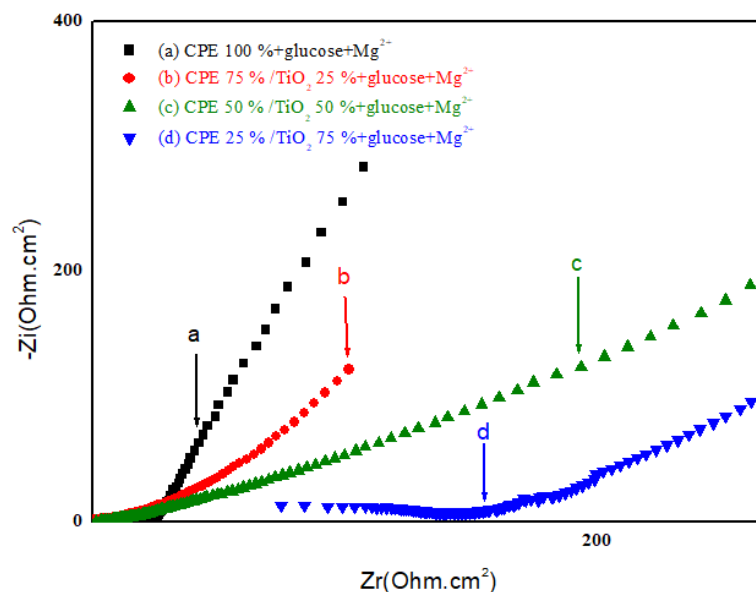


Figure 8. E of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1M NaCl solution containing 0.08M of glucose and 1% Mg²⁺

3.3.2. Influence of Cr²⁺ addition

The addition of 1% Cr²⁺ had an even more profound effect on the electrochemical behavior of glucose (Figure 9).

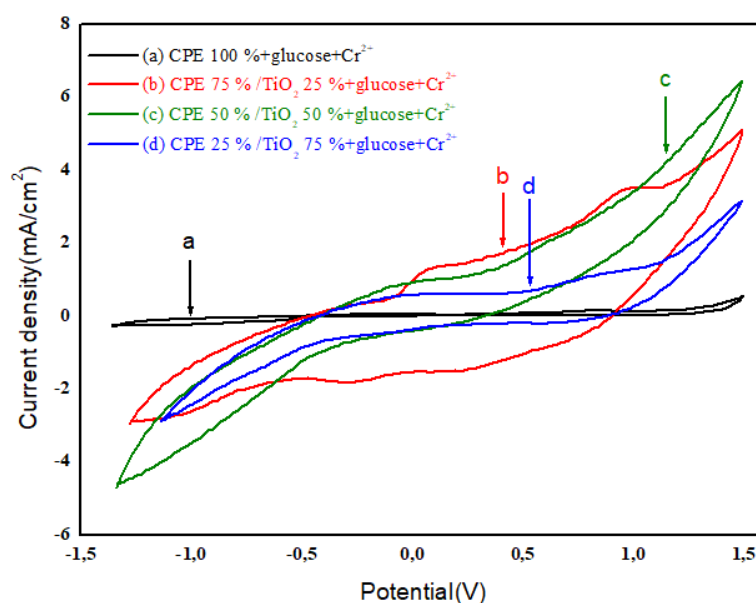


Figure 9. Cyclic voltammograms of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1M NaCl solution containing 0.08M of glucose and 1% Cr²⁺

The cyclic voltammograms showed substantially increased current densities, particularly for the CPE 50%/TiO₂ 50% electrode, which exhibited the highest anodic peak currents. The shape of the voltammograms also changed significantly, with more pronounced redox features, indicating altered reaction mechanisms in the presence of Cr²⁺.

The EIS measurements (Figure 10) revealed dramatic decreases in charge transfer resistances for all electrode compositions in the presence of Cr²⁺. The CPE 75%/TiO₂ 25% electrode showed the most significant improvement, with its Nyquist plot exhibiting a much smaller semicircle diameter compared to the Mg²⁺-containing and additive-free solutions. This suggests that Cr²⁺ ions may act as powerful electron transfer mediators, significantly enhancing the electrochemical activity of glucose.

The superior effect of Cr²⁺ compared to Mg²⁺ can be attributed to several factors:

1. Stronger complex formation with glucose molecules
2. More favorable redox properties of Cr²⁺/Cr³⁺ compared to Mg²⁺
3. Potential catalytic effects on glucose oxidation pathways

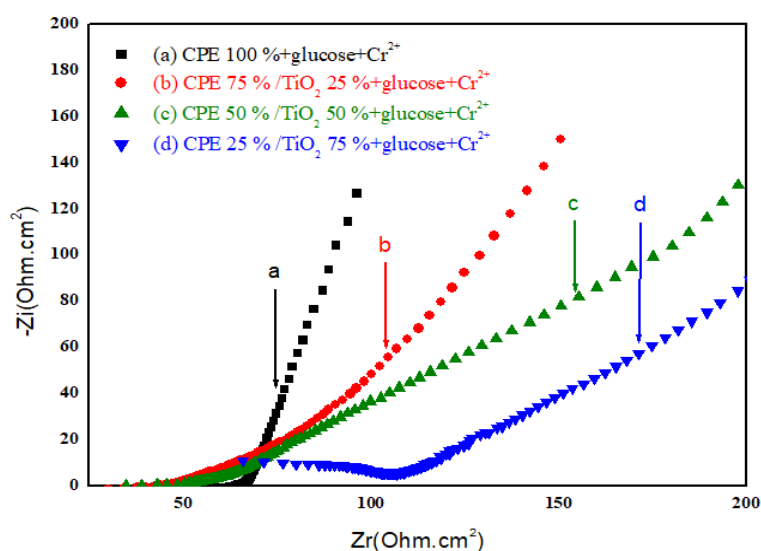


Figure 10. EIS diagrams of the different electrode compositions (CPE 100%, CPE 75%/TiO₂ 25%, CPE 50%/TiO₂ 50%, and CPE 25%/TiO₂ 75%) in 1M NaCl solution containing 0.08M of glucose and 1% Cr²⁺

3.4. Implications for table sugar formulations

The observed enhancement in glucose electrochemistry with TiO₂-modified electrodes and metal ion additives has potential implications for developing novel table sugar formulations. The improved electrochemical properties could translate to enhanced flavor profiles, stability, or functional properties in sugar products. Specifically, the incorporation of controlled amounts of TiO₂, Mg²⁺, or Cr²⁺ into sugar formulations might alter the way sugar interacts with taste receptors or how it performs in food applications.

The optimal composition appears to be a combination of glucose with 1% Cr²⁺ using a detection system based on CPE 50%/TiO₂ 50% electrodes. This combination showed the most favorable electrochemical properties, including high current densities, well-defined redox features, and low charge transfer resistances. However, for practical food applications, further studies on taste, safety, and stability would be necessary.

4. CONCLUSION

This study investigated the electrochemical behavior of glucose in a neutral medium using TiO₂-modified carbon paste electrodes and examined the effects of Mg²⁺ and Cr²⁺ additives. The following conclusions can be drawn:

1. The incorporation of TiO₂ into carbon paste electrodes significantly enhances the electrochemical response toward glucose, with the CPE 50%/TiO₂ 50% composition showing optimal performance.
2. The electrochemical techniques (CV, polarization curves, EIS) consistently demonstrated improved glucose detection capabilities with TiO₂ modification, attributed to increased surface area, catalytic effects, and enhanced electron transfer kinetics.
3. The addition of metal ions (Mg²⁺ and Cr²⁺) further modifies the electrochemical behavior of glucose, with Cr²⁺ showing the most substantial enhancement in current density and reduced charge transfer resistance.
4. The combination of a CPE 50%/TiO₂ 50% electrode with 1% Cr²⁺ additive demonstrated the most favorable electrochemical properties for glucose detection and potential table sugar formulations.

These findings provide valuable insights for developing modified electrodes for sensitive glucose detection and suggest potential pathways for creating enhanced table sugar formulations with improved electrochemical properties. Future work could focus on optimizing the composition and exploring the practical applications of these findings in food technology and sensor development.

Declarations of interest

The authors declare no conflict of interest in this reported work.

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