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Pollution Monitoring via Potentiometric Membrane Sensors for the Determination of Chlorpromazine Hydrochloride in the Presence of Its Main Photo-Degradation Products in River Water

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Abstract: The utilization of membrane sensors for the monitoring and determination of pharmaceutical environmental pollutants has emerged as a crucial objective in recent years. Given the extensive use of chlorpromazine hydrochloride (CPZ) in medicine, its presence in the environment, particularly in surface water such as rivers, is highly probable. Prolonged exposure of river water to sunlight and the photo-degradability of CPZ may enhance its photo-degradation. For the purpose of measuring CPZ in the presence of its primary photo-degradants, two sensitive and selective membrane electrodes were developed. These were synthesized utilizing two ion-pairing agents: sodium tetraphenylborate (TPB) and phosphotungstic acid (PTA). The electrodes exhibited a linear range that extended from 1×10^{-6} M to 1×10^{-2} M. The membrane electrodes of CPZ-TPB and CPZ-PTA exhibited slopes of 59.90 ± 0.60 mV/decade and 58.90 ± 0.80 mV/decade, respectively. The sensors mentioned above showed acceptable performance in a pH range of 2.0 to 6.0. All test parameters were optimized to provide superior electrochemical performance. The fabricated membranes were effectively employed to sensitively quantify CPZ in the presence of its principal photodegradants. The developed sensors were successfully employed to quantify CPZ in river water samples without necessitating pre-treatment procedures.

Keywords: sensors; chlorpromazine hydrochloride; ion-selective membranes; sustainability; water pollution; river water

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1. Introduction

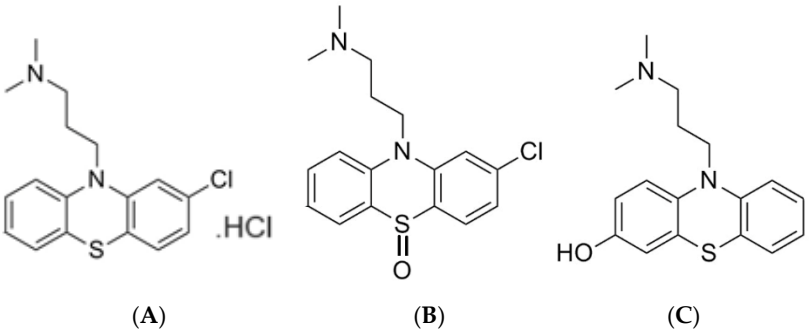
Chlorpromazine hydrochloride (CPZ) is a phenothiazine molecule that functions as a central dopamine receptor blocker, specifically targeting the central nervous system [1]. It is derived from dimethylamine and has a chemical name of [3-(2-chloro-10H-phenothiazin-10-yl) propyl] dimethylamine hydrochloride. It is commonly employed as an antipsychotic medication for the treatment of schizophrenia and other mental illnesses. Veterinarians use CPZ for sedation, anesthesia, pain relief, and other medical treatments. Nevertheless, it is occasionally employed illicitly in animal husbandry to stimulate animal development and diminish mortality during transportation [2]. When CPZ is abused, it can build up in the environment and in animals, which can then affect humans by way of the food chain and result in illnesses, including dyskinesia, hepatomegaly, hematological problems, and hypotensive consequences [3].

The term "photo-stability" in the context of pharmaceuticals refers to the impact of light on the stability of the active ingredients and/or end products of medications. Light-sensitive medications can be influenced by both natural and artificial light sources. Exposure to sunlight can lead to interactions between the molecules of the medication and substances naturally present in the body, causing the medication to turn into harmful byproducts that can produce several oxygenated free radicals which can harm human body

in different ways. Even a small amount of light exposure can have significant impacts on photosensitive medications. Therefore, it is not always essential to subject them to prolonged light exposure [4]. The phototoxicity mechanism of CPZ has been thoroughly described using both in vitro and in vivo experimental paradigms. Exposing CPZ to light results in the formation of the promazyl radical, which is a free radical that has undergone dechlorination. This radical readily forms adducts with deoxyribonucleic acid (DNA) and/or generates singlet oxygen, which can result in numerous detrimental effects [5].

The increasing prevalence of drug usage in recent years has raised concerns regarding their presence in the environment. CPZ has been commonly detected in river and surface waters over the past few years. Surface waters can undergo abiotic changes through processes such as oxidation, hydrolysis, and photolysis. Phenothiazines degrade when exposed to light, whether in liquid or solid form. The adverse effects of those medications on humans when exposed to sunlight, such as phototoxicity—particularly photogenotoxicity, photoallergy, and photocarcinogenicity—are extensively documented [6].

Jimenez et al. [7] investigated the degradation of CPZ in river water. It was possible to identify sixteen CPZ photo-degradation products. The main degradation products were chlorpromazine sulfoxide (CPS) and 2-hydroxypromazine (2-HP), which resulted from hydroxylation and oxidation processes. Figure 1 illustrates the chemical formulas of CPZ and its primary photo-degradants.



(**A**) (**B**) (**C**)

Figure 1. Chemical structure of CPZ (**A**), chlorpromazine sulfoxide (**B**), and 2-hydroxypromazine (**C**).

Various methods were utilized to quantify CPZ, such as capillary electrophoresis [8,9], gas chromatography coupled to tandem mass spectrometry (GC-MS/MS) [10], high-performance liquid chromatography (HPLC) [11], and liquid chromatography coupled to tandem mass spectrometry (LC-MS) [12,13].

Quantifying active pharmaceutical ingredients (APIs) in the presence of their degradation products is an essential aspect of quality control for any drug, particularly in the case of CPZ, which is known to be prone to photo-degradation [6]. Takahashi [14] analyzed the compound CPZ and its degradation products, sulfoxide and sulfone, using HPLC combined with a fluorescence detector. Simultaneously, the identical chromatographic approach was utilized as a stability-indicating assay to quantify CPZ in its dosage form [15]. Furthermore, third derivative spectrophotometry was employed to identify CPZ and its sulfoxide in medicinal dosage forms [16].

Ion-selective electrodes (ISEs) offer numerous advantages in the field of pharmaceutical analysis, such as ease of preparation, quick response time, specificity, the ability to handle cloudy analyte solutions, and affordability. In addition, they respond regardless of the sensor's surface area, allowing for the reduction in size of the electrodes. Moreover, they need no sample pre-treatment. Also, they can be considered as a non-destructive analytical technique [17,18].

Various membrane sensors were developed and employed to detect CPZ in its pure form, as well as in dosage forms and biological fluids [19–21]. The work entitled in this article exceeds the reported membranes used for the CPZ determination in that the described membranes can quantify the studied drug in the presence of its main degradation products commonly found in the sample matrix (river water).

Recently, solid contact electrodes have become increasingly popular as a solution to the challenges posed by the liquid contact electrodes. They eliminate the need for an inner filling solution by creating a solid-state junction between the metal electrode and the membrane. The use of solid contact electrodes in CPZ analysis has several benefits, including smaller size, simpler construction, and lower cost compared to traditional liquid contact electrodes [22].

The extensive and prevalent use of antipsychotics, namely CPZ, poses a possible environmental hazard. Therefore, it is possible that the examined medicine may be present in rivers where compost or sludge is deposited into soils or where hospital effluent is discharged into the neighboring stream [23]. Exposing the surface water to sunlight can enhance the likelihood of photo-degradation of photo-sensitive pharmaceuticals such as CPZ.

Determination of the studied drug in environmental samples was performed using different analytical techniques, including GC-MS/MS [24], capillary zone electrophoresis (CZE), and ultra-performance liquid chromatography (UHPLC) [25]. The mentioned techniques suffer from the presence of tedious sample-pre-treatment procedures, which are not encountered in this work. Moreover, the described potentiometric membrane sensors are more economical if compared with the GC-MS/MS, CZE, and UHPLC. At the same time, CPZ was also determined in wastewater samples through the fabrication of screen-printed carbon electrodes (SPCEs) modified with the co-precipitation of nickel molybdate/cobalt molybdate, and the electrochemical behavior was investigated using cyclic voltammetry (CV), electrochemical impedance spectroscopy (EIS), and differential pulse voltammetry (DPV) without considering the stability of the studied drug [26]. On the other hand, the work in this article focuses on the determination of CPZ in the presence of its major photo-degradants, which are commonly found together with the studied drug in river water.

Upon conducting an extensive examination of the existing literature, it was discovered that there is presently no published work on the application of potentiometric membrane sensors to quantify the examined medicine in the presence of its primary photo-degradants.

The primary objective of this study is to develop, enhance, and verify solid-contact glassy carbon membrane electrodes that use potentiometric measurements to accurately quantify CPZ in the presence of its primary photo-degradants (CPS and 2-HP). Additionally, these electrodes are targeted to reliably determine the concentration of CPZ in real river water samples.

2. Materials and Methods

2.1. Instrumentation

The potentiometric measurement was conducted using a Jenway (UK) mV/pH meter, which is connected to an Ag/AgCl reference electrode. A glassy carbon electrode with a diameter of 3 mm, obtained from CH Instruments in Bee Cave, TX, USA, was utilized to establish the solid contact. Additionally, it serves as a structural foundation for the manufactured membranes and facilitates the transmission of the produced membrane potential.

2.2. Chemicals, Reagents, and Standard Solutions

The CPZ, CPS, and 2-HP materials, with purities of 99.94%, 100.35%, and 100.12% respectively, were acquired from Cymit Quimica S.L. in Barcelona, Spain.

A set of chemicals, including NaOH, hydrochloric acid (37%), tetrahydrofurane (THF), KCl, phosphotungesic acid (PTA), and tetraphenyl borate (TPB), was acquired from Prolabo (France). However, Sigma (Germany) provided dibutyl sebacate (DBS), *o*-nitrophenyl octyl ether (*o*-NPOE), polyvinyl chloride (PVC), and dioctyl phthalate (DOP). All the used chemicals are of analytical-grade purity. The deionized water was acquired from an Aquatron water still.

A stock standard solution of CPZ (1×10^{-2} M) was prepared in deionized water. By carefully mixing the stock CPZ with the same solvent, working-standard solutions were prepared, with concentrations ranging from 1×10^{-3} to 1×10^{-8} M.

2.3. Sensors' Fabrication, Calibration, and Optimization

The mixture of PVC (190 mg), o-NPOE (400 mg), and either TPB (TPB-sensor) or PTA (PTA-sensor) (10 mg) was combined in two separate Petri plates. The solutions were dissolved in 6 mL of THF. The glassy carbon electrodes were dipped in the THF solution for 15 s and withdrawn quickly. The electrodes were left to dry in a desiccator for 1 h. The procedure was repeated twice to ensure homogenous membrane formation. The membrane was conditioned by immersing it in a 0.01 M CPZ stock standard solution for 24 h. The electrodes were stored using the same CPZ solution.

After the conditioning period, the sensors underwent calibration by being immersed in CPZ reference solutions with concentrations ranging from 1×10^{-2} to 1×10^{-8} M. Following each measurement, the membrane was thoroughly rinsed with deionized water. The calibration graphs were plotted according to the established conventions. Subsequently, these calibration curves were employed to ascertain the unknown CPZ concentrations in different samples.

The ideal membrane performance was reached through the process of evaluation and modification of the factors affecting membrane performance. The competence of the fabricated electrodes was evaluated using the recommendations of the IUPAC [27]. Three distinct plasticizers (DOP, DBS, and o-NPOE) with varying polarities were tried to assess their impact on the functioning of the membrane performance. The objective was to identify the plasticizer that yielded the most optimal performance of the fabricated electrodes. The impact of pH on the performance of the fabricated membranes was investigated by gradually adding sodium hydroxide or hydrochloric acid, both at a concentration of 0.1 M, to a standard solution of CPZ with a concentration of 1×10^{-4} M. A graph was plotted to determine the optimal working pH by correlating the potential of the electrode being investigated with the pH of the solutions. During a one-month period, the repeatability and potential stability of the fabricated CPZ sensors were studied. Every day, CPZ standard solutions with concentrations ranging from 1×10^{-2} M to 1×10^{-6} M were used to monitor the potential of the fabricated sensors. Then, for each membrane, the slope was determined in millivolts per decade. The authors compared the estimated slopes to the initial ones.

The modified separate solution method of applying the rearranged Nicolsky equation was employed to assess membrane selectivity [28]. The potentiometric selectivity coefficient (PSC) for each interferent was determined by analyzing the potential responses of the built electrodes in the presence of various interferents, including inorganic ions (Na^+, K^+, and NH_4^+) and co-interfering phenothiazine drug derivatives (perphenazine hydrochloride, fluphenazine hydrochloride, thioridazine hydrochloride, prochlorperazine dihydrochloride, and trifluoperazine hydrochloride). The PSCs were subsequently computed utilizing the following formula [28]:

$$\text{Log } K_{D,B}{}^{pot} = ((E_1 - E_2)/S) + (1 + (z_1/z_2)) \log a$$

E_1 represents the potential recorded in a solution with a concentration of 1×10^{-3} M of CPZ. E_2 represents the potential measured in a solution with a concentration of 1×10^{-3} M of the interfering compound. z_1 and z_2 represent the charges of CPZ and the interfering species, respectively. S represents the slope of the electrode calibration plot.

2.4. Application

2.4.1. Quantification of CPZ in the Presence of Its Main Photo-Degradants

Laboratory-prepared mixtures were prepared using varying proportions of intact CPZ (ranging from 90% to 10%) and its major photo-degradants (ranging from 10% to 90%). The pH levels of the produced mixtures were modified to range from 2.0 to 6.0. The membranes were immersed in the mixes, and the resulting potentials were utilized to

determine the concentration of CPZ using the calibration graphs. The recovery percentages were calculated by dividing the measured CPZ concentrations obtained from the calibration graphs by the CPZ concentrations present in the prepared mixtures, and then multiplying by 100.

2.4.2. Determination of CPZ in Different Water Samples

Several distilled- and tap-water samples were prepared with precise amounts of CPZ. The pH of the produced samples was adjusted within the range of 2.0–6.0. The drug concentrations were measured using the fabricated sensors, and the percentage of drug recovery was calculated.

Three river water samples, free from CPZ, were collected from three distinct places along the River Nile in Cairo, Egypt. The pH of the samples was adjusted to a range of 2.0 to 6.0. Nylon filters were used to eliminate minuscule particle contamination from the samples. In order to avoid the deterioration of the samples, the filtered solutions were stored in opaque glass vials. Different volumes of 0.01 M CPZ standard solution (10 mL, 1 mL, and 0.1 mL) were transferred to three separate 100 mL measuring flasks. The volume of each flask is completed to 100 mL using the filtered CPZ-free river water to prepare three samples with CPZ concentrations of 1×10^{-3} M, 1×10^{-4} M, and 1×10^{-5} M. The fabricated membranes were employed along with the standard curves to determine the concentrations of CPZ, and the recovery % was calculated using the initial spiking CPZ concentrations.

3. Results and Discussion

This study showcases the skillful use of solid-contact potentiometric measurement to analyze CPZ samples, employing TPB and PTA as ion-pairing agents within a PVC matrix. The measured potential of the developed sensors is determined by the process of ion exchange across the fabricated membranes, which is directly proportional to the concentration of CPZ in its solution.

This work describes the construction of two membrane electrodes that have the ability to selectively detect and measure CPZ in river water samples, even in the presence of its primary photo-degradants, which have a high degree of structure similarity with CPZ.

3.1. Evaluation and Validation of the Fabricated Membranes

The assessment parameters that indicate the performance efficiency of the manufactured electrodes are presented in Table 1. An ideal Nernstian behavior was achieved within the concentration range of 1×10^{-6} M and 1×10^{-2} M CPZ., as indicated in Table 1. Figure 2 exhibits standard graphs.

Table 1. Electrochemical response characteristics of the fabricated electrodes.

Parameter	CPZ-TPB Sensor	CPZ-PTA Sensor
Slope (mV/decade) *	59.90 ± 0.60	58.90 ± 0.80
Response time (s)	15	15
Working pH range	2.0–6.0	2.0–6.0
Concentration range (M)	1×10^{-6}–1×10^{-2}	1×10^{-6}–1×10^{-2}
Stability (days)	25	25
Accuracy (Mean * ± SD)	100.67 ± 0.76	101.44 ± 0.56
Detection limit (M)	5×10^{-7}	5×10^{-7}
Ruggedness †	100.11 * ± 1.01	99.87 * ± 1.23
Robustness Ψ	99.78 * ± 0.96	101.43 * ± 0.78

* Average results of five determinations. † Comparing the results with those obtained by different sensor assemblies using Hanna digital ion-analyzer. Ψ Carried out by measuring different known CPZ concentrations on carrying out slight pH change (pH 4 ± 0.2).

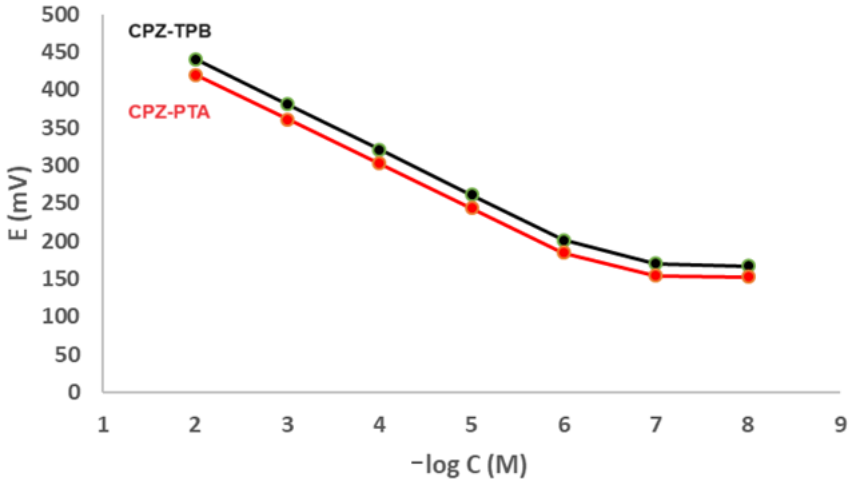


Figure 2. Profile of the potential (in mV) versus −log concentration (in M) for CPZ sensors at pH 4.

In accordance with IUPAC standards [27], the response time, ideal pH range, linearity, impact of plasticizer type, and detection limit of the produced membranes were examined.

Three plasticizers with varying degrees of polarity (DBS, o-NPOE, and DOP) were used to demonstrate how the type of plasticizer affected the results. Membranes fabricated using o-NPOE showed Nernestian slopes of 59.90 ± 0.60 mV/decade (n = 5) and 58.90 ± 0.80 mV/decade (n = 5), for TPB and PTA membranes, respectively. On the other hand, DBS sensors showed slopes out of the Nernestian behavior which are 49.60 ± 0.90 mV/decade (n = 3) and 48.90 ± 0.50 mV/decade (n = 3), for TPB and PTA membranes, respectively, and those fabricated using DOP as plasticizer also exhibited non-Nernestian slopes of 48.70 ± 0.80 mV/decade (n = 3) and 47.60 ± 0.60 mV/decade (n = 3), for TPB and PTA membranes, respectively. Regarding the response time, o-NPOE membranes showed a faster response (15 s), but DBS and DOP sensors took a longer time to give their response (25 s). In view of lifetime, o-NPOE membranes have a longer lifetime of 25 days. On the other hand, DBS and DOP sensors have a shorter lifetime of 21 days. Based on the previous comparison study, the plasticizer that yielded the most favorable outcomes was *o*-NPOE. This is due to the comparable polarities of CPZ and o-NPOE. This combination facilitated the most effective ion exchange via the constructed membranes.

The sensitivity of the constructed sensors was assessed by determining the detection limit at the point where the standard curve linear segments intersected [29]. The sensitivity of the detection method was outstanding, with detection limits as low as 5×10^{-7} M (Table 1). The proposed sensors exhibit remarkable sensitivity, making them suitable to be applied in the field of environmental analysis. In addition, they demonstrated a rapid response when examining a diverse array of concentrations. The specified parameters are crucial for accurately measuring CPZ in real environmental samples (river water samples) when using the developed membranes.

The pH of the media has an impact on the functioning of the sensors. It is evident that the electrode potential remains consistent regardless of the pH level within the range of 2.0 to 6.0. Therefore, the sensors that have been developed can be confidently utilized for determining CPZ in this pH range (Figure 3). The reduction in potential measurements at a pH level below 2 could be attributed to the interference which may be attributed to the hydronium ion. Higher pH levels (pH > 6.0) cause free-base to precipitate in the test solution. Consequently, reduced potential measurements were documented.

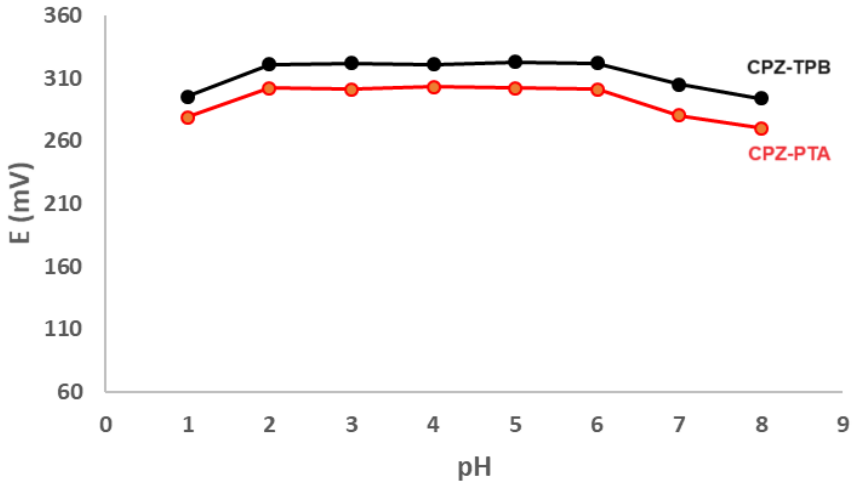


Figure 3. pH effect on the potential response of CPZ membrane sensors.

The membranes' lifetimes were estimated to be 25 days by plotting the calibration graphs and regularly evaluating their characteristics (Figure 4).

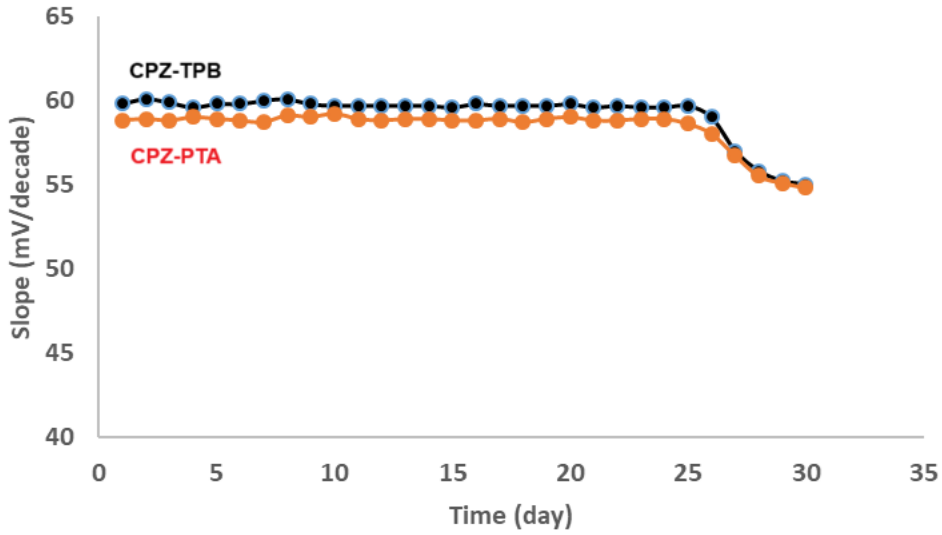


Figure 4. Stability of the CPZ-fabricated membrane sensors.

The response time, a crucial characteristic, significantly influences the membrane evaluation process. The provided information indicates the time needed for the manufactured sensor to stabilize and maintain a constant potential value within a range of ±1 mV, following a ten-fold rise in concentration [27]. The response time of the constructed sensors was found to be 15 s.

By using the manufactured sensors to analyze CPZ samples with definite specific CPZ concentrations, assay accuracy was assessed (Table S1). The robustness of the analytical assay's procedure was evaluated by looking at its resistance to deliberate shifts in working conditions, such as slight pH variations. In addition, the procedure's ruggedness was assessed to determine its reproducibility. Table 1 provides a concise overview of these factors.

The selectivity of the suggested method is a crucial factor that must be carefully validated to guarantee its effectiveness, even with diverse interferents in actual samples. The lipophilicity of the sample ion, the interferent ion on the sample side, and its three-dimensional (3D) structure all influence the selectivity of the proposed method. The 3D structure of the ion exchanger's receptor also has an impact on the membrane's selectivity.

The selectivity of a sensor is greatly affected by its ingredients, the solvent type, and the ratio of plasticizer to PVC. The presence of lipophilic ionic sites accelerates interfacial ion-exchange kinetics. TPB and PTA are ionic sites integrated into the membranes to augment membranes' selectivity. During the preconditioning phase, the positively charged nitrogen of CPZ sequesters the TPB or PTA molecules until an equilibrium is reached, at which point the sensor may detect the target drug ion. Plasticizers are necessary for membrane sensors, as they facilitate fast movement of ions and ensure the produced membrane has favorable physical properties [29].

The modified separate solution method [28] was employed to evaluate the selectivity of the constructed membranes. This goal was achieved on testing various inorganic interferents such as Na^+, K^+, and NH_4^+, as well as co-interfering phenothiazine drug derivatives like perphenazine hydrochloride, fluphenazine hydrochloride, thioridazine hydrochloride, prochlorperazine dihydrochloride, and trifluoperazine hydrochloride. The PSC was then calculated for each interferent. Table 2 presents the computed PSCs. The low values of the estimated PSCs may validate the method's excellent selectivity.

Table 2. Potentiometric selectivity coefficients of the proposed CPZ-selective sensors by the modified separate solution method.

Interferent	CPZ-TPB Sensor (Mean * ± S.D.)	CPZ-PTA Sensor (Mean * ± S.D.)
Na^+	$1.2 \times 10^{-3} \pm 0.76$	$1.3 \times 10^{-3} \pm 0.52$
K^+	$1.1 \times 10^{-4} \pm 0.78$	$1.2 \times 10^{-4} \pm 0.55$
NH_4^+	$2.2 \times 10^{-4} \pm 0.56$	$2.3 \times 10^{-4} \pm 1.11$
Perphenazine hydrochloride	$1.7 \times 10^{-3} \pm 0.59$	$1.6 \times 10^{-3} \pm 0.66$
Fluphenazine hydrochloride	$1.9 \times 10^{-4} \pm 0.45$	$1.8 \times 10^{-4} \pm 0.69$
Thioridazine hydrochloride	$5.3 \times 10^{-4} \pm 0.89$	$5.4 \times 10^{-4} \pm 0.73$
Prochlorperazine dihydrochloride	$3.1 \times 10^{-4} \pm 0.55$	$3.0 \times 10^{-4} \pm 0.69$
Trifluoperazine hydrochloride	$4.7 \times 10^{-4} \pm 1.01$	$4.9 \times 10^{-4} \pm 0.91$

* Average of five measurements.

3.2. Method Application

3.2.1. Determination of CPZ in the Presence of Its Main Photo-Degradation Products

In the presence of up to 90% major CPZ photo-degradants, the method's selectivity was investigated. The challenge involved utilizing sensors to examine a range of laboratory-prepared mixtures, which contained concentrations of CPZ ranging from 9×10^{-4} M to 1×10^{-4} M and concentrations of degradants ranging from 1×10^{-4} M to 9×10^{-4} M. The data shown in Table 3 demonstrate the specificity of the proposed technique and validate its capacity to accurately measure the mentioned drug even in the presence of up to 90% degradation products of CPZ.

Table 3. Results obtained for the analysis of laboratory-prepared mixtures containing different ratios of intact CPZ and its main photo-degradation products using the fabricated sensors.

Intact CPZ	CPS	2-HP	CPZ-TPB Sensor (Mean * ± S.D.)	CPZ-PTA Sensor (Mean * ± S.D.)
90% (9×10^{-4} M)	5%	5%	99.87 ± 0.78	100.63 ± 0.77
70% (7×10^{-4} M)	15%	15%	101.43 ± 0.68	100.56 ± 0.95
50% (5×10^{-4} M)	25%	25%	101.43 ± 0.66	101.24 ± 0.85
30% (3×10^{-4} M)	35%	35%	101.31 ± 0.74	101.46 ± 0.46
10% (1×10^{-4} M)	45%	45%	100.16 ± 0.47	102.14 ± 0.52

* Average of three measurements.

3.2.2. Assay of CPZ-Loaded Water Samples

The sensors were effectively employed to measure the concentration of CPZ in both distilled- and tap-water samples loaded with the studied drug. Furthermore, the sensors were utilized to examine several river water samples that were free of CPZ and loaded with known quantities of CPZ. This was conducted to verify the sensors' performance in various water matrices. Table 4 displays the computed percentages of recovery.

Table 4. Determination of CPZ in spiked river water samples using the fabricated membrane sensors.

Specimen	CPF-TPB Sensor (Rec.% * ± S.D.)	CPF-PTA Sensor (Rec.% * ± S.D.)
Distilled water	101.13 ± 0.80	101.19 ± 0.78
Tap water	99.91 ± 0.68	101.21 ± 0.56
CPZ free river water (sample 1)	98.45 ± 0.78	101.01 ± 1.11
CPZ free river water (sample 2)	101.34 ± 1.13	100.31 ± 0.78
CPZ free river water (sample 3)	101.76 ± 0.68	100.56 ± 0.89

* Average of five measurements.

4. Conclusions

The work's originality stems from the absence of prior research work on the potentiometric evaluation of the target medication in the presence of its primary photo-degradants, frequently encountered in river water containing CPZ due to its susceptibility to photo-degradation. The existence of CPZ photo-degradation products in river water samples containing CPZ presents an important obstacle for its quantification due to the substantial chemical similarity between CPZ and its primary photo-degradants. The lack of a sample pre-treatment step demonstrates the method's superiority relative to the spectroscopic and chromatographic techniques employed for CPZ analysis. Moreover, the proposed method is more cost-effective than HPLC and LC-MS/MS due to its reduced expenses per sample.

The electrochemical performance of the fabricated sensors is well optimized and revealed to be almost the same, regarding the working pH, response time, detection limit, and membranes' life time. At the same time, both membranes have acceptable validation parameters, including linearity, sensitivity, ruggedness, and robustness. From these perspectives, both membranes have been successfully utilized for the precise and sensitive photo-stability-indicating assay of CPZ in river water samples.

The future vision knows no bounds, particularly when it comes to the sensitivity of the method. From this point, the future work will concentrate on studying different improvement approaches and their impact on the fabricated solid-contact electrodes' sensitivity. The upcoming work will comprise the employment of conductive polymers like polypyrrole or polyaniline, which may improve the charge transfer kinetics at the electrode–analyte interface. Also, the incorporation of nanomaterials like carbon nanotubes or graphene, which may increase the effective surface area of the fabricated membranes, will be tried in an attempt to increase membrane sensitivity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/chemosensors12110240/s1, Table S1: The potentiometric response of the fabricated membrane sensors at different CPZ concentrations.

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Conflicts of Interest: The authors declare that they have no competing interests in this manuscript.

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