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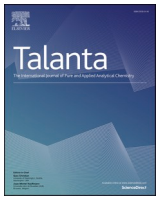

A novel electrochemical method for detecting synthetic cannabinoids in e-cigarette and biological samples using a lab-made electrode

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ABSTRACT

Synthetic Cannabinoid Receptor Agonists (SCRAs) are a class of Novel Psychoactive Substances (NPS) that interact with the same receptors (CB1 and CB2) as delta-9-tetrahydrocannabinol (THC). The identification of SCRAs, such as AB-CHMINACA and MDMB-4en-PINACA, is of significant forensic and toxicological interest due to their widespread consumption in several countries and their potential involvement in overdose cases resulting from their high potency, posing a serious public health and safety concern. Currently, no standardized screening methods exist for the detection of SCRAs in forensic and toxicological contexts. This study introduces a novel electroanalytical method that combines laboratory-fabricated boron-doped diamond screen-printed electrodes (SP/BDDE) with square-wave adsorptive stripping voltammetry (SWAdSV) for the detection of AB-CHMINACA and MDMB-4en-PINACA in e-cigarette samples and real biological matrices. For the first time, the electrochemical behavior of these SCRAs is comprehensively investigated, and all their redox processes (P_{c1}/P_{a2} and P_{a3}) are utilized for selective and accurate identification. The proposed method exhibited a wide linear range (20–100 μM for AB-CHMINACA and 20–70 μM for MDMB-4en-PINACA) with a low detection limit of 0.282 μM, making it highly suitable for forensic applications involving seized samples and toxicological analyses of biological specimens. The stability of the electrochemical response was assessed, with SP/BDDE showing relative standard deviations (RSD) below 10 % for E_p and I_p. Interference studies confirmed the high selectivity of the method for SCRA detection. AB-CHMINACA and MDMB-4en-PINACA were successfully identified in e-cigarette and biological samples, with recovery rates approaching 100 %, indicating minimal matrix effects in these complex samples. Therefore, the proposed method proves to be a promising, rapid, and selective screening approach for the detection of SCRAs in forensic and toxicological scenarios, as a screening test.

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1. Introduction

Synthetic cannabinoid receptor agonists (SCRAs), commonly referred to as "Spice," represent a broad class of compounds that bind to cannabinoid receptors (CB1 or CB2), which are widely expressed in humans and nearly all members of *Animalia* [1–3]. Also known as synthetic cannabinoids or synthetic cannabimimetics, most of these substances belong to the class of new psychoactive substances (NPS), evade international control laws, and are marketed in various forms, including herbal blends, impregnated papers, gummies, extracts, and electronic cigarettes [4–8]. By mimicking the psychoactive effects of Δ9-THC, the primary active compound in *Cannabis sativa* L. (marijuana) [1,9], SCRAs have gained prominence in the illicit drug market, and their widespread use is associated with a high potential for abuse and significant public health risks, including fatal outcomes.

The United Nations Office on Drugs and Crime's Early Warning Advisory Summary Dashboard (UNODC EWA SD) reports 387 distinct SCRAs identified across 95 countries and territories, of which only 21 (6.2 %) are currently controlled under the Convention on Psychotropic Substances (1971) [10,11]. Despite some SCRAs being under international control, the structural diversity of these compounds poses a significant challenge to regulatory frameworks. These substances continue to be detected in seizures and raise substantial concern due to their unpredictable pharmacological profiles and serious adverse health effects, including fatalities [12,13].

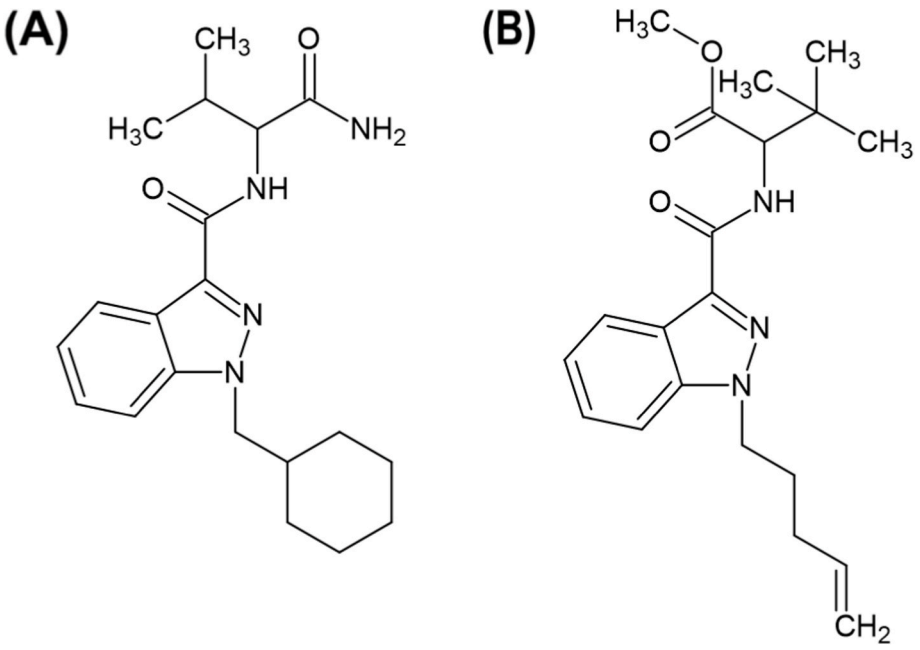
Given the fast-evolving nature of SCRAs, with clandestine laboratories continually modifying structures to circumvent legal control, establishing a standardized nomenclature has become increasingly important. Consistent naming supports the effectiveness of early warning systems and enhances health risk reduction initiatives by enabling clearer communication among forensic laboratories, regulatory agencies, and healthcare providers. Two notable efforts have emerged to address the need for systematic nomenclature: one led by researchers at the European Union Drugs Agency (EUDA, formerly EMCDDA) [14], and another developed through a joint initiative between the Centre for Forensic Science Research & Education and Cayman Chemical [15]. In this study, we adopt the nomenclature system used in Cayman Chemical's online analytical standards catalog.

Among the internationally scheduled SCRAs are AB-CHMINACA (since 2018) and MDMB-4en-PINACA (since 2021) [12]. Both compounds belong to the indazolecarboxamide class of synthetic cannabinoids. AB-CHMINACA exhibits high affinity for CB1 receptors and moderate affinity for CB2, while MDMB-4en-PINACA is up to ten times more potent than THC [16]. Structurally, AB-CHMINACA contains a cyclohexylmethyl group, whereas MDMB-4en-PINACA features a methyl ester group and a pent-4-enyl chain, contributing to its enhanced stability and potency (Scheme 1). Both compounds are associated with severe adverse effects, including tachycardia, paranoia, seizures, and a risk of fatal overdose, particularly with MDMB-4en-PINACA [17].

Currently, there are no internationally standardized methods for the preliminary detection of AB-CHMINACA and MDMB-4en-PINACA [18]. Nevertheless, several analytical techniques have been employed to identify these compounds in biological samples and seized materials. Among them, liquid chromatography (LC) and gas chromatography (GC) coupled with mass spectrometry (MS) [19–21] are widely used due to their high sensitivity and specificity. In addition, recent literature highlights the development of portable, on-site screening methods [22,23], including electrochemical approaches [24–26].

Rapid and accurate identification of SCRAs such as AB-CHMINACA and MDMB-4en-PINACA is critical in forensic investigations, given their association with life-threatening intoxications and fatalities [17,27]. Early detection of new psychoactive substances is crucial for anticipating and disrupting synthetic drug trafficking, enabling health and public safety authorities to implement timely preventive and control measures [23]. Moreover, the prompt detection of these compounds supports the preparation of reliable forensic reports, which are essential for legal proceedings and criminal investigations related to their use and distribution [28]. Identification in toxicological contexts is equally important, as it facilitates immediate and targeted medical treatment for individuals suffering from SCRAs poisoning [29–31].

In this study, we comprehensively investigate – for the first time – the complete redox behavior of AB-CHMINACA and MDMB-4en-PINACA to facilitate their detection in complex matrices such as e-cigarette and biological fluids. This was achieved using square-wave adsorptive stripping voltammetry (SWAdSV) with a custom-designed boron-doped diamond screen-printed electrode (SP/BDDE).



Scheme 1. Chemical structure of AB-CHMINACA (**A**) and MDMB-4en-PINACA (**B**).

2. Experimental

2.1. Chemicals and samples

Analytical standards of AB-CHMINACA and MDMB-4en-PINACA, provided by the United Nations Office on Drugs and Crime (UNODC), were solubilized in HPLC-grade methanol. A stock solution (1×10^{-2} mol L^{-1}) was prepared and subsequently diluted in a supporting electrolyte for electrochemical measurements.

The electrochemical behavior of AB-CHMINACA (used as the model analyte) was investigated in Britton–Robinson (BR) buffer solutions composed of a mixture of boric, phosphoric, and acetic acids over a pH range of 2.0–12.0. The pH was adjusted using sodium hydroxide. Additional buffer systems, including phosphate, McIlvaine, and BR buffers (0.1 mol L^{-1} at pH 3.0), were evaluated for their suitability as supporting electrolytes. BR buffer was selected for further measurements and tested at three different ionic strengths (0.05, 0.1, and 0.2 mol L^{-1}).

Nicotine, three other indazolecarboxamine-class SCRAs – AB-FUBINACA, 5-fluoro APINACA (5-fluoro AKB48), and APINACA (AKB48) – and the phenylacetylindole representative JWH-250 were assessed as potential interferents in the electrochemical detection of AB-CHMINACA using the proposed method. All reagents were of analytical grade and purchased from Sigma-Aldrich (Lancashire, UK). Solutions were prepared using deionized water with a resistivity of at least 18.2 MΩ cm (at 25 °C), obtained from a Milli-Q purification system (Millipore, USA).

An e-cigarette liquid with a "smokey ice strawnana" flavor (containing 50 % nicotine) was spiked with 40 μmol L^{-1} AB-CHMINACA and analyzed using the developed method. Authentic oral fluid samples were voluntarily and anonymously collected from participants at electronic music festivals and parties in Brazil using Quantisal™ oral fluid collection devices (Abbott Immunalysis, USA). The study was conducted in accordance with ethical guidelines approved by the University of Campinas Research Ethics Committee (CAAE 88770318.0.0000.5404) and complied with the principles outlined in the 1964 Helsinki Declaration. The presence of MDMB-4en-PINACA in these oral fluid samples was investigated using the proposed electrochemical method and confirmed by a previously validated liquid chromatography-tandem mass spectrometry (LC-MS/MS) method [32].

2.2. Instrumental and apparatus

All voltammetric experiments were conducted using a PGSTAT 101 N potentiostat (Metrohm Autolab BV, Utrecht, Netherlands) controlled by NOVA 2.1 software. Prior to measurement, pure nitrogen gas was bubbled through all solutions for 5 min to remove oxygen.

The electrochemical behavior of AB-CHMINACA was characterized using a laboratory-fabricated boron-dopeed diamond screen-printed electrode (SP/BDDE), fabricated with a BDD layer grown in the gas phase at a B/C ratio of 312,500 ppm [33], donated by the Slovak Diamond Group (Slovak University of Technology in Bratislava). The SP/BDDE incorporated a boron-doped diamond (BDD) working electrode (WE), a counter electrode, and an Ag/AgCl pseudo-reference electrode (WE surface area: 3.14 mm^2; internal diameter: 2 mm; B/C ratio: 312,500 in the gas phase; resistivity: 0.017 Ω cm; charge carrier concentration: 2.9×10^{21} cm^{-3}, determined by the Hall method) [33–36]. This three-electrode system was fabricated using a novel selective nucleation method for the working and counter electrodes, and screen-printing techniques for electrical contacts, the reference electrode, and the passivation layer. The SP/BDDE demonstrated superior long-term stability compared to sensors employing screen-printed BDD or BDD only as the working electrode.

Prior to use, the SP/BDDE was electrochemically conditioned via cyclic voltammetry (CV) in 0.1 mol L^{-1} BR buffer solution (pH 3.0) over ten cycles, within a potential window of −1.0 V to +1.0 V (*vs.* pseudo-RE) at a scan rate of 100 mV s^{-1}. CV was employed to investigate the electrochemical behavior, whereas square-wave adsorptive stripping voltammetry (SWAdSV) was used for the screening of AB-CHMINACA. All measurements were performed using 40 μL of sample solution, in triplicate (N = 3).

The SWAdSV parameters for AB-CHMINACA detection were optimized using a univariate approach, evaluating pulse amplitude (10–100 mV), step potential (1–10 mV), frequency (10–100 Hz), and pre accumulation time (0.0–1.0 min). The second SWAdSV scan was used for quantitative analysis. All voltammograms were baseline-corrected using NOVA 2.1 software.

Chromatographic analyses were carried out on a Nexera UHPLC system coupled to an LCMS-8060 triple quadrupole mass spectrometer (Shimadzu, Kyoto, Japan). Chromatographic conditions, MRM transitions, and qualitative validation data were previously reported by da Cunha et al. (2020) [32].

3. Results and discussion

3.1. Electrochemical behavior of AB-CHMINACA on SP/BDDE

The electrochemical behavior of AB-CHMINACA, used as a model synthetic cannabinoid receptor agonist, was investigated on SP/BDDE using CV. Experiments were carried out in Britton-Robinson (BR) buffer solutions (0.1 mol L^{-1}) across a pH range of 2.0–12.0. The voltammetric profiles are presented in Fig. S1 (Supplementary Information – SI).

As observed in Fig. S1, AB-CHMINACA exhibited two irreversible oxidation processes (P_{a3} and P_{a4}) and a quasi-reversible redox couple (P_{c1}/P_{a2}), the latter becoming more prominent in the second scan. Additionally, a reduction process (P_{c4}) was observed only at pH values above 6.0, whereas oxidation peak P_{a3} appeared exclusively between pH 2.0 and 6.0. For improved visualization of the redox behavior, the voltammogram recorded at pH 3.0 is shown in Fig. 1.

3.2. Effect of pH and scan rate on the electrochemical behavior of AB-CHMINACA

The influence of pH on the peak potentials (E_p) of the redox processes

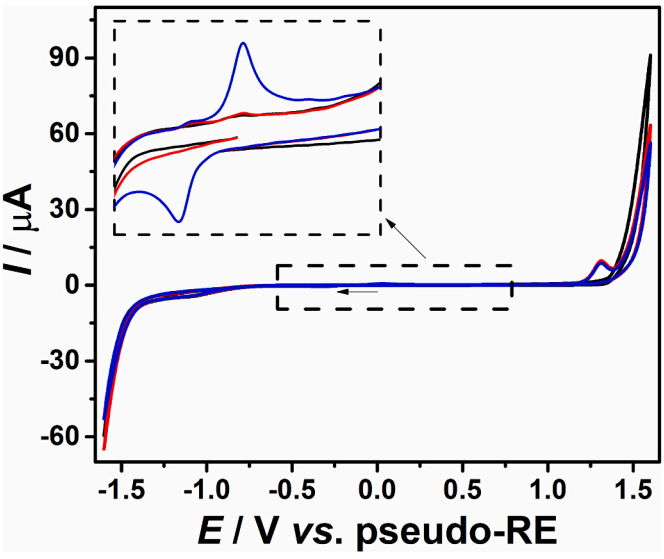


Fig. 1. Cyclic voltammograms recorded in 0.1 mol L^{-1} BR buffer (pH 3.0) on SP/BDDE. Black line: blank; red line: first scan after addition of 1.0×10^{-3} mol L^{-1} AB-CHMINACA; blue line: second scan. All scans initiated at 0.0 V in the cathodic direction, scan rate of 50 mV s^{-1}. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of AB-CHMINACA at SP/BDDE was evaluated using CV (Fig. S2A–SI). As shown in Fig. S2A, the peak potentials of processes P_{c1}/P_{a2} and P_{a4} were pH-dependent, with their linear regressions of E_p *vs.* pH presented in Table S1 – SI. The slopes obtained for these processes were similar to the theoretical Nernstian value of 0.0592 V pH^{-1}, indicating the involvement of an equal number of electrons and protons. In contrast, the EP of P_{a3} exhibited no dependence on pH, suggesting the absence of proton transfer in this process.

As shown in Fig. S1–SI and Fig. 1, the redox processes of AB-CHMINACA were most clearly resolved at pH 3.0 in 0.1 mol L^{-1} BR buffer, with peak potentials around +1.31 V for P_{a3} (first scan), and –0.32 V (P_{c1}) and +0.03 V (P_{a2}), both observed in the second scan. Under this condition, the voltammograms exhibited sharper peaks and more favorable current responses (Fig. S2B–SI). Therefore, pH 3.0 was selected for further electrochemical measurements.

Alternative buffer systems, including phosphate and McIlvaine buffers at pH 3.0, were also evaluated (Fig. S3A–SI). However, BR buffer provided superior peak resolution and was thus selected. To assess the effect of ionic strength, the BR buffer concentration was varied (0.05, 0.1, and 0.2 mol L^{-1}) (Fig. S3B–SI), and 0.05 mol L^{-1} was ultimately chosen for subsequent experiments due to its improved signal characteristics.

To investigate the mass transport control of the electrochemical processes, CV experiments were performed at different scan rates (v) (Fig. S4A–SI). All redox processes exhibited linear correlations between peak current (I_p) and both the scan rate (Fig. S4B–SI) and the square root of the scan rate (Fig. S4C–SI). To assess the mass transport behaviors of each process, log I_p *vs.* log v plots (Fig. S4D–SI) were performed, and the corresponding linear regressions (Table S2–SI) revealed that the P_{c1} and P_{a2} processes from AB-CHMINACA involve both adsorption and diffusion control on SP/BDDE surface, as indicated by the slope values between 0.5 and 1.0 [37]. In contrast, the P_{a3} process is predominantly controlled by diffusion.

3.3. Determination of AB-CHMINACA by SWAdSV

Following the characterization of the redox processes of AB-CHMINACA by cyclic voltammetry, a square-wave adsorptive stripping voltammetry (SWAdSV) method was developed for its sensitive detection in forensic samples. For comparative purposes, differential pulse adsorptive stripping voltammetry (DPAdSV) was also evaluated (Fig. S5–SI). SWAdSV demonstrated superior sensitivity and was therefore selected for further studies.

Under optimized conditions – pulse amplitude of 70 mV, step potential of 5 mV, frequency of 60 Hz, and pre accumulation time 30 s – repeatability (3 measurements on the same electrode on the same day) and reproducibility (triplicate measurements using 3 different electrodes inter-days) tests were performed using the same SP/BDDE. Intra-day (N = 3, Fig. 2A) and inter-day (N = 3, Fig. 2B) measurements are shown in Fig. 2.

The proposed method demonstrates consistent performance across multiple assays using the same SP/BDDE (Fig. 2). It exhibited good stability in the electrochemical responses of AB-CHMINACA, with relative standard deviations (RSD) for peak potential (E_p) below 5.6 % and peak current (I_p) below 6.0 % for intra-day measurements. For inter-day tests conducted over three different days, RSD values were lower than 1.3 % for E_p and lower than 9.8 % for I_p (Table S3–SI). These results confirm the reliability and robustness of the SP/BDDE-SWAdSV platform for the screening of SCRAs.

Subsequently, the linear working range for AB-CHMINACA detection was evaluated using standard solutions from 1 to 100 μmol L^{-1}, as shown in Fig. 3.

As shown in Fig. 3, a linear response was obtained for the

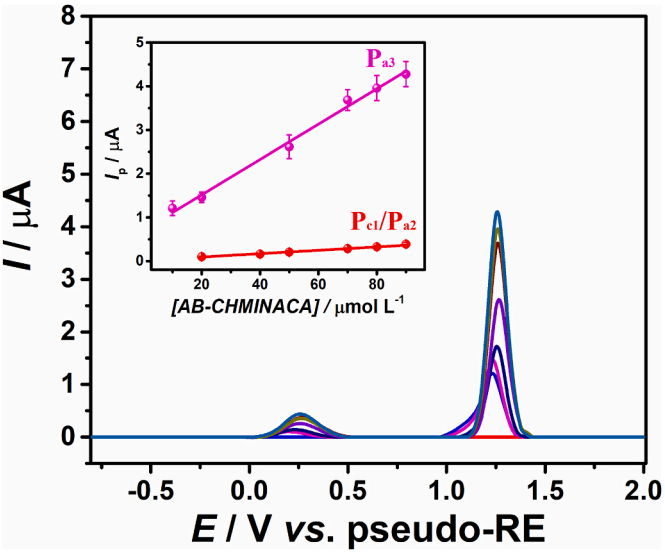


Fig. 3. Voltammograms recorded by SWAdSV in 0.05 mol L^{-1} BR buffer (pH 3.0) on SP/BDDE before and after the addition of 1.0–100.0 μmol L^{-1} AB-CHMINACA. Experimental conditions were the same as in Fig. 2. The inset shows linear regression plots for P_{c1}/P_{a2} (red) and P_{a3} (magenta), with error bars representing triplicate measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

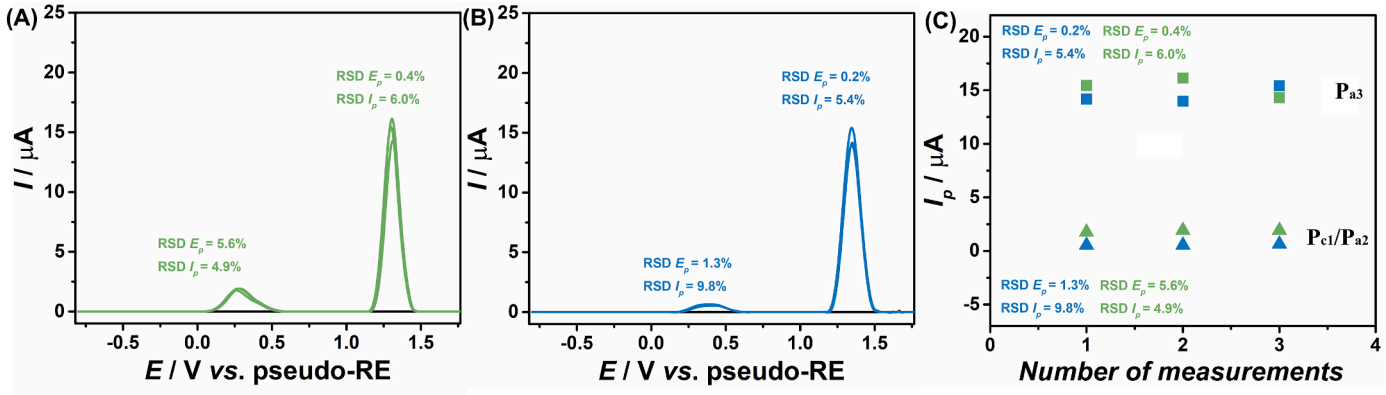


Fig. 2. Second voltammogram scans recorded by SWAdSV for 1.0 × 10^{-3} mol L^{-1} AB-CHMINACA in 0.05 mol L^{-1} BR buffer (pH 3.0) using SP/BDDE: (A) same-day measurements; (**B**) measurements on different days; (**C**) plot of peak current (I_p) versus number of measurements performed on the same day (green) and on different days (blue). Experimental conditions: pulse amplitude, 70 mV; step potential, 5 mV; frequency, 60 Hz; pre accumulation time, 30s. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

quantification of AB-CHMINACA using both redox processes. For P_{c1}/Pa_2, the linear range extended from 20 to 100 μmol L^{-1} ($R^2 > 0.990$), while for the Pa_3 oxidation process, a linear range from 10 to 100 μmol L^{-1} was achieved ($R^2 = 0.995$). These results indicate that both redox processes are suitable for quantifying this SCRA. The corresponding linear regression equations are provided in Table S4–SI.

The theoretical limits of detection (LOD) were calculated to be 2.97 μmol L^{-1} for P_{c1}/P_{a2} and 0.28 μmol L^{-1} for P_{a3}, using equation $(3S)_B/m$ [38], where S_B is the standard deviation (N = 10) of the background (blank) signal, and m is the slope of the calibration curve. The limits of quantification (LOQ), calculated as $10S_B/m$ [38] were 9.80 μmol L^{-1} for P_{c1}/P_{a2} and 0.93 μmol L^{-1} for P_{a3}. These low detection limits support the suitability of the proposed method for the analysis of real forensic samples, which may contain AB-CHMINACA concentrations range from 50 to 600 mg [4].

3.4. Interference studies

Recent studies have indicated that approximately 56 % of SCRAs samples contain two or more synthetic cannabinoids [39]. To evaluate the real-world applicability of the proposed method for forensic analysis, interference studies were conducted using structurally related SCRAs – AB-FUBINACA, 5-fluoro AKB48, AKB48, and JWH-250 – as well as nicotine. The corresponding voltammetric responses and molecules are presented in Fig. 4A and B. Additionally, Fig. 4C shows the results for mixtures of AB-CHMINACA and nicotine at concentration ratios ranging from 1:1 to 1:10 ([AB-CHMINACA]: [nicotine]), simulating conditions typically found in e-cigarette formulations. These studies aimed to assess the method's selectivity and suitability for detecting AB-CHMINACA in the presence of common interferents.

As shown in Fig. 4A, the studied SCRAs exhibited a common oxidation process at +0.19 V (*vs.* pseudo-RE), likely associated with an electroactive group present in the central core structure shared by all compounds (highlighted in red in Fig. 4B). In addition to this electrochemical process, an oxidation peak at +1.20 V (*vs.* pseudo-RE) was observed for AB-FUBINACA and AB-CHMINACA. These SCRAs possess highly similar chemical structures and, consequently, display nearly identical electrochemical behavior. It is important to note that AB-CHMINACA and AB-FUBINACA cannot be selectively identified when present in mixtures. The method detects only the presence of a SCRAs from the same structural class, without enabling specific differentiation of AB-CHMINACA in the presence of AB-FUBINACA.

In contrast, 5F-AKB-48, AKB-48, and JWH-250 differ structurally from AB-CHMINACA and AB-FUBINACA by lacking heteroatoms at their terminal positions, sharing only the central core of the molecule. These findings suggest that the proposed method may also be suitable for the selective identification of other SCRAs, based on their class-dependent electrochemical signatures.

Nicotine exhibited an oxidation peak at + 1.32 V (*vs.* pseudo-RE), which is close to the P_{a3} peak of AB-CHMINACA and could lead to signal overlap. To assess the potential interference, mixtures of AB-CHMINACA and nicotine were analyzed at concentration ratios ranging from 1:1 to 1:10 (Fig. 4C). Although the nicotine oxidation process overlapped with P_{a3}, the characteristic P_{c1}/P_{a2} redox couple of AB-CHMINACA appeared at a sufficiently distinct potential, allowing its selective detection even in the presence of nicotine (RSD <10 %). These findings confirm the method's high selectivity for the detection of AB-CHMINACA and related SCRAs in complex matrices.

3.5. Determination of synthetic cannabinoids in e-cigarette and biological samples

To further validate the applicability of the proposed method in real biological samples, another SCRA (MDMB-4en-PINACA) was analyzed using Quantisal™ (a biological sample dilution medium) as the supporting electrolyte. The calibration curve was constructed over the range of 10–100 μmol L^{-1} (Fig. S6–SI). As shown, a linear response for MDMB-4en-PINACA ($R^2 = 0.996$) was obtained between 20 and 70 μmol L^{-1} using the P_{c1}/P_{a2} process. The corresponding linear regression equation was:

$$I_p\ (\mu A) = -56.76\ (\pm 0.02) \times 10^{-6} + 0.0084\ (\pm 0.0003) \times [MDMB-4en-PINACA]\ (\mu mol\ L^{-1})$$

These results demonstrate that the proposed method is suitable not only for AB-CHMINACA, but also for the detection and quantification of other SCRAs in biological samples, requiring minimal sample

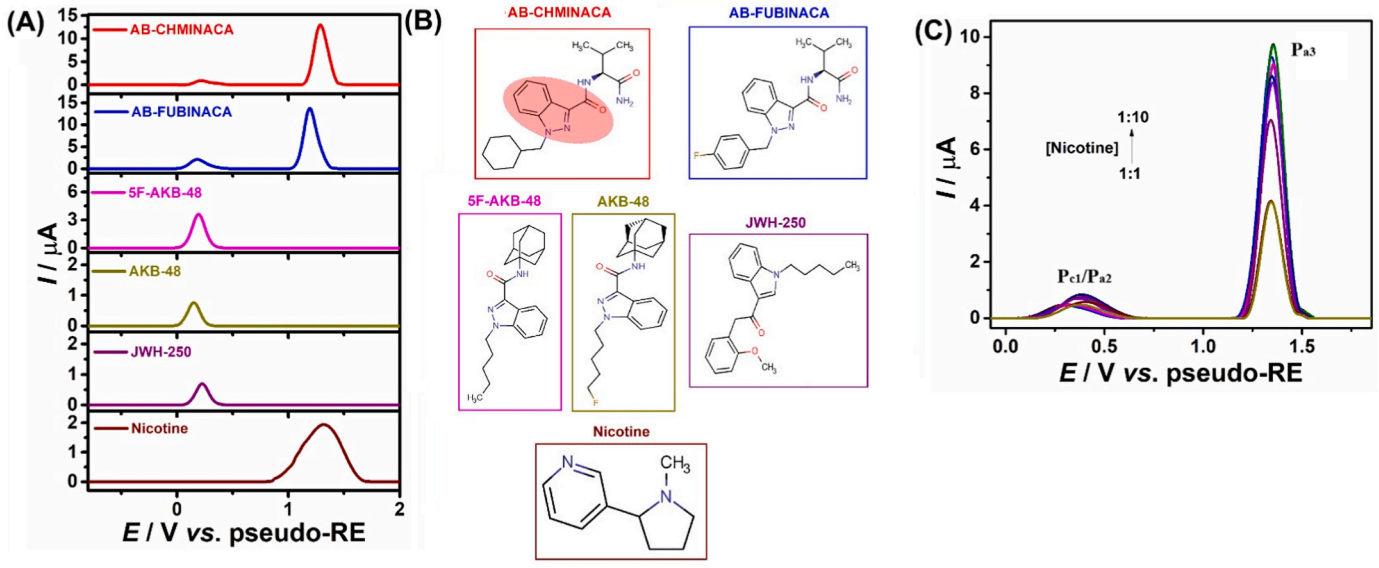


Fig. 4. (**A**) Voltammograms recorded by SWAdSV in 0.05 mol L^{-1} BR buffer (pH 3.0) on SP/BDDE before and after the addition of 1×10^{-3} mol L^{-1} AB-CHMINACA (red), AB-FUBINACA (blue), 5-fluoro AKB48 (magenta), AKB48 (dark yellow), JWH-250 (violet), and nicotine (wine). (**B**) Chemical structure of all analytes in the same colors as (A). (**C**) Voltammograms recorded for mixtures of AB-CHMINACA at 1×10^{-3} mol L^{-1} and nicotine at concentration ranging from 1×10^{-3} mol L^{-1} to 10×10^{-3} mol L^{-1}, in 0.05 mol L^{-1} BR buffer (pH 3.0). Experimental parameters were the same as those described in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

preparation when Quantisal™ is used directly.

E-cigarette samples were spiked with AB-CHMINACA at two concentration levels and analyzed for compound detection. The corresponding voltammograms are presented in Fig. S7–SI, and recovery results are summarized in Table 1 using P_{c1}/P_{a2} redox process. Similarly, an authentic oral fluid sample was processed according to the experimental section and tested for MDMB-4en-PINACA using the developed method (Fig. S8–SI).

As shown in Fig. S7 and S8 – SI, oxidation peaks were observed around +0.25 V and +1.3 V for AB-CHMINACA in BR buffer (pH 3.0), and near + 0.85 V for MDMB-4en-PINACA in Quantisal™, consistent with previous observations. Further confirmation was achieved by spiking the samples with standard solutions: 20 μmol L^{-1} (blue line) and 50 μmol L^{-1} (magenta line) AB-CHMINACA in the e-cigarette matrix, and 20 μmol L^{-1} (blue line) and 40 μmol L^{-1} (magenta line) MDMB-4en-PINACA in the biological sample. In both cases, increased peak currents confirmed the presence of the target SCRAs.

Notably, the presence of MDMB-4en-PINACA in the oral fluid sample was confirmed by LC-MS/MS analysis, supporting the reliability of the proposed electrochemical method for preliminary screening in complex forensic samples [32].

Fig. S7 and S8 – SI demonstrate that the electrochemical behavior of SCRAs in e-cigarette liquid and biological samples is consistent with that observed in standard solutions – namely, BR buffer at pH 3.0 and Quantisal™ (for biological samples, without requiring additional dilution). These results confirm the applicability of the proposed method for the detection of SCRAs in both sample types.

As shown in Table 1, quantification of AB-CHMINACA and MDMB-4en-PINACA in all tested matrices yielded satisfactory recovery values using the P_{c1}/P_{a2} process, with recoveries ranging from 95.2 to 106.7 %. These findings indicate that the method is not significantly affected by matrix effects and can be reliably applied to the analysis of seized e-cigarette products and biological specimens in forensic settings.

4. Conclusion

This work presents, for the first time, a comprehensive investigation of the electrochemical behavior of AB-CHMINACA and introduces a novel voltammetric method for the sensitive and selective detection of SCRAs in forensic samples. The developed approach – based on SWAdSV using a SP/BDDE – enabled the rapid detection and quantification of AB-CHMINACA and MDMB-4en-PINACA in both biological fluids and e-cigarette matrices. The methods demonstrated linear responses from 10 to 100 μM for AB-CHMINACA and from 20 to 70 μM for MDMB-4en-PINACA, with a detection limit as low as 0.2 μM. Two key electrochemical signatures were identified: an irreversible oxidation process (P_{a3}) and a quasi-reversible redox couple (P_{c1}/P_{a2}), both of which were successfully applied for AB-CHMINACA detection and quantification. Notably, the P_{c1}/P_{a2} process provided greater selectivity, particularly in complex matrices containing potential interferents such as nicotine. The method exhibited excellent reproducibility and stability, with intra-day and inter-day relative standard deviations (RSD) below 10 % for both peak potential (E_p) and peak current (I_p), using the same electrode. Requiring only 40 μL of sample, the system is highly compatible with portable or field-based applications, offering a simple, cost-effective, and robust tool for the preliminary screening of SCRAs. Overall, the proposed method represents a valuable alternative for the rapid, reliable, and on-site forensic analysis of SCRAs in diverse real-world samples.

CRediT authorship contribution statement

Cecília N.F. Barroso: Visualization, Methodology, Investigation. **Larissa M.A. Melo:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Lívia M.S. Aranha:** Methodology, Investigation. **Thiago F.L. Pereira:** Methodology, Investigation.

Table 1
Recovery (±RSD) of peak current (I_p) for the synthetic cannabinoids receptor agonists (SCRAs) AB-CHMINACA and MDMB-4en-PINACA.

Sample	SCRAs	[Add]/μmol L^{-1}	Recovery (±RSD)/%
e-cigarette	AB-CHMINACA	20	105.2 (±5.2)
e-cigarette	AB-CHMINACA	50	106.7 (±5.3)
oral fluid	MDMB-4en-PINACA	20	95.2 (±4.6)
oral fluid	MDMB-4en-PINACA	40	99.7 (±4.7)

Karla A.O. Souza: Methodology, Investigation. **Jose L. Costa:** Writing – review & editing, Visualization, Resources, Conceptualization. **Luciano C. Arantes:** Writing – review & editing, Visualization, Resources, Conceptualization. **Marian Marton:** Writing – review & editing, Visualization, Resources, Conceptualization. **Marian Vojs:** Writing – review & editing, Visualization, Resources, Conceptualization. **Wallans T.P. dos Santos:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.talanta.2025.128574.

Data availability

Data will be made available on request.

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