The Leading-Edge Detection of Caffeine by a Green Electrode.

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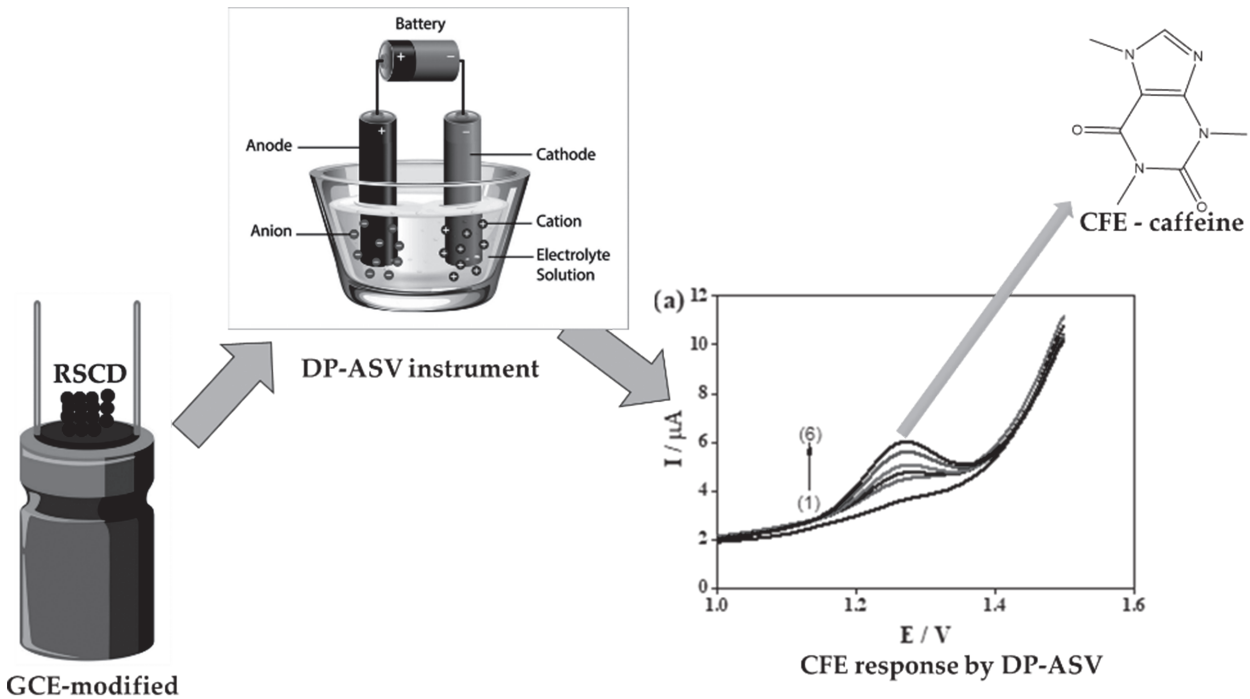

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Abstract:

The RSCD-modified electrode has excellent catalytic electrochemistry properties to CFE with a well-defined electrochemical peak, at 1.26 V. The linear correlation of the peak current, Ip of CFE and the concentration range (0.2 μM – 1.4 μM) give a small LOD value of 0.095 M and LOQ value of 0.313 M. This illustrates good sensitivity and the ability to apply the modified electrode to detect CFE in several practical matrix samples.

Keywords: *novel detection of CFE, CFE detection, DP-ASV method, CQDs, electrochemical detection*

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Nomenclature

GFR	glomerular filtration rate
PTDA	Photodiode array
DP-ASV	Differential pulse anodic stripping voltammetry
LOD	Limit of detection
CQDs	Carbon quantum dots
GC	Gas chromatography
LC	Liquid chromatography
MS	Mass spectrometry
MWCNT	Multi-walled carbon nanotube
PL-asp/MWCNT	Poly (L-aspartic acid)@MWCNT
PLCY	Poly L-cysteine

Introduction

Caffeine (C8H10N4O2, CFE, Figure 1), also referred to as 1,3,7-trimethyl xanthine, is an originally occurring xanthine alkaloid prevalent in various plant-derived products and drinking waters, like coffee, kola nuts, yerba mate, guarana berries, and others. (Oestreich-Janzen, 2016) It is a central anxiety system stimulant, reducing sleep propensity, and developing short-time records. It exerts stimulatory effects on the people's central nervous system, increases urinary Ca out-excretion, and enhances Ca secretion in the tiny intestine, reducing cartilage mass; these physiological impacts are dose-dependent. (Gaspar & Ramos, 2016) In moderate amounts, caffeine can improve concentration and elevate the glomerular filtration rate (GFR), facilitating toxin elimination. Caffeine is one of the most widely consumed pharmacological substances globally, exerting several significant

effects, including central nervous system stimulation, diuresis, and a positive impact on the cardiovascular scheme. (McLellan et al., 2016) Nonetheless, an enormous intake of CFE can lead to adverse impacts, like cardiovascular symptoms, depression symptoms, and hyperactivity illness. Consequently, there is a need for a precise, rapid, easy, and economically-saving method for determining CFE content in popular consumption products. (Moore et al., 2008)

Caffeine, a methylxanthine compound, acts as a central nervous system stimulant by blocking adenosine receptors, leading to increased alertness and reduced fatigue. Its moderate consumption has been associated with enhanced cognitive performance, improved physical endurance, and a lower risk of certain neurodegenerative diseases. However, excessive intake has been linked to adverse effects, including insomnia, hypertension, and arrhythmias. Recent statistics indicate that approximately 80% of adults globally consume caffeine daily, with an average intake ranging from 100 to 200 mg per individual. These figures underscore the necessity for reliable methods to quantify caffeine levels in commonly consumed products to safeguard public health. (Fekry et al., 2020; Švorc et al., 2018; Wang et al., 2018)

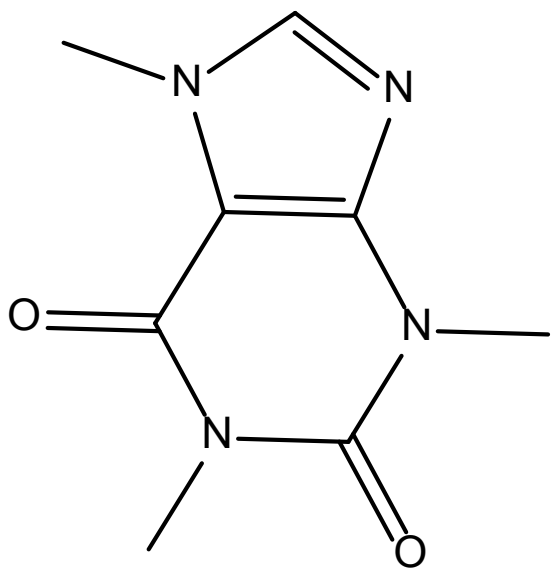

Figure 1. The structure of CFE.

Conventional analytical methods, including GC and LC, linked with MS or PTDA detectors, have demonstrated excellent sensitivity features, selectivity features, and detection limits below picomolar. (Kurbanoglu & Ozkan, 2018) However, these methods are often constrained by several drawbacks: they are expensive, time-intensive, and necessitate sample pre-treatment processes like extraction stages, pre-concentration steps,

and derivatization stages. Additionally, the requirement for skilled personnel further restricts their applicability for routine analysis. (Oestreich-Janzen, 2016)

The literature has documented the voltammetry determination of CFE on several modified-electrode materials, predominantly bare surfaces and modified-NPs electrodes. (Cheng et al., 2016; Thakur et al., 2017) Electrochemical techniques offer numerous practical benefits, including straightforward implementation, cost-effective instrumentation, and potential for miniaturization. Additionally, these methods exhibit high sensitivity, an extensive content range, a propensity for real-period detection, and diminished susceptibility to complicated impacts. (Batista et al., 2010)

Modified electrodes offer significant advantages over conventional electrodes in various applications, such as electrocatalysis and electrochemical sensors. The voltammetry signals acquired using bare GCEs may sometimes lack clear peaks. Consequently, the surface zone of GCE is altered to develop the voltammetry reactions of these groups. (Dubinin, 1960) The development of novel electrode materials is essential for advancing analytical chemistry due to the growing demand for rapid, accurate, and cost-effective detection methods in diverse applications. In particular, the determination of caffeine, a widely consumed psychoactive compound, necessitates innovative detection systems to overcome the limitations of traditional techniques. This study aims to bridge this gap by introducing an eco-friendly, carbon-based electrode, emphasizing both its economic feasibility and environmental sustainability. (D. M. Nguyen et al., 2022; Verma et al., 2020; Zhang, 2024)

Carbon-based electrodes have been extensively employed for the electrochemical determination of various analyzed compounds (Torres et al., 2014) including caffeine. (Trani et al., 2017) Recently, NPs carbons have garnered attraction as promising electrochemical examiners, (Santos et al., 2012) primarily because of their large surface zone, adjustable pore diameter, and effective preparation methods. In this context, carbon quantum dots are acknowledged as highly effective materials for numerous applications and could be synthesized from biomass wasters or residues through various activation techniques. (Fekry et al., 2020) Rice straw was chosen as the precursor for carbon quantum dots (CQDs) due to its abundant availability, low cost, and potential to address agricultural waste management challenges. Unlike conventional methods reliant on expensive and non-renewable precursors, utilizing rice straw aligns with the principles of green chemistry by repurposing biomass waste into high-value materials. Additionally, the synthesis of CQDs from rice straw offers comparable or superior electrochemical properties, including a large surface area and high conductivity, making it a sustainable alternative to synthetic carbon sources. (Kumari et al., 2022; Phuong & Loc, 2022)

In this study, carbon quantum dots derived from biomass were utilized as electrochemical sensors for caffeine detection. The carbon quantum dots were previously prepared and characterized. Subsequently, the electrochemical sensors were fabricated via the dip-dropping technique with the Nafion agent. The modified electrodes underwent electrochemical characterization. Therefore, CFE-existed drinking waters were analyzed using the modified electrodes to detect caffeine concentration voltammetry. The results closely matched the recorded outcomes for these models, describing the potential use of these carbon materials as effective and cost-effective voltammetry detectors.

Material and apparatus

Materials and agents

NaH_2PO_4 99%, Na_2HPO_4 99%, CH_3COOH 99%, citric acid ($C_6H_8O_7$, 99%), boric acid (H_3BO_3, 99%), NH_4OH, 25% and CFE ($C_{18}H_{10}N_4O_2$, 99%) were received from Merck industry (Germany).

The buffer solution, BRBS in the pH range from 3 to 8 was prepared from 0.2 M H_3BO_3, 0.25 M H_3PO_4, and 0.25 M CH_3COOH. The wanted solution pH 7.0 buffer was modified by employing 1.5 M KOH or 1.5 M H_3PO_4 liquid solutions.

Apparatus

A CPA–HH5 (aka Computerized Polarography Analyzer, Vietnam) was applied for electrochemical experiments. All tests were carried out in a cell with 03 electrodes: a GCE with a diameter value of 2.8 ± 0.1 mm employed for structuring the changed electrode as the WE, an Ag/AgCl, 3.5 M KCl as a reference one, and a Pt wire as an auxiliary one. All examinations were replaced at room heat.

The synthesis of CQDs

RSCD-CQDs were synthesized using the hydrothermal method. Rice straw was washed multiple times with twice-distilled water, then heated at 80 °C and finely chopped. A sample of 1.0 g of the chopped rice straw was dispersed in 50 mL of twice-distilled rain and then, stirred for 15 mins before being transferred to a 100 mL sample digestion vessel with a stainless steel shell. The hydrothermal method was conducted in an oven at 180 °C for 1 day. The reaction mixture was then allowed to cool naturally to ambient temperature. The mixture was transferred to a 15 mL centrifuge tube and centrifuged at 3.000 rpm for 30 minutes. The solid residue was discarded, and the resulting light yellow solution was the RSCD quantum dot solution. (N.-A. Nguyen et al., 2021)

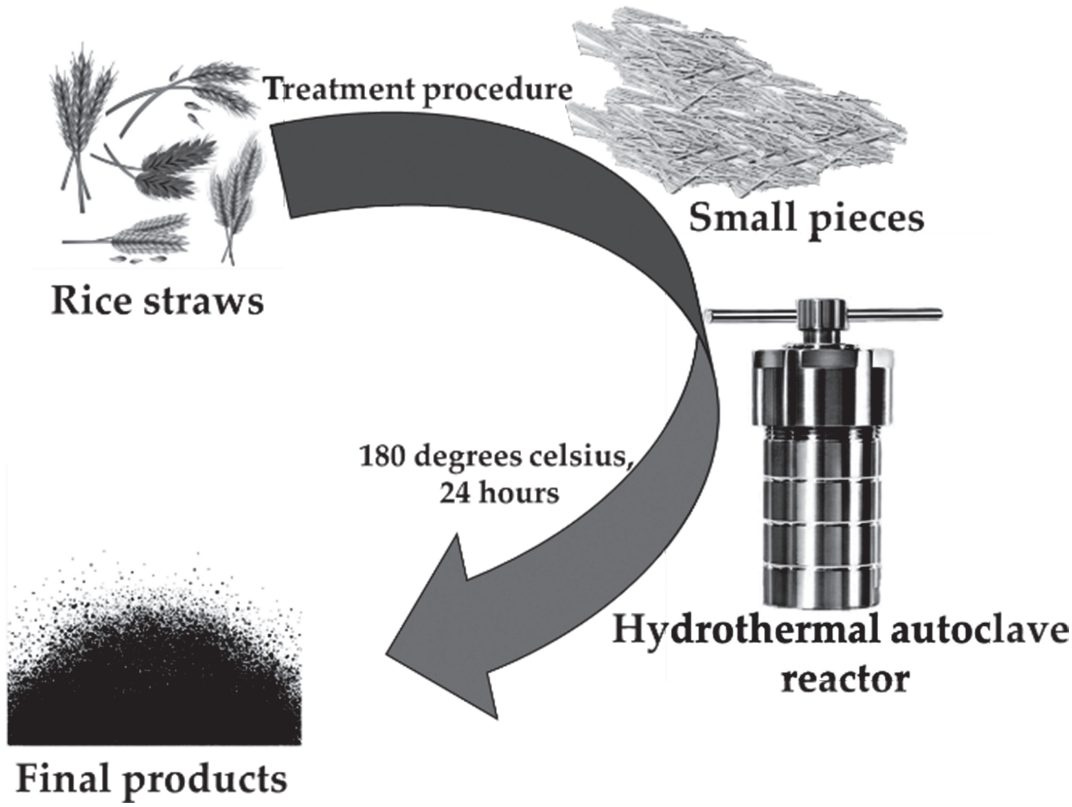

Figure 2. The synthesis procedure of RSCD.

The modification of electrode

A GCE (diameter 2.8 ± 0.1 mm) was polished and buffed using alumina powder (Al) (0.05 μm). It was subsequently rinsed with double-distilled water. The electrode surface was cleaned using ultrasonic waves in an ethanol-water mixture (1:1, v/v). The GCE surface was dried under a tungsten lamp heat source (40 °C).

A suspension of 10 mg RSCD was prepared in 10 mL of double-distilled water and subjected to ultrasonication for approximately 24 hours. Following this, 50 μL of 1% Nafion was added to 1.0 mL of RSCD with a 1 mg/mL concentration. Nafion served as a binding agent for adhering the material to the GCE. (Li et al., 2020)

Results and discussions

The electrochemical detection of CFE with DP-ASV method

Figure 3a displays the DP-ASV curves for different CFE concentrations (0.2×10^{-6} M to 1.4×10^{-6} M). It is clear that peak currents Ip rose with the rising contents from 0.2×10^{-6} M to 1.4×10^{-6} M; thus, it expresses that oxidation procedures occurred solely. The linear regressions of $I_{p,CFE}$ versus $C_{CFE,\mu M}$ can be expressed as follows:

$I_{p,CFE}$ = (-0.142 ± 0.039) + (1.433 ± 0.044).$C_{CFE,\,\mu M}$ R = 0.998 (1)

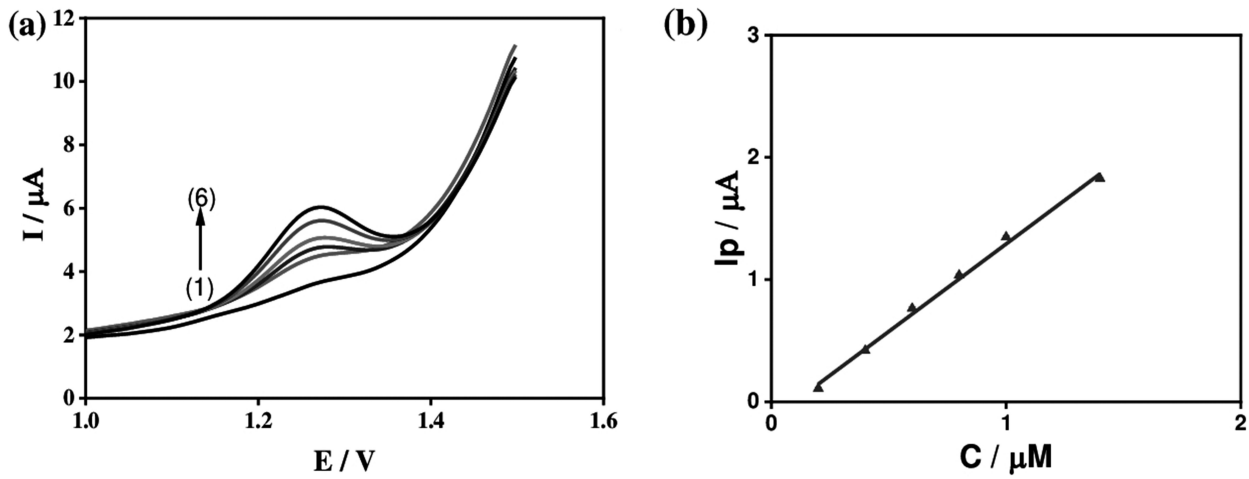

Figure 3. a) The DP-ASVs acquired for the oxidation of CFE in the 0.2 M BRBS buffer solution pH 5 in: (1) 0.2, (2) 0.4, (3) 0.6, (4) 0.8, (5) 1.0 and (6) 1.4 µM; b) The linear correlation of $I_{p,CFE}$ with its concentration.

(Experimental conditions: scan rate = 0.02 $V{\cdot}s^{-1}$; ΔE = 80 V; t_{acc} = 45 s; E_{acc} = –0.1 V)

From Figure 3b, It was detected that Ip linearly depended on the concentration. The LOD and LOQ were determined employing the 3σ method. The obtained results were 0.095 µM and 0.313 µM. The sensitivity could be determined from the regression equation and the sensitivity value was the slope value of the equation (1), 1.433 µA μM^{-1} cm^{-2}. This illustrates that the proposed electrode could detect CFE because of its sensitivity, moderate LOD and LOQ.

The evidence of the cutting-edge electrochemical detection of caffeine

A comparative analysis of the proposed methodology with other voltammetric techniques for quantifying CFE is presented in Table 1. It can be observed that the LOD value for CFE achieved by the employed method is either smaller or would comparable to those obtained using NPs-modified electrodes as reported in earlier studies. In summary, RSCD/GCE has demonstrated its efficacy as an electrode modifier for determining CFE.

Table 1. The reports of determining CFE in various published studies.

No.	Material/Electrode	Method	LOD (µM)	REF.
1	Fe_2O_3/PEDOT	DPV	0.33	(Gao et al., 2018)
2	PLCY@NCNT	DPV	0.20	(Wang et al., 2018)
3	P(L-Asp)/MWCNT	SWV	0.28	(Mekassa et al., 2017)
4	PDDA@MWCNT	DPV	0.05	(Zhang et al., 2017)

No.	Material/Electrode	Method	LOD (μM)	REF.
5	ZnO NPs	DPV	0.038	(Jagadish et al., 2017)
6	NAHGO	DPV	0.008	(Jose et al., 2021)
7	RSCD	DP-ASV	0.095	**This work**

Conclusions

For examining CFE, the suggested method DP-ASV has described good electrocatalytic impact. RSCD was employed to modify the GCE and it is attractive for the CFE determination with various benefits such as high sensitivity, stability and small detection limit (LOD). The LOD and LOQ values acquired by the mentioned electrode are 0.095 μM and 0.313 μM. In addition, it is not difficult to apply this proposed electrode to detect CFE in several practical samples like beverages, urine, and biological fluid… in the next studies.

The proposed RSCD-modified electrode demonstrates significant potential for practical applications in the detection of caffeine across various matrices, including beverages and biological fluids. Its high sensitivity, stability, and eco-friendly synthesis process position it as a viable alternative to conventional detection methods. Future research should focus on scaling the synthesis process, exploring the electrode's compatibility with portable analytical devices, and expanding its application to other pharmacologically relevant compounds. Additionally, the development of multi-analyte detection platforms incorporating RSCD-based electrodes warrants investigation.

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