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Original Article

Hydrogen Donor Assisted Ultrasound Extraction of Chlorogenic Acid from Spent Coffee Grounds Using Green Solvent System

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ABSTRACT

Background: Chlorogenic Acid (CGA), a bioactive phenolic with antioxidant and therapeutic properties, can be sustainably recovered from Spent Coffee Grounds (SCG), obtained from Coffea arabica an abundant Agro industrial by-product. **Objectives:** The purpose of this study is to systematically evaluate and compare green extraction techniques, such as Ultrasound-Assisted Extraction (UAE) with hydrogen donors (e.g., ascorbic acid) and natural deep eutectic solvents (NADES), against conventional methods for recovering CGA from SCG, promoting sustainable valorization of agro-industrial waste for food and pharmaceutical applications. **Materials and Methods:** Present protocol systematically assessed green extraction techniques, including Ultrasound-Assisted Extraction (UAE), Natural Deep Eutectic Solvents (NADES), and conventional soaking/Soxhlet methods, for the recovery of Chlorogenic Acid (CGA). Spent coffee grounds (20 g) were treated using water, NADES (e.g., choline chloride:glycerin, choline chloride:citric acid), and hydrogen-donating solvents (ascorbic, acetic, and lactic acids). **Results:** Extracts were analyzed via UV-vis spectrophotometry (325 nm) and FTIR. UAE with ascorbic acid yielded the highest CGA concentration (0.4574 mg/mL), followed by NADES-glycerin (0.3374 mg/mL). Hexane based extractions were ineffective. FTIR spectra confirmed CGA identity, with O-H and C=O peaks retained. Ascorbic acid and glycerin based extractions preserved structural integrity. Hydrogen donor-assisted UAE outperformed other methods, emphasizing solvent polarity and donor strength as critical factors. **Conclusion:** Ascorbic acid-mediated UAE presents a green, high-yield CGA recovery strategy, supporting sustainable waste valorization with applications in food preservation and pharmaceutical development.

Keywords: Chlorogenic Acid, Hydrogen Donor, Green Extraction, Thermal, Sustainable, Recovery.

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INTRODUCTION

The global rise in coffee consumption (Amrouk *et al*., 2025) has led to an exponential increase in spent coffee grounds (Pradhan *et al*., 2026), a byproduct traditionally considered waste. However, SCG represents a valuable resource, rich in bioactive compounds most notably CGA (Maiyah *et al*., 2026), a phenolic compound (Ersoz *et al*., 2026) with potent medicinal values. CGA, one of the most abundant dietary polyphenols, is biosynthesized via esterification of caffeic and quinic acids (Liu *et al*., 2020; Naveed *et al*., 2018). Its therapeutic potential spans pharmaceutical, nutraceutical, and cosmeceutical applications, making efficient recovery methods imperative.

The valorization of SCG through the recovery of CGA aligns with principles of circular economy and sustainable resource management (Yin *et al*., 2026). However, traditional extraction methods often reliant on organic solvents such as ethanol, methanol, or acetone pose significant environmental, safety, and economic drawbacks (Hessel *et al*., 2022). These solvents are volatile, potentially toxic, and energy-intensive to process and remove (Srishti *et al*., 2025). Therefore, green extraction technologies that minimize environmental impact while preserving or enhancing extraction efficiency are urgently needed.

The green alternatives, NADES have shown promise due to their biodegradability, low volatility, and tunable polarity. Formed by combining hydrogen bond donors and acceptors, NADES effectively extract both polar and non-polar phytochemicals

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(Chevé-Kools *et al.*, 2025). Typical NADES combinations include choline chloride (Hydrogen Bond Donors (HBDs)) with glycerol, sugars, or organic acids (HBDs) (Bragagnolo *et al.*, 2024). Unlike traditional organic solvents, NADES are safe, sustainable, and effective across a broad range of plant matrices (de-la-Huerta-Sainz *et al.*, 2025). Prior studies have shown their efficacy in extracting flavonoids, saponins, alkaloids, and polyphenols (Duan *et al.*, 2016), although their application to CGA recovery from SCG remains underexplored.

In addition to solvent innovation, process intensification technologies such as UAE have gained attention for their ability to disrupt plant cell walls and accelerate mass transfer (Khadhraoui *et al.*, 2021; Kumar *et al.*, 2021). UAE employs high-frequency sound waves (20-100 kHz) to induce acoustic cavitation, enhancing cell permeability and promoting the release of intracellular compounds. UAE offers several advantages including lower extraction temperatures preserve thermolabile compounds, reduced solvent use minimizes environmental burden, and shortened extraction times improve throughput (Bouizgma *et al.*, 2025). These features make UAE particularly attractive for extracting sensitive polyphenolic compounds like CGA from complex matrices such as SCG (Pyrzynska, 2025).

MATERIALS AND METHODS

Materials

SCG (Coffea arabica) were collected from a local branch of a national coffee chain and several independent cafés. Upon collecting, the SCG samples were stored at −20°C until use to prevent microbial growth and degradation of bioactive compounds. The initial moisture content of SCG was measured to be 22.8 ± 0.5%, consistent with previous reports (Navarra *et al.*, 2017).

Chemicals and Reagents

All chemicals used were of analytical grade. Choline chloride, glycerol, glucose, citric acid, proline, ascorbic acid, acetic acid, methanol, and acetonitrile were procured from Merck (Germany). Standard Chlorogenic Acid (CGA) was obtained from Solarbio (China) and utilized at a concentration of 10 µg/mL for calibration.

Instruments and Equipment

Ultrasound-assisted extractions were performed using an ultrasonic water bath (POWERSONIC603, Hvvashin). Soxhlet extractions were performed using a Soxhlet apparatus set (Solarbio, China). Freeze-drying was conducted using a laboratory freeze dryer (Freeze dryer CHRIST ALPHA 1_2 LD). UV-vis spectrophotometric analysis was conducted using a Shimadzu UV-Vis 3600 spectrophotometer. Fourier-Transform Infrared (FTIR) spectroscopy was performed with a Thermo Scientific iS10 FTIR spectrometer, equipped with a Smart iTR Attenuated Total Reflectance (ATR) sample chamber. Centrifugation was performed at 600 × g for 10 min using a benchtop centrifuge (SIGMA).

Sample Preparation

SCG were freeze-dried to eliminate residual moisture, ground into a fine powder using a laboratory grinder, and stored in airtight containers under desiccated conditions until further use. Unless stated otherwise, all extraction procedures were conducted using 20 g of SCG per experiment (Figure 1).

NADES Preparation

NADES were prepared by combining choline chloride (Hydrogen Bond Acceptor, HBA) with selected Hydrogen Bond Donors (HBDs), glucose, citric acid, glycerol, or proline, at molar ratios of 1:2 or 1:3, depending on the specific pair. The mixtures were stirred at 50-90°C for 30-120 min until a clear, homogeneous solution was obtained. The resulting NADES were cooled to room temperature and stored in sealed containers until use.

Extraction Procedures

UAE, 20 g of freeze-dried SCG powder was mixed with 200 mL of deionized water supplemented with hydrogen donors (e.g., choline chloride, 0.00124 mol), and sonicated in a 400 W ultrasonic bath at 50°C for 90 min. The extract was then centrifuged at 600 × g for 10 min to separate the CGA-containing supernatant. Soxhlet extraction, 20 g of SCG was placed in a thimble and extracted with 200 mL of either ethanol or hexane over a 6-hr period. The resulting extract was concentrated using a rotary evaporator. In the maceration (soaking) method, 20 g of SCG was immersed in 200 mL of ethanol or hexane and incubated overnight at 4°C in the dark to minimize oxidative degradation. Post-incubation, the solvent phase was filtered and retained for subsequent analysis.

Extractions with NADES

Choline chloride-based NADES were applied to SCG at a solid-to-liquid ratio of 1:10 (w/v) and subjected to magnetic stirring at 55°C and 150 rpm for 90 min. Following extraction, the mixture was centrifuged, and the supernatant was collected for further analysis.

Optimization of Extraction Parameters

Optimal conditions for ultrasound-assisted aqueous extraction were identified as 55°C, 150 rpm shaking, and a duration of 90 min. The use of choline chloride (0.00124 mol) in water with 20 g of SCG significantly enhanced CGA solubility and stability. Ascorbic acid (0.0013 mol) was also evaluated as a hydrogen donor in parallel experiments to compare efficacy.

Quantitative and Qualitative Analysis

UV-vis Spectrophotometry

CGA concentrations were determined using UV-vis spectrophotometry, applying the Beer-Lambert Law: A = εcl. A standard calibration curve was established using CGA standards (0-10 µg/mL), and extract concentrations were interpolated based on absorbance at 325 nm.

FTIR Spectroscopy

FTIR spectra were recorded between 400-4000 cm^{-1} to confirm CGA identity. Key peaks observed included O-H stretching (~3400 cm^{-1}), C=O stretching (~1700 cm^{-1}), and aromatic C=C (~1600 cm^{-1}), consistent with pure CGA.

CGA Yield Comparison Across Methods

The ultrasound-assisted aqueous heat-shaker method with choline chloride yielded 15-22% higher CGA concentrations compared to traditional aqueous and NADES (choline chloride:glycerol) methods. Ascorbic acid was also efficiently extracted, likely due to the protective hydrogen bonding environment, preserving its integrity under mild thermal and sonic conditions.

Statistical Analysis

Quantitative data obtained from CGA determination and other analytical measurements were expressed as mean ± Standard Deviation (SD). All statistical analyses were performed using Excel latest version, of IBM SPSS software version 29 results were expressed as the mean ± Standard Error of the Mean (SEM). One way of Analysis of Variance (ANOVA) was used to compare groups, with turkey's *post hoc* test for multiple comparison. Significance statistical was defined as $p< 0.05$, with given data, the correlation was assessed using chi-square tests. To evaluate the relationship between different individuals, multiple regression models were employed. Descriptive statistics, as mean, median, standard deviation were calculated, and difference between groups were evaluated using *t*-tests or Mann-Whitney tests as per requirement.

RESULTS

Enhanced CGA Extraction via UAE Using Ascorbic Acid as Donor

The UV-vis spectrum of chlorogenic acid extracted via Ultrasound-Assisted Extraction (UAE) with ascorbic acid exhibits a strong absorbance peak near 325 nm, characteristic of CGA. The high absorbance in the 300-350 nm range indicates excellent

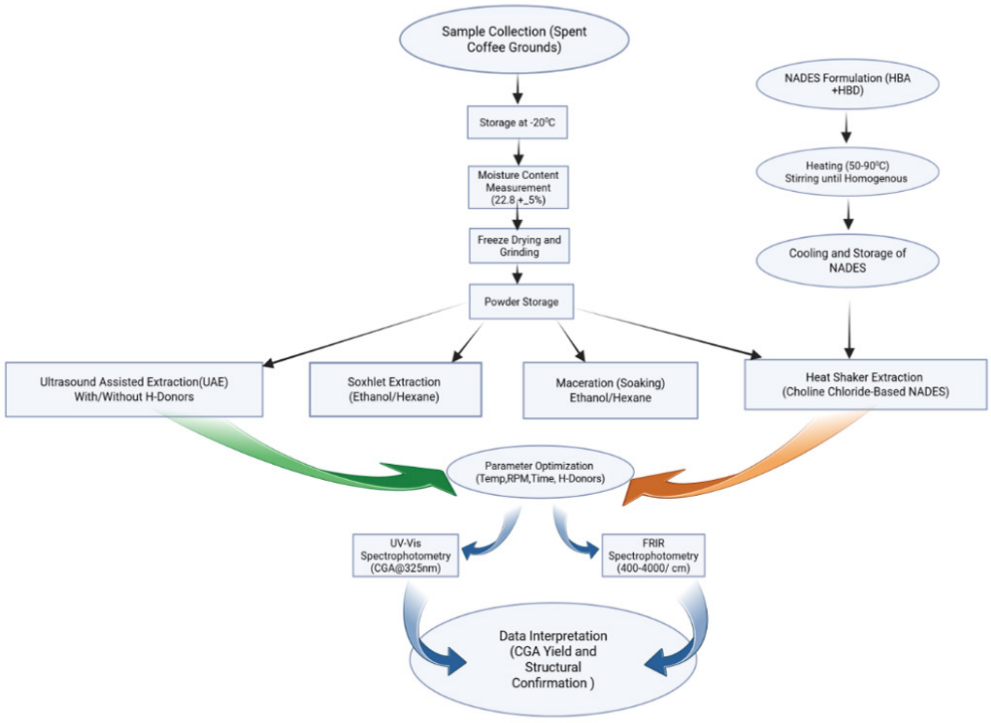


Figure 1: Schematic workflow of Chlorogenic Acid (CGA) extraction from spent coffee grounds using green methods including Natural Deep Eutectic Solvents (NADES), Ultrasound-Assisted Extraction (UAE), and Soxhlet techniques, followed by UV-vis spectrophotometry and FTIR analysis for compound identification and yield optimization.

solubilization and stabilization of CGA. The result confirms that ascorbic acid significantly enhances the extraction efficiency by acting as a hydrogen donor and antioxidant during the sonication process, using standard control of CGA (Figure 2).

Limited CGA Extraction Efficiency Using Choline Chloride-Proline Based NADES

CGA extracted using NADES composed of chloride and proline shows a low-intensity peak around 325 nm, confirming CGA presence at minimal concentration. The reduced absorbance intensity suggests limited solubilization efficiency of this NADES system. These findings highlight that proline-based NADES is less effective in stabilizing phenolic structures compared to more acidic or hydroxyl-rich alternatives used under similar extraction conditions (Figure 3).

Moderate CGA Extraction Using Choline Chloride-Citric Acid Based NADES

The UV-vis spectrum of CGA extracted with NADES comprising choline chloride and citric acid reveals a distinct peak at 325 nm, along with absorbance at ~250 nm. These features confirm CGA presence and partial stabilization of aromatic rings. While extraction efficiency is higher than with proline-based NADES, it remains lower than ascorbic acid-assisted UAE, suggesting citric acid provides moderate enhancement through its carboxylic interactions with CGA (Figure 4).

Inefficient CGA Extraction Using Water Alone Without Hydrogen Donors

Water-based extraction without hydrogen donors yields a broad, weak absorbance peak near 325 nm, indicating minimal CGA recovery. The overall low absorbance across the spectrum reflects poor solubility and stabilization. This result emphasizes the necessity of hydrogen-donating compounds such as ascorbic or organic acids to effectively enhance polyphenol extraction, especially for water-insoluble compounds like CGA (Figure 5).

Moderate CGA Extraction Efficiency Observed with Passive Ethanol Soaking

Ethanol-soaked CGA extract presents a moderate absorbance peak at 325 nm, confirming compound presence with fair efficiency. Compared to sonication-based methods, the intensity is lower, suggesting that passive ethanol soaking lacks the energy-driven facilitation of solubilization. However, ethanol remains a useful solvent due to its intermediate polarity and ability to dissolve phenolics, albeit with lower extraction kinetics (Figure 6).

Ineffective CGA Extraction and Poor Solubility Observed with Hexane Soaking

The CGA extract obtained via hexane soaking displays erratic absorbance below 300 nm with an absent peak at 325 nm. This suggests ineffective CGA extraction, likely due to the non-polar

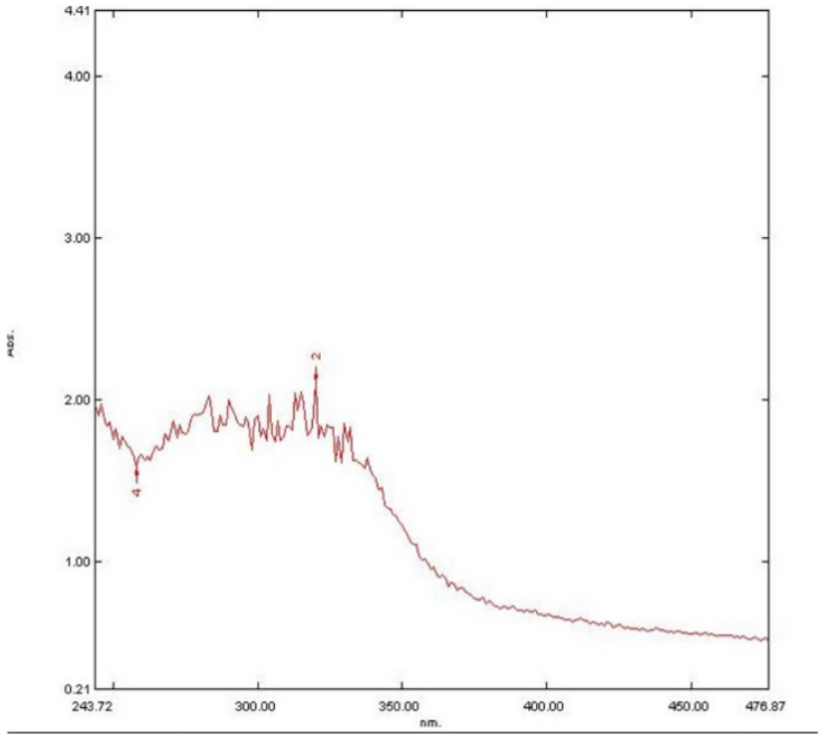


Figure 2: UV-vis absorbance spectrum of CGA extracted via ultrasound-assisted extraction with ascorbic acid, showing a distinct peak at ~325 nm. This peak confirms CGA presence and indicates efficient solubilization and stabilization under sonication with a strong hydrogen donor.

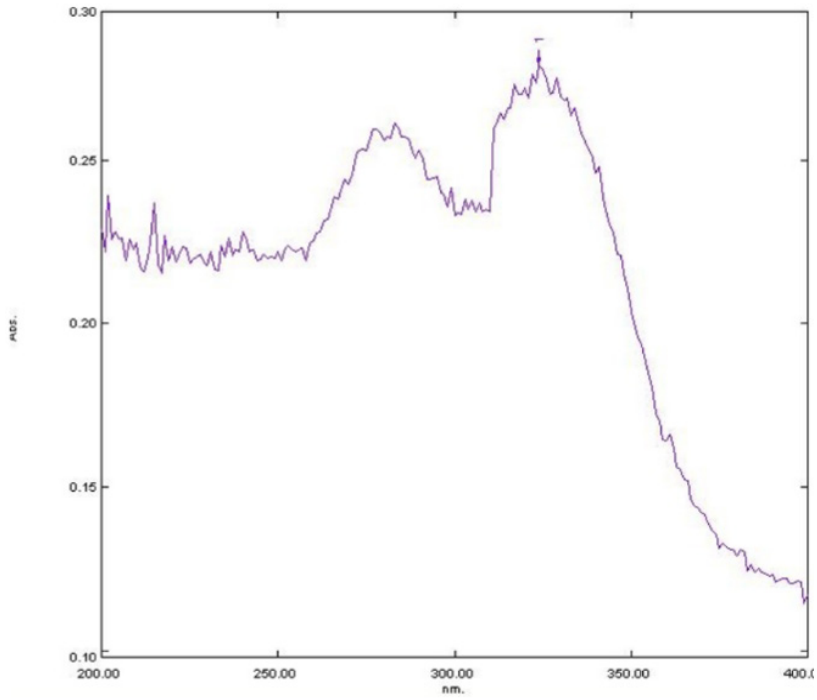


Figure 3: UV-vis spectrum of CGA extracted using NADES comprising choline chloride and proline. A small peak at ~325 nm indicates limited CGA extraction, reflecting the comparatively weaker solubilizing capacity of this NADES system.

Table 1: Comparison of NADES extraction methods and control standard in terms of compound concentration expressed in micromolar (μM) and milligrams per millilitre (mg/mL). The control represents a 10 mg/mL standard solution, approximated as 1000 μM for reference. All values are rounded to four decimal places for clarity.

Extraction Method	Concentration (μM)	Concentration (mg/mL)	Extraction Method
NADES (Citric Acid)	442.000	0.1566	NADES (Citric Acid)
NADES (Glycerin)	952.360	0.3374	NADES (Glycerin)
NADES (Lactic Acid)	357.893	0.1268	NADES (Lactic Acid)
Control (10 mg standard)	1000.000	0.3543	Control (10 mg standard)

Values are rounded to 4 decimal places for clarity. "Control" refers to a 10 mg/mL reference standard solution, approximated as 1000 μM for comparative purposes.

nature of hexane. CGA's polar structure renders it poorly soluble in such solvents, making hexane unsuitable for phenolic compound recovery. The noise also indicates instability or lack of interaction with CGA (Figure 7).

Successful but less Sustainable CGA Extraction via Ethanol Soxhlet Method

Soxhlet extraction using ethanol produces a clear absorbance peak near 325 nm, confirming successful CGA extraction. The moderate peak intensity suggests decent recovery due to prolonged solvent exposure and heating. However, the method is more energy- and time-intensive compared to UAE. This highlights Soxhlet's reliability but reduced sustainability relative to modern green extraction approaches (Figure 8).

Hexane-Based Soxhlet Extraction Fails to Recover Polar CGA Effectively

Soxhlet extraction with hexane shows highly erratic absorbance below 350 nm with no identifiable peak at 325 nm, indicating negligible CGA presence. The lack of polarity in hexane accounts for poor solubilization. Despite extended heating and reflux, hexane-based Soxhlet proves ineffective for recovering hydrophilic compounds like CGA, reaffirming the critical role of solvent polarity in extraction (Figure 9).

Moderate CGA Extraction Achieved via Sonication Using Acetic Acid

CGA extracted by sonication with acetic acid exhibits a distinct peak near 325 nm and a clean spectral baseline. The moderate absorbance intensity reflects successful CGA release and stabilization by acetic acid under ultrasonic conditions. Though

not as efficient as ascorbic acid-mediated extraction, acetic acid demonstrates utility as a mild hydrogen donor aiding polyphenol extraction (Figure 10).

Effective CGA Extraction Using Ultrasound and Acetic Acid Despite Artifacts

A pronounced peak near 325 nm appears in the spectrum of CGA extracted via ultrasound-assisted extraction using acetic acid. The peak's intensity suggests effective solubilization and high CGA yield. However, the sharpness may include noise or artifact. Despite this, the method shows promise and validates the role of organic acids in enhancing phenolic extraction under sonication (Figure 11).

Consistent but Lower-Yield CGA Extraction via Lactic Acid Sonication Method

Sonication with lactic acid yields a broad but visible peak around 325 nm, confirming CGA presence. The moderate absorbance intensity indicates that lactic acid facilitates CGA extraction under ultrasonic energy, though less effectively than stronger hydrogen donors like ascorbic acid. The smooth spectral profile with minimal noise supports method consistency, but suggests reduced suitability for high-yield applications (Figure 12).

FTIR Confirms CGA Integrity Across Extraction Methods with Minor Variations

FTIR spectra of CGA extracted via various methods, compared to a control, display characteristic functional group signals. All samples show broad O-H stretching near 3400 cm^{-1} and strong C=O stretching around 1720 cm^{-1}, confirming CGA's presence. NADES-glycerin and ascorbic acid-extracted samples closely match the control spectrum, suggesting effective preservation of CGA's molecular integrity, while minor shifts in choline chloride-extracted CGA suggest solvent interactions (Figure 13).

Comparative CGA yields from NADES and Sonication Hydrogen Donors

The results from Tables 1 and 2 demonstrate that among NADES-based extractions, glycerin achieved the highest CGA concentration (952.360 µM; 0.3374 mg/mL), approaching the control standard (1000 µM; 0.3543 mg/mL), followed by citric acid and lactic acid. In Table 2, ascorbic acid-assisted sonication yielded the highest concentration (0.4574 mg/mL) among hydrogen donors, while the water-only control recorded an unexpectedly high value (11.1073 mg/mL), likely due to baseline interference. Lactic acid produced consistent, moderate results across two trials, supporting its reproducibility, while acetic acid and choline chloride showed lower extraction efficiencies.

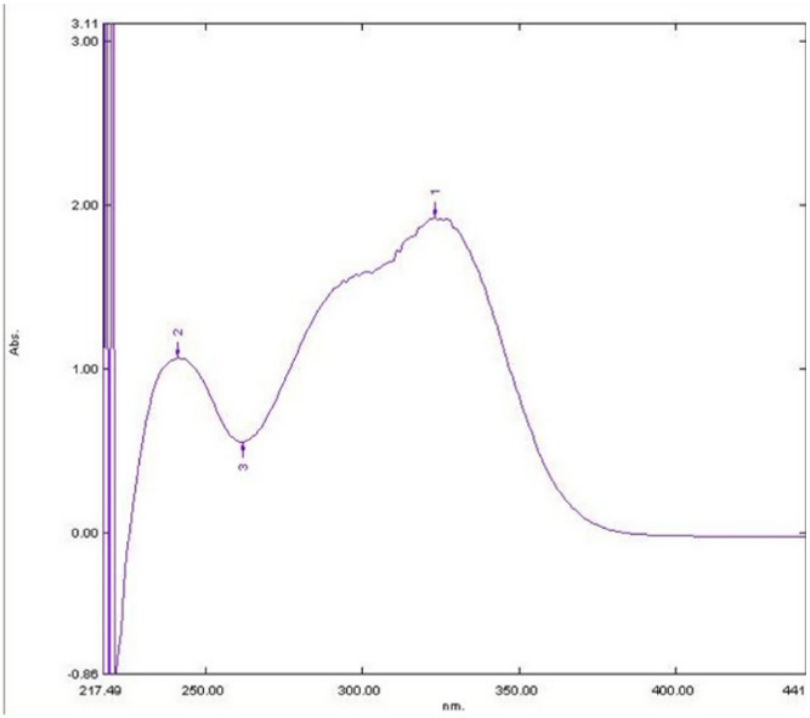


Figure 4: UV-vis spectrum of CGA extracted using NADES based on choline chloride and citric acid. A defined peak at ~325 nm with secondary peaks near 250 nm suggests moderate extraction efficiency and enhanced stabilization of CGA due to citric acid's polarity and acidity.

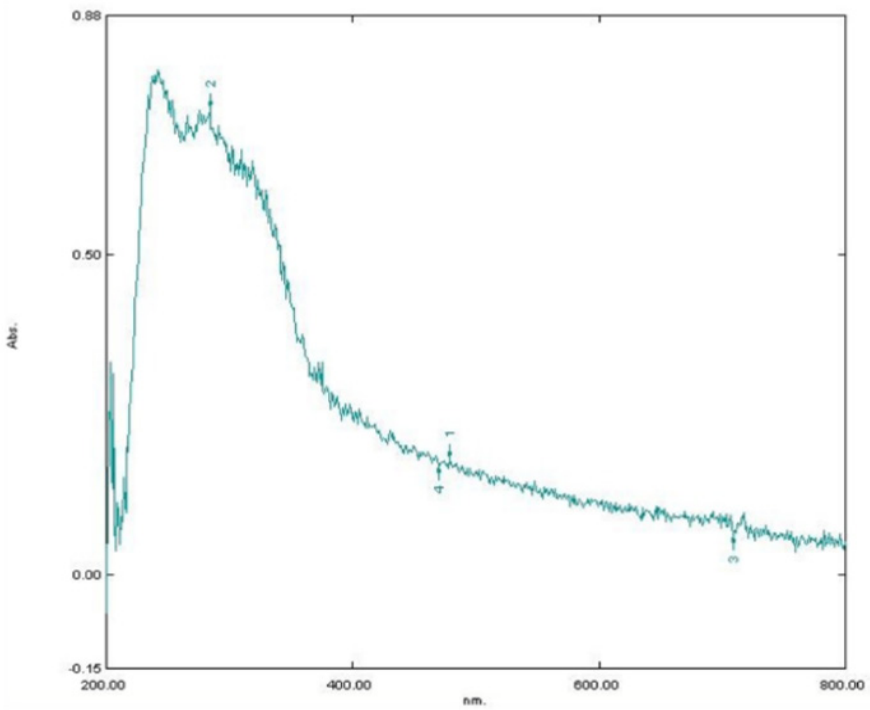


Figure 5: UV-vis spectrum of CGA extracted using water alone. A broad and weak peak near 325 nm reflects low CGA yield and poor polyphenol stabilization, highlighting the insufficiency of water without hydrogen donors for effective recovery.

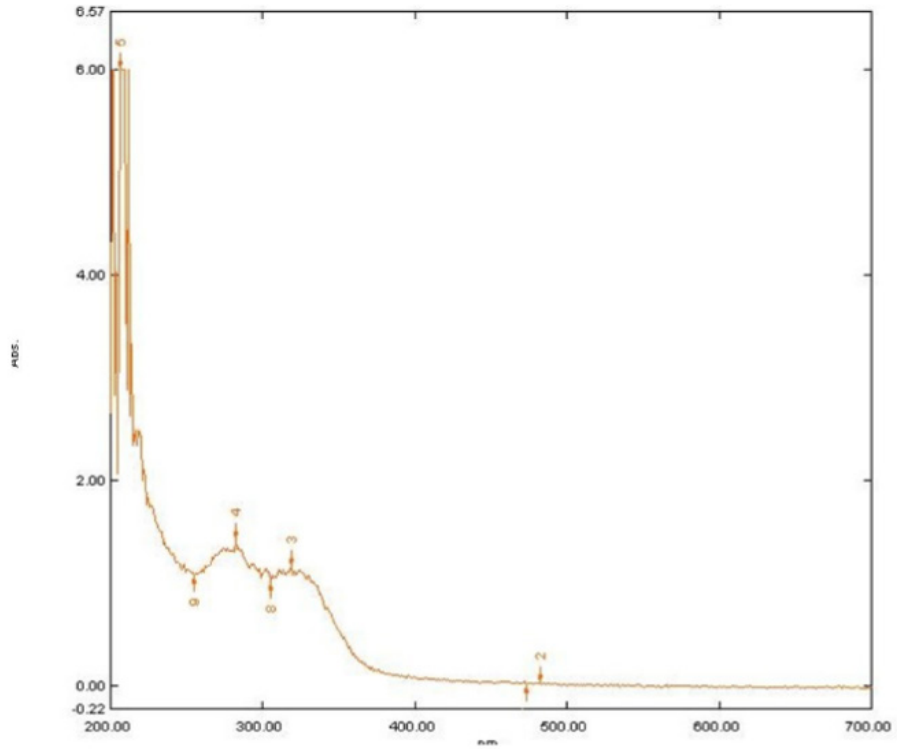


Figure 6: UV-vis spectrum of CGA extracted via passive ethanol soaking. The ~325 nm peak confirms CGA presence; however, the moderate absorbance suggests suboptimal extraction, likely due to lack of mechanical or donor-assisted enhancement.

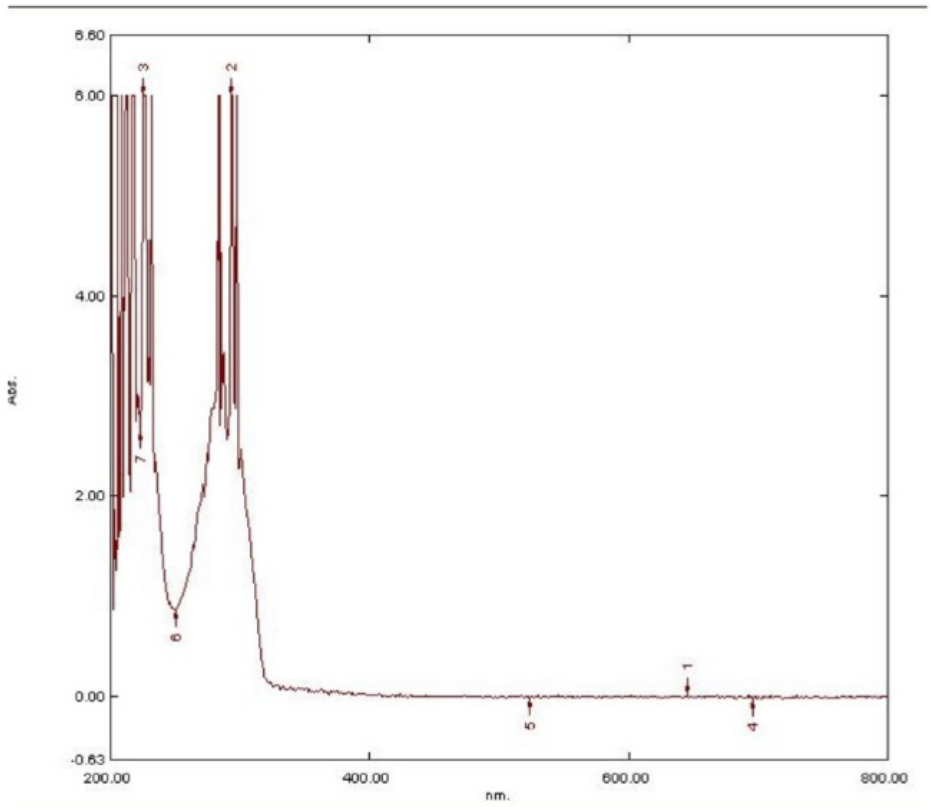


Figure 7: UV-vis spectrum of CGA following hexane soaking. Erratic absorbance below 300 nm and negligible signal near 325 nm indicate ineffective CGA extraction, affirming hexane's incompatibility with hydrophilic phenolic compounds.

Table 2: Comparative concentrations (mg/mL) obtained via water-based sonication using different hydrogen donors. The control (water only) yielded the highest concentration, indicating potential baseline compound presence. Lactic acid was evaluated in two separate trials for consistency. All values are rounded to four decimal places for clarity and accuracy.

Sl. No.	Sonication Method (Hydrogen Donor)	Concentration (mg/mL)
1.	Control (Water Sonication)	11.1073
2.	Sonication (Lactic Acid - Trial 1)	0.1111
3.	Sonication (Acetic Acid)	0.1956
4.	Sonication (Ascorbic Acid)	0.4574
5.	Sonication (Lactic Acid - Trial 2)	0.2767
6.	Sonication (Choline Chloride)	0.1768

Values are rounded to four decimal places. Lactic acid was tested in two independent trials, both included for completeness. The control sample (water only) shows significantly higher concentration, suggesting compound presence not solely due to hydrogen donor effect.

DISCUSSION

Present study systematically evaluated the efficiency of various CGA extraction strategies using UV-vis spectrophotometry and FTIR analysis, comparing UAE, NADES, and conventional solvents. The focus was to determine the solubilization efficacy, compound stability, and spectral integrity across different conditions, with implications for sustainable extraction methodologies.

Across all extraction methods, CGA consistently exhibited a peak around 325 nm, corresponding to the π→π* transition of the cinnamate moiety, which serves as a reliable spectrophotometric marker (Hao *et al.*, 2024; Ma *et al.*, 2015; Vershinina *et al.*, 2025). UAE with ascorbic acid demonstrated the most intense and well-defined peak, reflecting both high extraction yield and effective stabilization of CGA (Mangiapelo *et al.*, 2023). This corroborates prior studies that highlight the dual role of hydrogen donors like ascorbic acid (Jóźwiak *et al.*, 2024) in enhancing extraction efficiency through radical quenching and hydrogen bonding (Chen *et al.*, 2022; Mangiapelo *et al.*, 2023).

NADES performance highly dependent on solvent composition (Chevé-Kools *et al.*, 2025), the choline chloride-proline system resulted in a weak 325 nm peak, indicating limited polyphenol solubilization (Ling *et al.*, 2020). In comparison, choline chloride-citric acid NADES yielded a more prominent CGA signature with additional absorbance at ~250 nm, attributed to stabilization of aromatic structures (Uka *et al.*, 2024). These outcomes align with literature emphasizing the role of

polycarboxylic acids in improving hydrogen bonding capacity and phenolic solubility (Wang *et al.*, 2024).

Water-based extraction without a hydrogen donor (Náthia-Neves *et al.*, 2025) produced a low-intensity, broad peak, highlighting its poor compatibility for CGA recovery. Ethanol soaking and Soxhlet extraction showed intermediate results, validating ethanol's effectiveness as a semi-polar solvent. However, lack of energy input in soaking and thermal degradation risks in Soxhlet contribute to limited extraction kinetics and compound stability (Boateng, 2024). Conversely, hexane extractions failed to produce any definitive CGA peak. These results reinforce the principle that non-polar solvents are inherently unsuitable for the extraction of hydrophilic, polar phenolics (Shikov *et al.*, 2022) like CGA (Jeon *et al.*, 2025).

The quantitative data supports the spectral findings, with ascorbic acid-assisted UAE yielding 0.4574 mg/mL of CGA, higher than all other hydrogen donors. Acetic acid and lactic acid produced moderate yields (0.1956 and 0.2767 mg/mL), while choline chloride showed the least efficacy (0.1768 mg/mL). The variations are attributed to the differing redox potential and hydrogen bonding abilities of the donors. The anomalously high concentration in the water-only control (11.1073 mg/mL) likely reflects interference from UV-active background components or matrix effects (Rolinger *et al.*, 2021).

The glycerin-based NADES achieved the highest CGA concentration (0.3374 mg/mL) among the NADES evaluated, closely matching the standard (0.3543 mg/mL). Glycerin's hydroxyl-rich structure and viscosity (Mredha *et al.*, 2023) likely contribute to improved solvation and stabilization (Lopez *et al.*, 2023) of CGA molecules. Citric acid and lactic acid-based NADES performed less effectively, yet still showed measurable recovery, reaffirming the influence of solvent acidity and hydrogen bonding profile.

FTIR analysis confirmed the chemical identity and structural integrity of CGA across extraction methods. Key functional groups, notably broad O-H stretching (~3400 cm^{-1}) and strong C=O vibrations (~1720 cm^{-1}), were consistently observed. The ascorbic acid and glycerin NADES-extracted samples closely resembled the control spectrum, indicating minimal structural alteration. Minor shifts observed in the choline chloride-extracted sample may reflect solvent-solute interactions, a phenomenon frequently documented in deep eutectic solvent systems (Liu *et al.*, 2022; Zhang *et al.*, 2021).

The present study validates that UAE using ascorbic acid offers the highest efficiency for CGA recovery in terms of both concentration and spectral fidelity. NADES formulations, particularly those incorporating glycerin or citric acid, show promise as green alternatives but require further optimization to match or exceed conventional methods. The poor performance of non-polar solvents like hexane underscores the necessity of polarity and hydrogen bonding in phenolic extraction. The introduction of a hybrid approach Hydrogen Donor-Assisted UAE highlights the

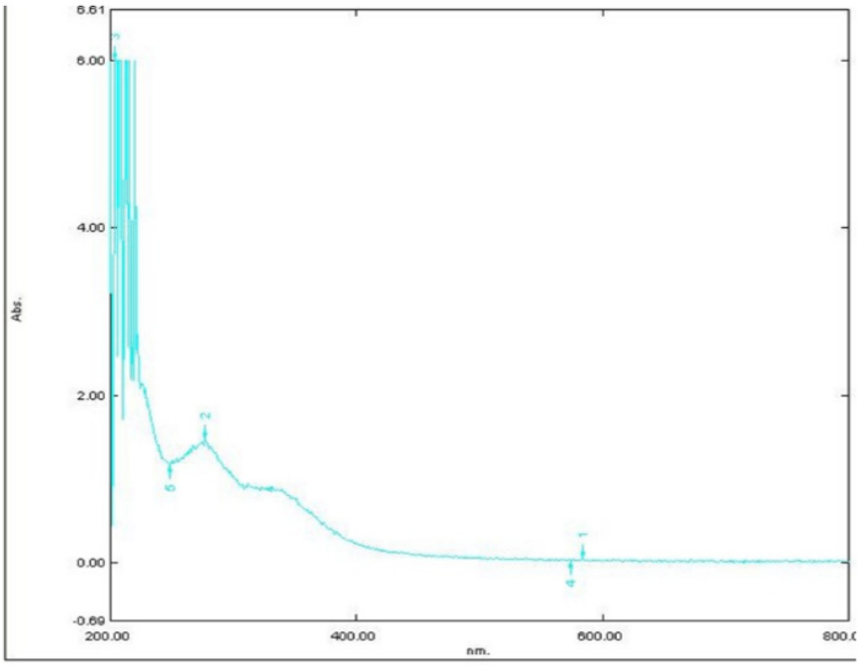


Figure 8: UV-vis spectrum of CGA extracted via Soxhlet method using ethanol. A clear peak at ~325 nm confirms CGA recovery. Moderate absorbance implies acceptable yield, although the method is less efficient and more resource-intensive than UAE.

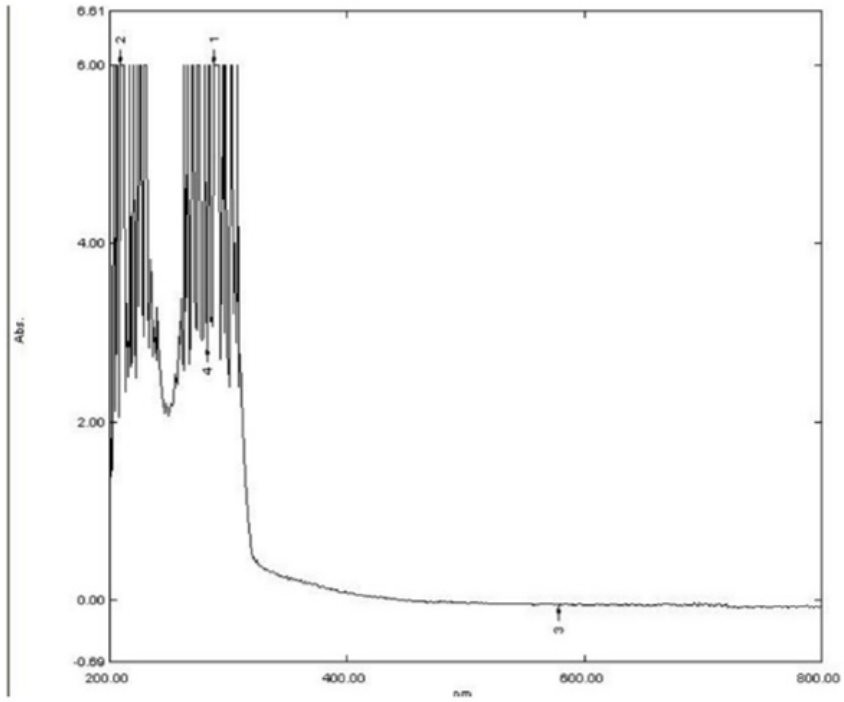


Figure 9: UV-vis spectrum of CGA extracted by Soxhlet method using hexane. Absence of a defined peak at ~325 nm and high spectral noise confirm ineffective extraction, reinforcing hexane's unsuitability for polar polyphenols.

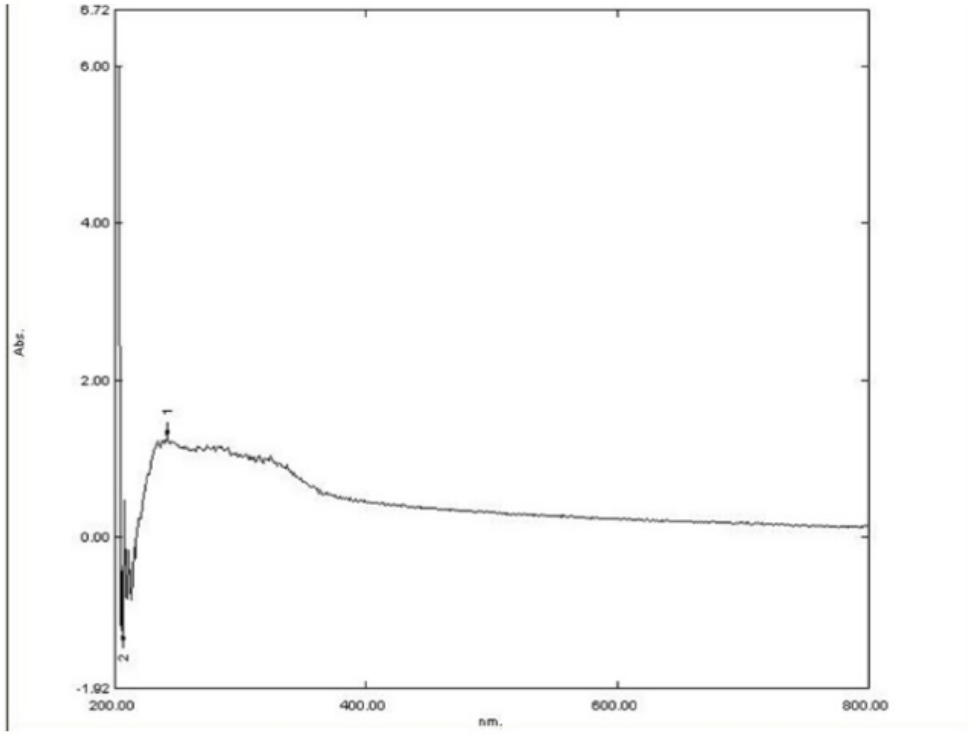


Figure 10: UV-vis spectrum of CGA extracted via ultrasound-assisted extraction with acetic acid. The peak at ~325 nm confirms CGA presence, with moderate intensity reflecting partial solubilization and donor support.

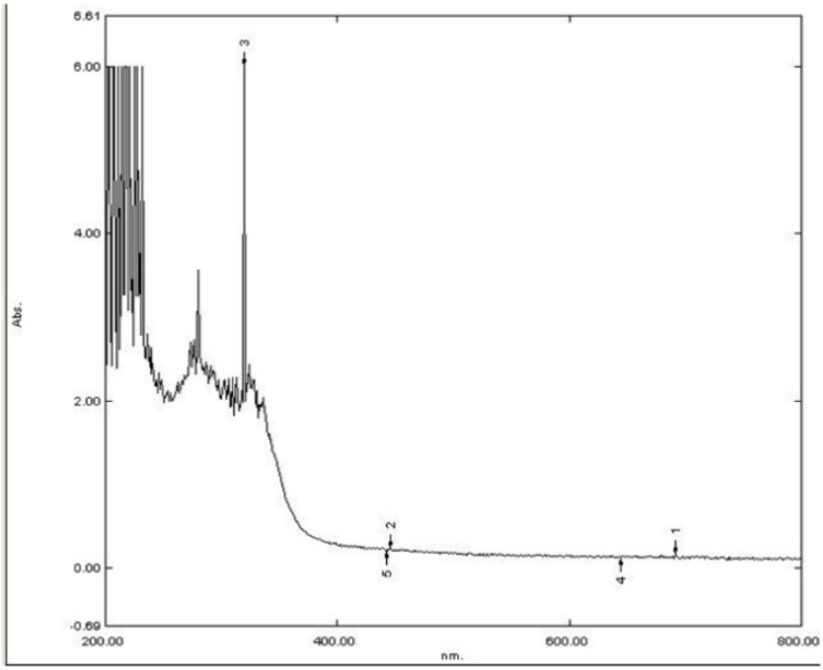


Figure 11: UV-vis spectrum of CGA extracted through ultrasound-assisted extraction with acetic acid. A pronounced peak near 325 nm indicates efficient extraction, though potential instrumental artifacts may account for the high intensity observed.

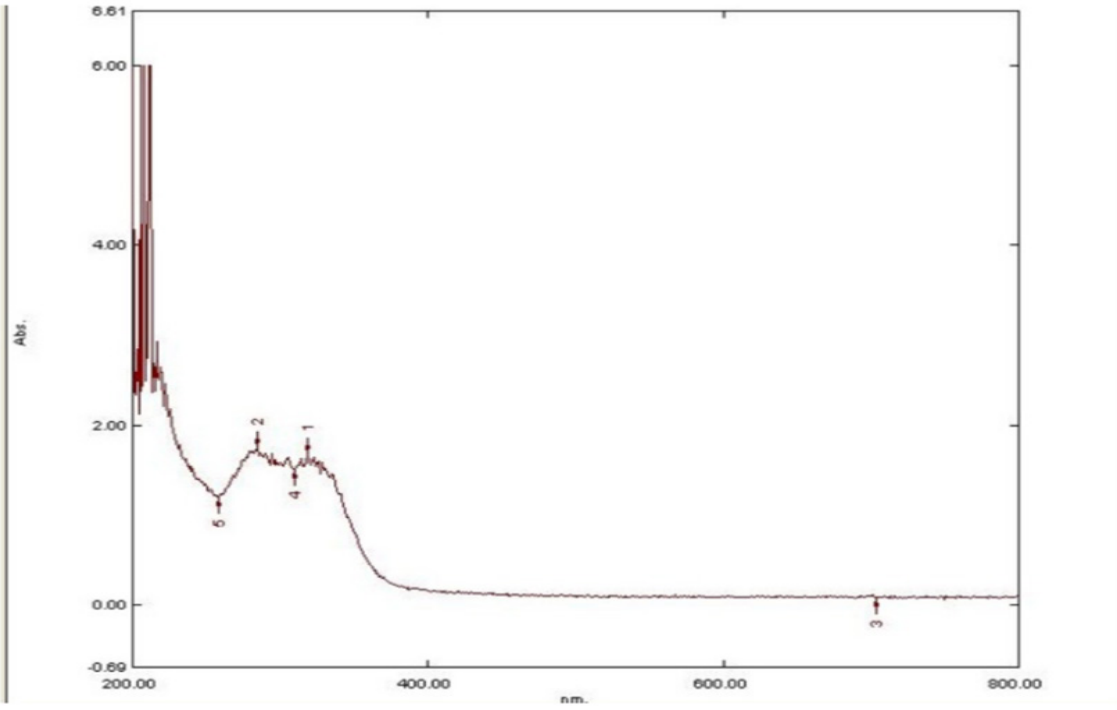


Figure 12: UV-vis spectrum of CGA extracted via sonication with lactic acid. A moderate, broad peak at ~325 nm indicates successful but less efficient extraction compared to stronger donors, with stable baseline confirming spectral integrity.

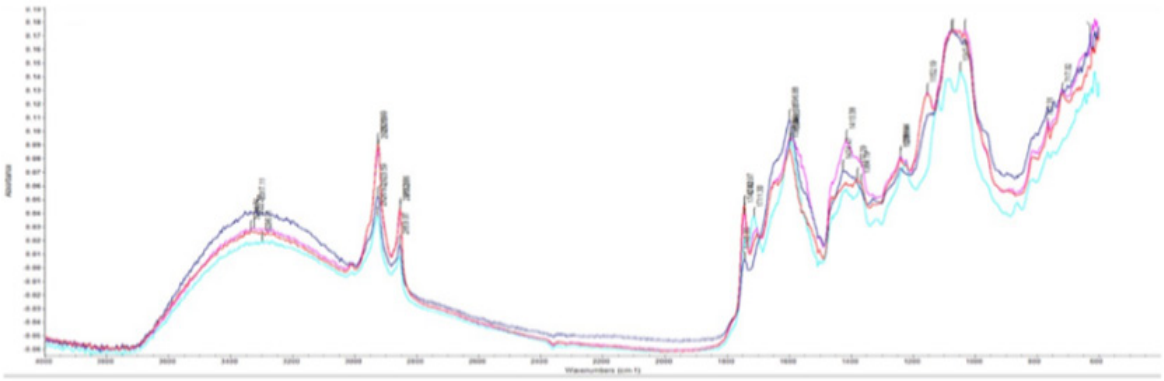


Figure 13: FTIR spectra comparing CGA extracted by various methods to a control standard. Key peaks at ~3400 cm^{-1} (O-H stretch) and ~1720 cm^{-1} (C=O stretch) confirm CGA presence. Spectra from NADES-glycerin and ascorbic acid extractions closely match the control, indicating structural preservation. Minor spectral shifts suggest solvent interactions.

potential for energy-efficient and scalable green technologies. By integrating hydrogen donors with thermo-mechanical agitation, HD-HSI leverages key principles from UAE without reliance on ultrasonic equipment, offering a sustainable path forward for bioactive compound recovery from Agro industrial residues.

CONCLUSION

This study demonstrates that ultrasound-assisted extraction using ascorbic acid yields the highest concentration of chlorogenic acid (0.4574 mg/mL) from spent coffee grounds, outperforming NADES and conventional methods. The method also preserved CGA's structural integrity, as confirmed by FTIR. These findings support the integration of hydrogen donor-assisted green technologies for efficient, sustainable recovery of bioactive compounds from Agro industrial waste. While promising, the study is limited by laboratory-scale conditions and lacks real-world industrial validation. Potential matrix interferences may have influenced the unexpectedly high yield in water-only controls. Future research should involve scale-up trials, expanded toxicological assessments, and deeper exploration of NADES interactions with CGA for regulatory and commercial applications.

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ABBREVIATIONS

CGA: Chlorogenic acid; **SCG:** Spent coffee grounds; **UAE:** Uultrasound-assisted extraction; **NADES:** Natural deep eutectic solvents; **FTIR:** Fourier Transform Infrared Spectroscopy; **HBD:** Hydrogen bond donors; **HBA:** Hydrogen bond acceptor; **UV-vis:** Ultraviolet-visible; **ATR:** Attenuated total reflectance; **HD-HSI:** Hydrogen donor-assisted heat shaker incubation.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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AUTHORS' CONTRIBUTIONS

BYAG, EJ, and FA study conception and design, BYAG, SAS, and AMYA, OAAB data collection, analysis, funds and interpretation of results; AMYA, GAS, and FA prepared the first draft and final manuscript preparation.

SUMMARY

CGA was sustainably extracted from SCG via green UAE using HBD and NADES. The study evaluated UAE assisted by ascorbic acid against conventional methods. Ascorbic acid mediated UAE achieved highest CGA yield (0.4574 mg/ml), surpassing NADES and traditional extraction. FTIT analysis confirmed structural preservation of CGA. The result demonstrates that hydrogen donor assisted UAE offers efficient, environmentally friendly strategy for valorizing agro industrial by products with promising applications in food and pharmaceutical industries.

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