Forensic Science International 384 (2026) 112902

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

# Analysis of cocaine samples from amnesty bins located at a major UK summer music festival over a 10-year period using both low-field benchtop NMR (60 MHz) and medium-field NMR (400 MHz) for comparison

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ARTICLE INFO

*Keywords:*
Cocaine
QNMR
Illicit drug trends
Quantitative analysis

ABSTRACT

Cocaine is the second most popular traditional illicit drug in the European Union, after cannabis, and its high potential for addiction makes it a significant public health concern. Therefore, monitoring trends in the content and purity of street samples can provide valuable information to support harm reduction strategies. This study analysed a selection of 160 street cocaine samples collected at a large British summer festival between 2014 and 2024. A comparison between a low-cost, transportable 60 MHz benchtop nuclear magnetic resonance (NMR) instrument and a more expensive, larger laboratory-based 400 MHz NMR device was used to assess variations in composition and purity levels. Despite a lower signal-to-noise ratio and signal overlap causing some differences in values, the benchtop NMR produced almost identical results to those of the 400 MHz system. Until 2014, cocaine samples were highly adulterated; their purity increased sharply from 2015 onwards, with levels ranging from 80% to 98%, before showing a downward trend in 2024. The most commonly detected cutting agents were benzocaine, levamisole, caffeine, phenacetin, and lactose. Overall, this work demonstrates that low-field NMR can be effectively used to quantify cocaine in street samples. This could be especially beneficial on-site for guiding and enhancing harm reduction services and law enforcement.

## 1. Introduction

Originating from the Andean Highlands and the Northern Amazonian bioregion of South America, cocaine is a sympathomimetic tropane alkaloid (Fig. 1) synthesised from the leaves of *Erythroxylum coca* (*E. coca*) and *E. novogranatense*. The latter is widely distributed across the globe due to its greater adaptability to various climates and its tolerance of non-acidic soils, being initially misidentified as *E. coca*. [1,2].

Although the leaves have been chewed or brewed for thousands of years, cocaine was first isolated in the mid-1800s. However, the beneficial local anaesthetic and psychoactive effects were discovered later, when this substance was brought to Austria and studied by two Viennese scientists, the pharmacologist and psychoanalyst Sigmund Freud, and the ophthalmologist Karl Koller [3]. Found in two forms, as a hydrochloride salt (white powder) or as the free base, also known as crack cocaine (cream lumps/rocks), it was initially formulated as toothache drops, nausea pills, and tonic beverages, which were deemed safe [4].

To extract cocaine, dried coca leaves are treated with lime water and kerosene, then processed with sulfuric acid and lime to yield a cocaine base paste. After further purification and impurity removal, the base is dissolved and finally converted to cocaine hydrochloride using concentrated hydrochloric acid [5].

As a traditional drug of abuse, cocaine remains of significant concern for public health, being the second most used illicit substance in the European Union (after cannabis) and the most commonly abused stimulant, estimated to have been consumed by 2.7 million European adults and up to 23 million of the global population in 2023 [6,7]. Its global

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https://doi.org/10.1016/j.forsciint.2026.112902
Received 10 November 2025; Received in revised form 28 January 2026; Accepted 2 March 2026
Available online 7 March 2026

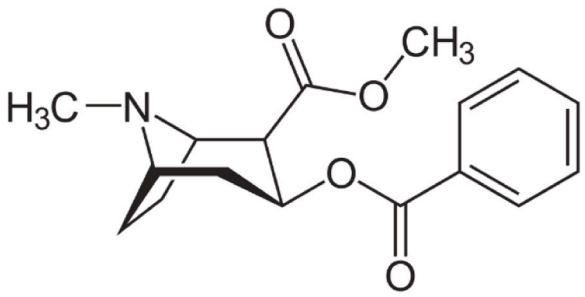


**Fig. 1.** Molecular structure of cocaine ($C_{17}H_{21}NO_4$).

production has reached an all-time high, as reflected by the increasing number of cocaine seizures, users and cocaine-related deaths [7]. Wastewater analysis in 128 European cities and towns showed that cocaine remains highest in western and southern Europe (Belgium, the Netherlands and Spain), with the most recent data reflecting a slight increase in most of the eastern European cities as well. Furthermore, the study showed higher amounts of benzoylecgonine (BE), the urinary metabolite of cocaine, in wastewater during the weekend, confirming the pattern of cocaine use in party settings [8].

Recreational use of cocaine has complex effects on the brain, increasing synaptic levels of dopamine (DA), nor-epinephrine (NE), and serotonin (5-HT) by binding to their transporters and blocking their reuptake [9]. Despite its stimulating and euphoric effects, described as a rush, excitability, and hypervigilance [10], the cardiovascular consequences of cocaine use are numerous. They can be severe, in rare cases, leading to myocardial infarction [11].

Despite increased cocaine trafficking in 2020 amid the COVID-19 pandemic, the UNODC estimated a strong correlation (0.88) between global production and seizures from 2005 to 2020, indicating that interceptions keep pace with rising supply [12]. Furthermore, drug trafficking is often linked to other crimes such as the marketing of counterfeit products, smuggling of migrants, human trafficking, and arms trafficking [13]. According to Europol and the National Crime Agency, mafia-like hierarchical organisations remain the most widespread type of criminal organisation in Europe and the United Kingdom [14,15]. Over recent years, the National Crime Agency in the UK has been monitoring a new form of trafficking known as “county lines”. This involves exploiting vulnerable adults and children (aged between 11 and 56 years old), making them sell illegal drugs, and allowing offenders to increase their profits while lowering the risk of being apprehended [15]. In South America, which represents the starting point for cocaine trafficking, the war on drugs brings with it atrocities and violence, having claimed the lives of almost 300,000 Mexican citizens since 2006, with perpetrators including both organised criminal gangs and state institutions such as security services [16].

Cocaine, like other illicit drugs, is typically sold diluted, contaminated and/or adulterated. Sugars, talc, and starch are the main diluents of cocaine added in transit. In contrast, benzocaine, lidocaine, levamisole, phenacetin, and caffeine are added to street samples to enhance the stimulant effects, increase the amount of product sold and hence increase profit [17–19]. In 2013, 63% of street-level seizures of cocaine hydrochloride (powder cocaine) contained benzocaine [20]. Monitoring the drugs misused on the street and their adulterants is crucial for understanding and minimising toxic effects, overdoses, and fatal reactions. Acute cocaine toxicity can cause tachycardia, dysrhythmia, hypertension, and coronary vasospasm, leading to serious outcomes such as acute coronary syndrome, stroke, and death [21]. Long-term use can also alter cardiac histology, resulting in fibrosis, myocarditis, and contraction band necrosis [22,23]. Another significant risk associated with cocaine use is the induction of excited delirium, which is often linked to aggression, hyperactivity, extreme paranoia, hyperthermia, incoherent screams, and unusual strength [24,25]. Hyperthermia caused by cocaine can reach as high as 45°C and is frequently associated with muscle breakdown, renal and liver injury, encephalopathy, disseminated intravascular coagulation, and metabolic acidosis [26,27].

Not only can identifying adulterants and other secondary chemicals help reduce the harm, but it can also assist in investigating trafficking routes and drug profiling [19,28]. The type and composition of cutting agents can vary as a drug moves along a trafficking route. Different adulterants may be added closer to the manufacturing site, while others might be mixed nearer to the distribution stage [29]. Changes in the chemical profile can reveal the different handovers between groups and the paths drugs took from the manufacturer to the streets. The chemical fingerprint of a drug can indicate its geographic origin, especially for plant-derived drugs such as heroin and cocaine [28].

Nuclear Magnetic Resonance (NMR) spectroscopy is a versatile yet underutilised tool in forensic science, primarily due to the high cost of purchasing and maintaining the necessary equipment and its low sensitivity. However, the very small fractional difference of nuclei in the high-energy state, which generates a weak signal, can be overcome by increasing the number of scans and measurement time, resulting in an improved signal-to-noise ratio (SNR) [30]. NMR enables the simultaneous identification and quantification of several compounds, providing extensive structural information without compromising the sample [31]. Furthermore, this method does not require high-purity reference standards, and no derivatisation is necessary. NMR is superior in reproducibility and intrinsic quantitative ability to mass spectrometry methods, being more accurate and precise, as it avoids the solute adsorption effects and imprecision of analysis that can cause problems with gas chromatography-mass spectrometry (GC-MS) methods [29,32]. Despite its numerous advantages over traditional analytical techniques, NMR is rarely used due to its high instrumental costs and the complexity of the technique. This stems from multiple sources, including the intrinsic complexity of the sample itself, experimental and instrumental challenges, and the significant computational resources required for data processing. However, the greater accessibility of benchtop NMR instruments seems to be influencing changes in their applications and employment. Benchtop or low-field NMR has been successfully used for MDMA quantification in ecstasy tablets [33,34]. It proved to be an effective qualitative method for the analysis of novel psychoactive substances and several other controlled drugs [35,36]. It demonstrated significant advances in the differentiation of analogues and regio-isomers [37,38].

The main goal of this study was to assess whether the 60 MHz low-field (LF) NMR instrument can perform as well as a 400 MHz medium-field (MF) system. Achieving this equivalence would be a major step forward in making drug analysis more accessible and cost-effective. The study examined a selection of 160 street cocaine samples collected at a large British summer music festival between 2014 and 2024. Although the sample size was limited, the results indicated shifts in cocaine purity, cutting agents, and residual solvents, which could help identify the regional origin of street drug samples. Since it is unknown where attendees purchased their cocaine, mapping the trafficking routes would have been difficult. Nonetheless, the findings enable more targeted harm-reduction efforts and give law enforcement a better ability to trace and disrupt illegal supply chains.

## 2. Materials and methods

### 2.1. Samples and chemicals

All street cocaine samples were collected by TICTAC Communications (London, UK) through their amnesty bin drug analysis projects at a large British summer festival between 2014 and 2024. At the organisers' request, the name of the festival will remain anonymous. From a large pool of cocaine samples, 160 samples, evenly representing all years of the festival between 2014 and 2024, were randomly selected. 3-(trimethylsilyl) propionic-2,2,3,3-$d_4$ acid sodium salt (TSP), deuterium

oxide (D, 99%, $D_2O$), and methanol-$d_4$ (D, 99.8%, $CD_3OD$) were purchased from Goss Scientific (Crew, UK). All cutting agents used as reference material for low and medium-resolution NMR identification were obtained from Sigma-Aldrich (Dorset, UK). The 5 mm thin-wall precision NMR tubes, 7 in. long, were purchased from Fluorochem (Glossop, UK). The Eppendorf 1.5 mL polypropylene centrifuge tubes used to dissolve the powder and mix it with the internal calibrant (IC) were purchased from Appleton Woods (Birmingham, UK).

### 2.2. Sample preparation

For NMR analysis, approximately 2 mg of each sample was accurately weighed on a five-digit balance (A&D Company, GH-202) and dissolved in 580 μL of $CD_3OD$. Then 20 μL of TSP solution (2 mg/mL in $D_2O$) was added, and the samples were mixed for 5 min. An aliquot of these solutions (550 μL) was transferred into the NMR tubes for analysis. The same NMR tubes were used on both medium- and low-field instruments, thereby requiring only one preparation per sample.

### 2.3. NMR methods

#### 2.3.1. Low-field NMR

Samples were analysed in $CD_3OD$ using a Nanalysis NMR system (Nanalysis, Canada) operating at 60 MHz. TSP was used as the internal reference and quantification standard (see above). $^1$D NMR spectra were obtained with a spectral width of 12.0 ppm, 60° pulse angle and an acquisition time of 5.57 s. The scan delay of 1 s allowed for full T1 relaxation, with 128 scans collected into 8192 points with 4 dummy scans. The spectrum central frequency was set to 4.87 ppm.

#### 2.3.2. Medium-field NMR

Samples were analysed using a Bruker Avance NMR spectrometer (Ettlingen, Germany) operating at 400 MHz, using a 5 mm tuneable probe. $^1$D NMR spectra were obtained with a spectral width of 12.0 ppm, 30° pulse angle and a pulse recycle time of 6.9 s, allowing full T1 relaxation, with 64 scans collected into 64 k points with 4 dummy scans. The spectrum central frequency was set to 4.87 ppm.

2D-COSY NMR spectra were obtained using a spectral width of 7.6 ppm with 2 k points and 256 increments with 16 scans per increment, and 8 dummy scans. Spectra were zero-filled to 2 k x 2 k and processed with a sine function in both dimensions. The spectrum central frequency was set to 4.87 ppm. All spectra were run at a temperature of 300 K.

### 2.4. Data analysis

All spectra were processed off-line using Bruker Topspin 4.4.0 software. Peak integrals were measured and compared with TSP using either the Bruker integration routines or a machine-learning deconvolution method available in TopSpin. The analysis was carried out by integrating the cocaine singlet methyl signal at 2.87 ppm in both 60 and 400 MHz spectra. This signal was chosen because it represents an isolated methyl group that is not spin-coupled to adjacent hydrogen atoms. This characteristic renders it highly suitable for interpretation in both medium-field MF and LF NMR data. The signal consistently appears as a singlet in both spectral regimes and can be readily integrated owing to minimal spectral overlap with neighbouring signals. In contrast, the alternative methyl group's resonance coincides with a crowded spectral region, thereby complicating accurate integration and quantitative analysis. The implementation of an integration routine utilising the machine learning-based peak deconvolution feature in TopSpin proved particularly advantageous in the context of this study. This approach was instrumental in accurately analysing and distinguishing overlapping spectral signals, thereby enhancing the reliability and precision of the resulting data interpretation. The purity calculation was performed using the modified formula below (1), which was also employed in the MDMA quantification study [33].

$$P_{cocaine} = \frac{I_{cocaine}\, N_{TSP}\, M_{cocaine}\, m_{TSP}\, P_{TSP}}{I_{TSP}\, N_{cocaine}\, M_{TSP}\, m_{cocaine}} \quad (1)$$

Where $P$ = purity, $I$ = integration area, $N$ = number of protons, $M$ = molar mass, $m$ = mass.

## 3. Results and discussion

Notoriously, street cocaine samples reflect a substantial variation in both qualitative and quantitative composition, which could impede their analysis [39]. The current study confirmed these findings, as most samples contained cutting agents, their amounts varying widely from almost none in some cases to large amounts in others. Although not the primary focus of the study, the 400 MHz integration values indicated benzocaine at approximately 80%, levamisole at 25%, phenacetin at 36%, and caffeine at 68%. These figures were obtained solely from the integration values, estimating the amount of the cutting agent in the sample relative to the original weight of the street cocaine. Several typical NMR spectra acquired in this study are shown in Fig. 2, showing cocaine mixed with some of the most common cutting agents such as benzocaine, caffeine, levamisole and lactose. Other studies similarly reported the common occurrence of cutting agents in cocaine street samples, with caffeine, benzocaine, levamisole, phenacetin, aminopyrine, lidocaine, and tetracaine being a few of the most common in Brazil and Colombia [40–42]. A list of the most common cutting agents encountered in cocaine street samples and their chemical structures is shown in Figure S1.

The assessment of the benchtop NMR, conducted in comparison with the medium-field instrument, showed almost identical purity values. A comparison of the spectra acquired at the two different resolutions is shown in Fig. 3.

For instance, sample 15–087 had a calculated purity of 30.0% (integration value of 272.9) according to the LF NMR and 30.1% (integration value of 273.8) on the MF NMR (Figure S2). The standard deviation of cocaine purity ranged from 0.02 to 14.40, falling well within the UNODC limit (20%) for quantitative method validation [43]. However, two samples from 2019 exhibited a significant discrepancy between the purity values determined by LF and MF NMR analysis. The most notable difference was observed for sample 19–104, with a standard deviation of 31.1 (Figure S3), while the other sample demonstrated a standard deviation of 20.7. Although the latter was near the threshold, both samples were considered to exceed the UNODC-recommended limits. This can be partially attributed to the noisier spectra acquired on the LF NMR unit, making their integration less precise. Another impediment could have been fluctuations in the laboratory temperature at which the LF NMR analyses were routinely conducted. On several days of analysis, the temperature exceeded 26°C for extended periods, preventing the instrument from being shimmed and resulting in slightly higher linewidth values (1.2–1.4 Hz). Furthermore, signal overlap could also impact the quality of the spectra, especially on the 60 MHz spectrometer, which has lower signal dispersion compared to the 400 MHz spectrometer. This was also reported by Bao *et al.*, who conducted a comparative evaluation of low-field and high-field NMR on virgin coconut oil adulterated with refined coconut oil. They concluded that the LF $^1$H NMR spectra are prone to extensive overlapping and have limited sensitivity/resolution [44]. In this study, the peak of interest was selected based on the minimal overlapping peaks. Another issue could be attributed to the increased presence of impurities, which result in overlapping signals, making their processing and integration more challenging. However, sample 14–460 contained a significant amount of benzocaine (~ 38%), causing overlap between the cocaine peaks at approximately 8 ppm, but this has not affected the cocaine quantification since the peak of interest is at 2.85 ppm (Fig. 4 *and* Figure S4*)*.

A potential way to maximise the reliability of LF NMR instrument

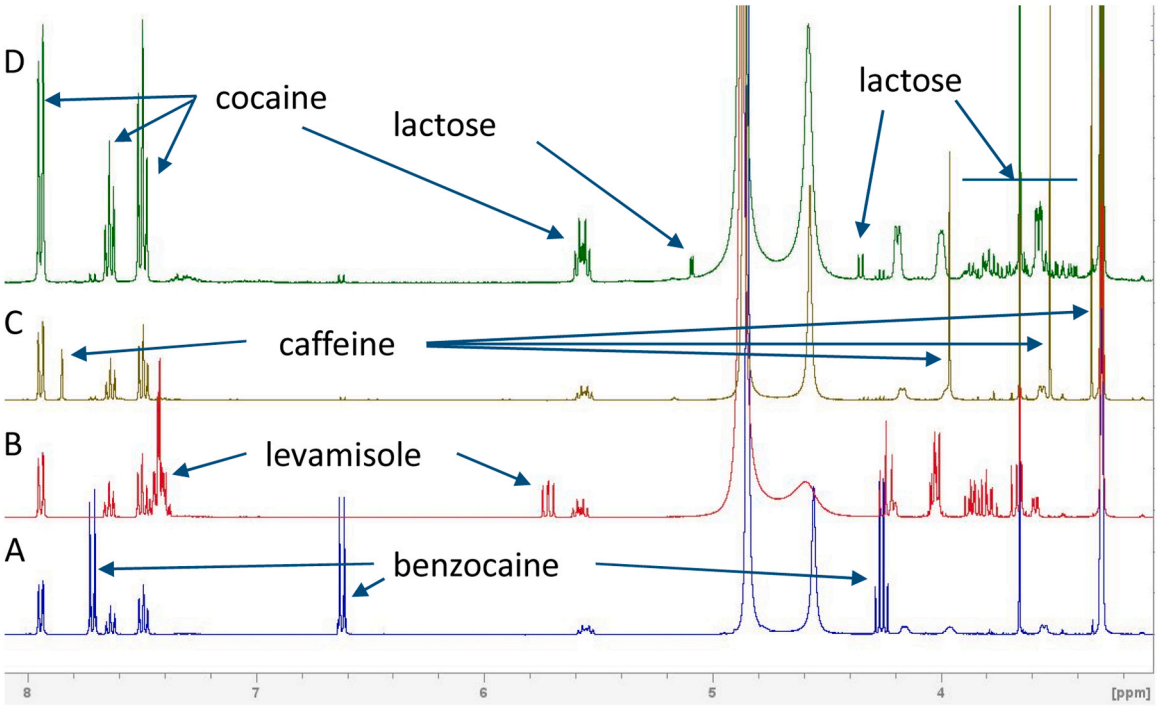


**Fig. 2.** Typical 400 MHz NMR spectra obtained in this study, revealing cocaine mixed with: **A** benzocaine, **B** a large amount of levamisole, **C** caffeine, and **D** lactose. Their chemical structures are shown in Fig. S1.

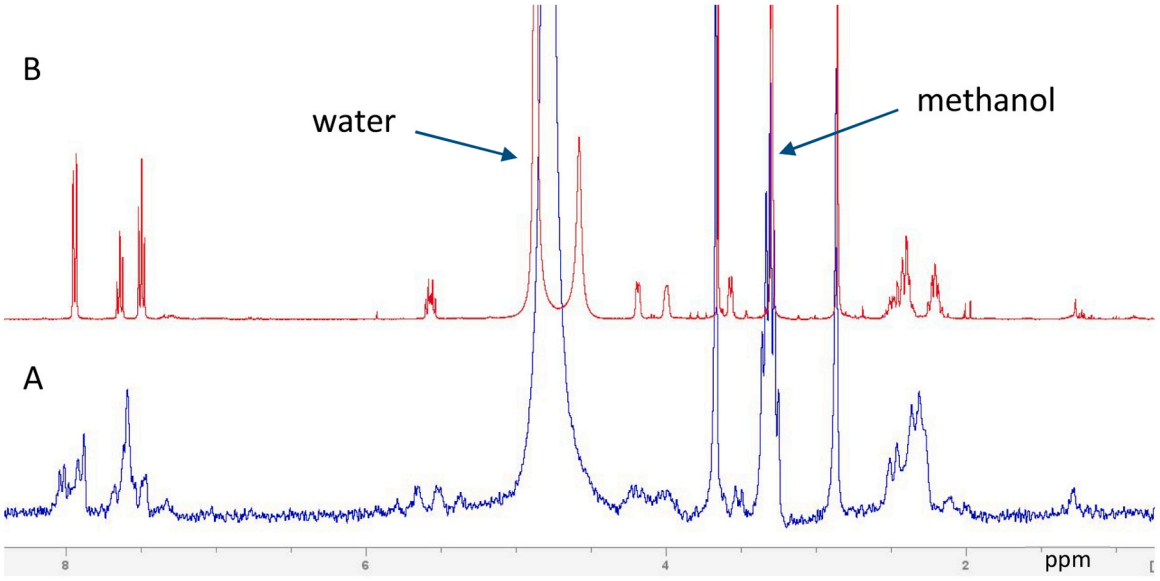


**Fig. 3.** Spectra of the same relatively pure cocaine sample acquired on the low-field 60 MHz (A) and medium-field 400 MHz (B) NMR spectrometers. Water and methanol are labelled, and the remaining peaks are from cocaine only.

performance could involve systematic integration of stringent environmental condition control, hardware enhancements, refined experimental protocols, and sophisticated software processing. Overcoming intrinsic limitations, such as reduced sensitivity and magnetic field instability, is essential to achieving robust, reproducible analytical performance. Although the temperature variation experienced while conducting the current study could not be addressed in a timely manner, placing the instrument in a controlled environment would enhance its performance. The development of a temperature- and humidity-controlled glove box was discussed with the manufacturers to ensure a stable environment. Ultimately, the quality of LF may be enhanced by increasing the amount of cocaine analysed, provided it is available. This adjustment would improve SNR with reduced acquisition time, thereby contributing to more effective shimming and overall spectral resolution. Despite inherent limitations in resolution and sensitivity, the results demonstrated the potential of the benchtop NMR unit for practical applications. Its compact size and simplified operational requirements offer substantial advantages in accessibility and field deployment. Moreover, when integrated with chemometric approaches, the benchtop NMR exhibited robust analytical performance, further strengthening its value as a versatile tool for rapid and reliable drug analysis [45]. The same instrument was assessed (on and off-site) at a music festival for

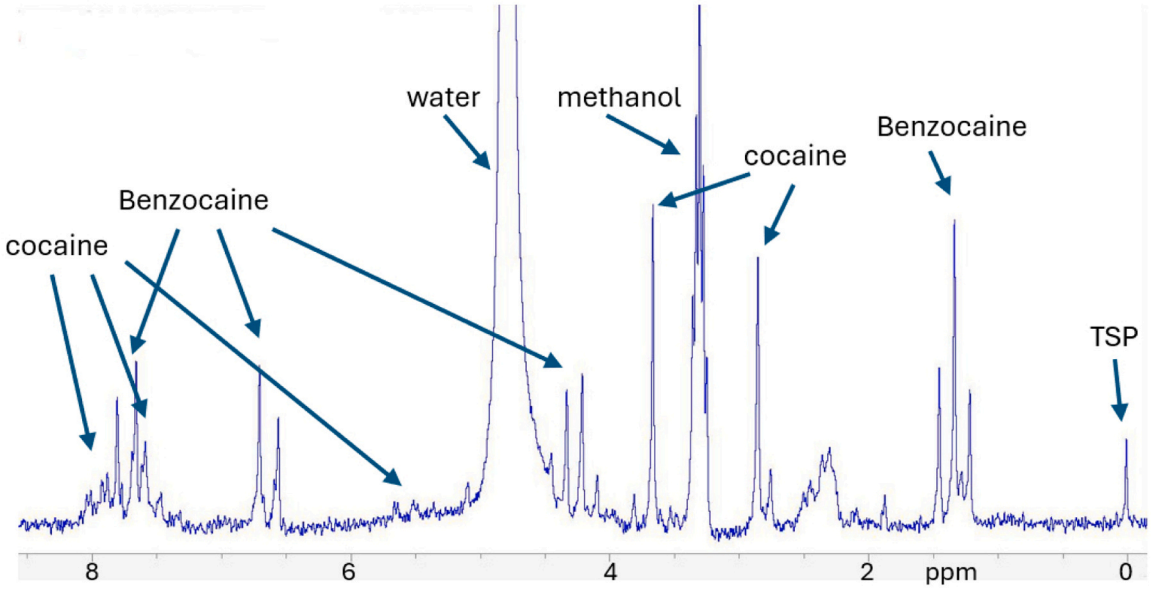


**Fig. 4.** An example of a poor-quality spectrum (sample 14–460) showing interference from impurities and overlapping peaks.

qNMR analysis of MDMA in ecstasy tablets [33], proving to be efficient and sufficient for quantitative analysis. Moreover, the variation in MDMA content in street tablets emphasised the need for constant monitoring of the market, and this also applies to cocaine samples [46], which could be achieved by using low-field NMR instruments. Other studies were also successful at applying benchtop NMR analysis to substandard and counterfeit medicines [47], food supplements laced with sildenafil [48], herbal mixtures possibly sprayed with synthetic cannabinoids [49], as well as other illegal drugs [50–52]. However, to the authors' knowledge, this is the first study of cocaine samples seized at music festivals, using a 60 MHz benchtop NMR instrument and comparing the results with those obtained on a 400 MHz NMR system.

Recent years have seen an increased but highly variable purity of the "end user" samples of street cocaine. This increases the risk of harm to users, especially if they are unaware of the rise in purity [53,54]. The over-time changes in cocaine purity recorded in the current study using the LF and MF NMR methods are shown in Fig. 5.

The correlation analysis between the 60 MHz and 400 MHz instruments yielded an $R^2$ value of 0.9233, indicating a strong positive linear association. The pronounced clustering of data points along the upward-sloping regression line, coupled with minimal scatter, provides further evidence that the two instruments produced highly consistent and comparable results. (Fig. 6).

As confirmed by a previous study, the 2014 cocaine samples were highly adulterated and had a median purity level of about 40% [55]. This trend appeared to have reversed from 2015 onwards, with levels ranging from 80% to 98%. However, in more recent years, cocaine purity appears to have returned to levels similar to those in 2014. Whilst the sample size per year (n = 20) may be too small to visualise temporal patterns or establish statistically significant trends accurately, it is

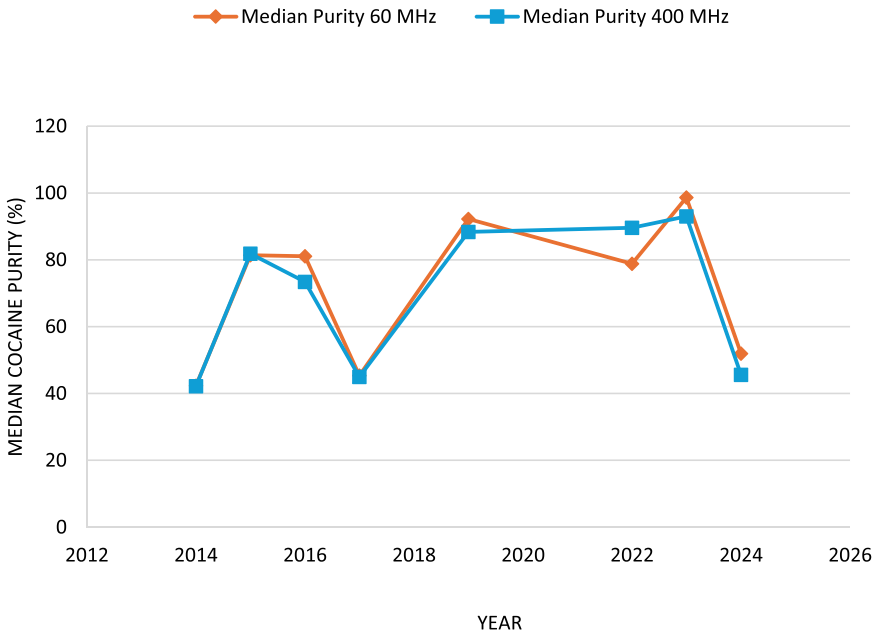


**Fig. 5.** The variation in median cocaine purity over a decade (N = 160) using the LF NMR instrument (orange diamonds) and the MF NMR (blue squares). Notably, cocaine was reported as an HCl salt, and spectra were acquired on the 60 MHz and 400 MHz NMR instruments.

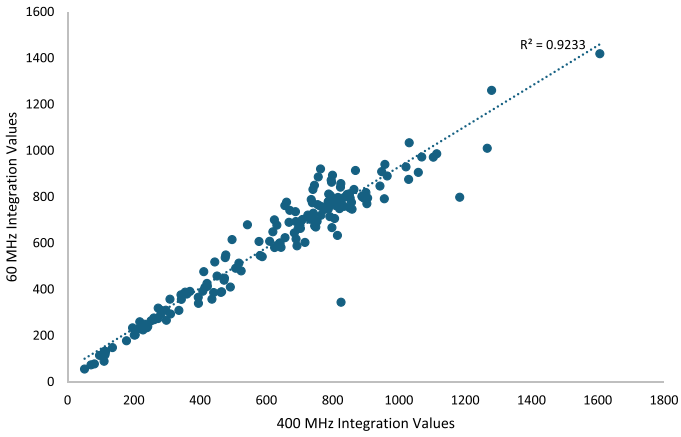


**Fig. 6.** A correlation plot highlighting the comparison between the results acquired on the LF and MF NMR instruments.

important to note that trend analysis was not the primary focus of the current study. Instead, the main objective was to evaluate the capability of the 60 MHz low-field LF NMR unit to provide results comparable to those obtained with a 400 MHz medium-field instrument. A critical difference was observed in the distribution of cutting agents. There was a higher predominance of benzocaine and levamisole in 2014 and 2015, with peaks even larger than the cocaine peak of interest. Although less predominant, caffeine and phenacetin were also detected over the years. In 2017, when the cocaine purity recorded a dip, falling to about 40% again, more cutting agents were detected individually or combined in the cocaine samples (Fig. 7).

Benzocaine, procaine, lidocaine and tetracaine are deemed to potentiate the local anaesthetic property of cocaine, misleading the users into thinking they have purchased highly concentrated samples [56]. Levamisole is an enantiomer of the anthelmintic drug tetramisole, discontinued due to serious side effects. It metabolises to an amphetamine like compound, aminorex [57], while caffeine is a stimulant itself; therefore, both potentiate the thrill produced by cocaine use [17].

From 2019 to 2023, the purity of the cocaine samples increased, and the occurrence of the cutting agents was minimal. However, 2024 showed a decrease in cocaine purity when compared with the previous few years (2019, 2022, and 2023), with the average purity dropping to about 43% [6]. This was also observed by various drug-checking organisations that reported their drug-monitoring results to the EUDA in 2024 [58]. Eleven of the analysed samples contained a significant amount of benzocaine, with one sample showing over 72% benzocaine content. Five of the samples contained phenacetin as the cutting agent, and one sample contained a substantial amount of lactose (32.4%).

The overtime changes become clearer when all 20 NMR spectra from each year were summed to get an average spectrum per year. The eight averaged spectra were created to facilitate and smooth the comparison. The main difference highlighted is the dominance of cutting agents in earlier years compared to 2019 onwards and their reappearance in 2024, as shown by the overlapping averaged spectra from 2014, 2019, and 2024 (Fig. 8).

Two-dimensional (2D) NMR spectroscopy was used to confirm the structure of the major cutting agents observed in 14 samples at 400 MHz.

For example, Fig. 9 shows a 2D-COSY spectrum of a cocaine sample (17–225B) that also contains a large amount of benzocaine (~61%), as indicated by the blue rectangles on the spectrum, with cocaine indicated by red rectangles (26.9%), and levamisole in green rectangles (~3%). The corresponding 1D spectrum is shown on the left side and at the top.

Mapping cocaine impurities can assist law enforcement, forensic intelligence, and public health authorities. It enables them to establish links between drug seizures, develop insights into illicit distribution networks, and track drug market trends to mitigate risks and harms [59]. Pagano et al. developed a $^{1}$H NMR method combined with multivariate analysis to study spectral regions of the minor components only in the cocaine samples. This demonstrated the positive impact of profiling cocaine seizures in Naples and mapping their origin and trafficking routes, showing that the 'minor compounds' can be used as chemical fingerprints that could assist law enforcement, revealing new distribution networks [29]. Notably, the present study identified up to eight distinct resonances (ranging from 0.8 to 2.05 ppm) in the cocaine spectra, manifesting as singlets, doublets, and triplets. These spectral features are attributed to residual solvents persisting in cocaine samples following production and purification. While a comprehensive investigation of these resonances falls beyond the immediate scope of this study, it will be pursued in a dedicated future publication. Subsequent research will rigorously explore the potential of NMR profiling to elucidate trafficking routes and synthesis methodologies, thereby providing valuable forensic intelligence to support law enforcement efforts in tracing the provenance of cocaine seizures.

## 4. Conclusions

Cocaine, the naturally occurring stimulant extracted from Coca leaves, remains one of the most popular drugs of abuse, posing a significant burden on the healthcare systems [60].

Although the number of samples included per year was limited, the current study revealed a 92.8% variation in cocaine free base concentration in street samples. This emphasises the need for constant

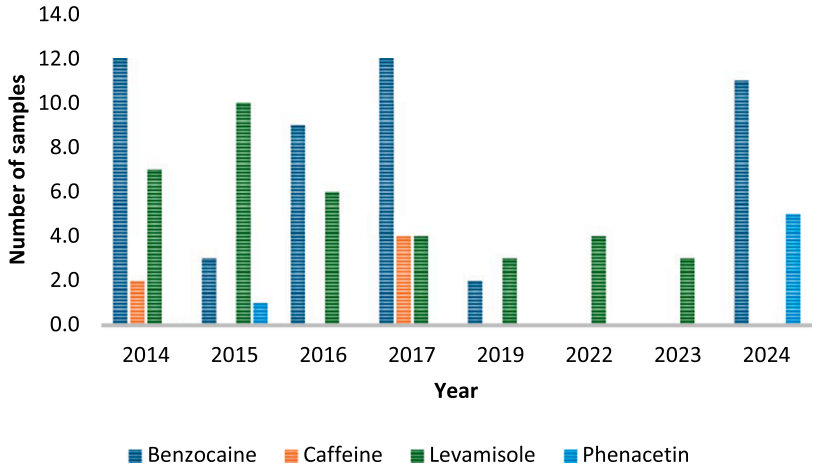


**Fig. 7.** The distribution of cutting agents over a decade.

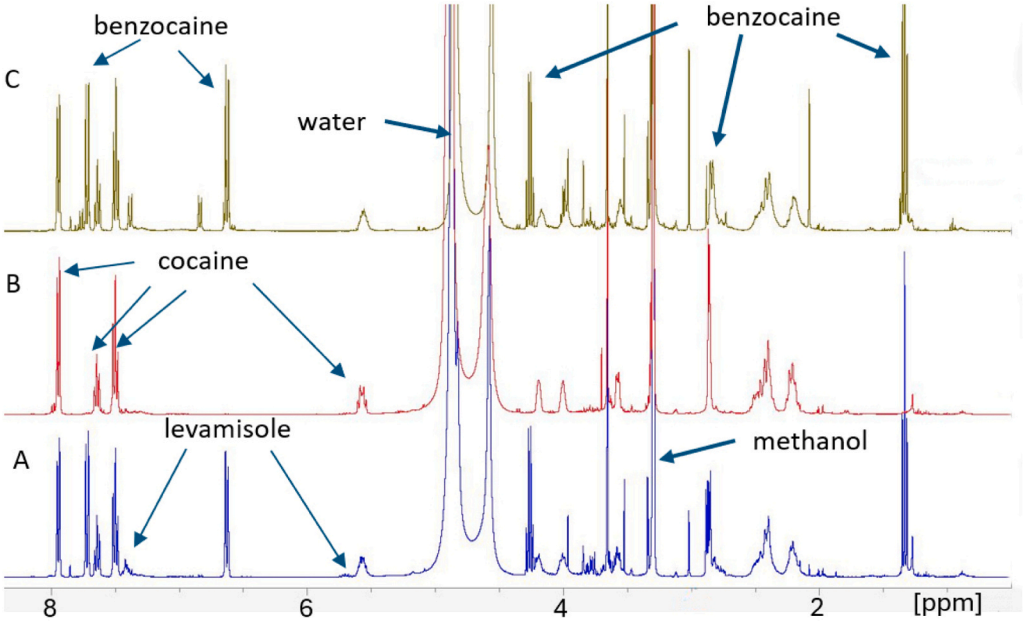


**Fig. 8.** The summed NMR data for 2014 (A), 2019 (B), and 2024 (C), highlighting the presence of benzocaine in 2014, its absence in 2019, and its reappearance in 2024.

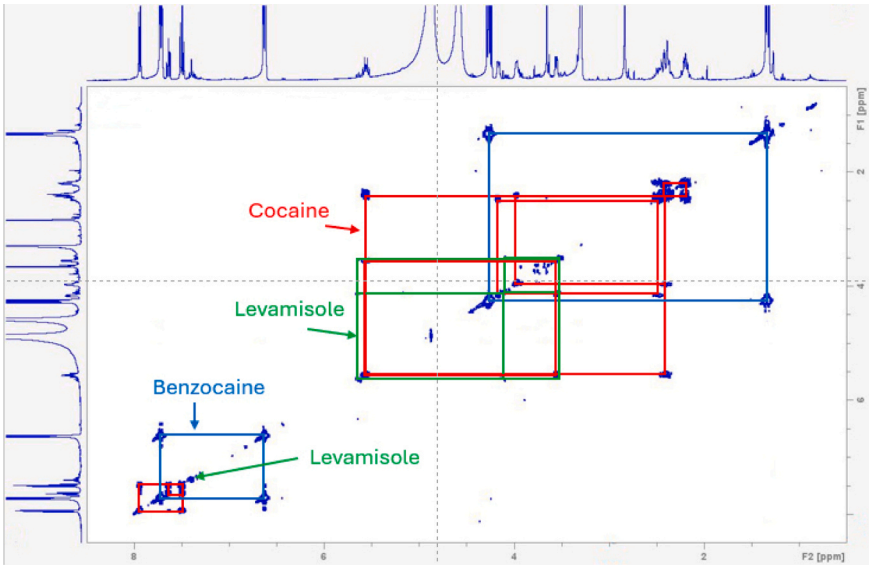


**Fig. 9.** A 2D-COSY experiment at 400 MHz of a cocaine sample that contained cocaine, a large amount of benzocaine, as well as levamisole. Red boxes show correlated peaks for cocaine, dark blue boxes show the correlated peaks of benzocaine, and green boxes show levamisole.

monitoring of the market to help reduce or prevent harm by informing law enforcement and harm reduction services about current trends and patterns of drug abuse. Furthermore, the occurrence of cutting agents varied significantly, with a higher number being detected before 2019. However, the 2024 data set suggests they have become prevalent again. The high predominance of benzocaine in cocaine street samples is alarming due to the methaemoglobinaemia-associated risk, which can lead to potentially life-threatening symptoms like bluish-grey skin, shortness of breath, fatigue, and confusion [61,62].

The study showed that low-field NMR spectroscopy can be reliably used to monitor the cocaine market. The results acquired on the 60 MHz unit were comparable to those acquired on a medium (400 MHz) instrument in terms of cocaine purity in the seized samples. Although there were a few discrepancies in the results due to the slightly noisier spectra on the LF NMR, most of the integration values fell within the 20% UNODC threshold, indicating that the benchtop instrument can be used reliably for quantitative analysis of cocaine street samples.

Currently, the analysis of the cocaine samples using $^{2}$D NMR spectroscopy at high field (700 MHz, data not shown) is being conducted to identify the origin of these resonances. The potential of using solvent signals as a fingerprint to help identify the original manufacturing site to assist law enforcement and forensic intelligence should be further investigated.

This study highlighted the increasing complexity of recreational cocaine use in high-risk and high-density social settings such as music festivals. The significant variation in composition and purity levels emphasised the need for constant monitoring of street sample content. Therefore, the use of LF NMR can bring us one step closer to improving analytical capabilities and integrating them with public health measures, directly guiding the safety management team and accurately

communicating risks and warnings.

## CRediT authorship contribution statement

**Anca Frinculescu:** Writing – original draft, Supervision, Methodology, Conceptualization. **Harold G Parkes:** Writing – review & editing, Software, Data curation. **John Ramsey:** Writing – review & editing. **Nunzianda Frascione:** Writing – review & editing, Supervision. **Fatima Patel:** Formal analysis. **Trevor Shine:** Writing – review & editing, Resources. **Vincenzo Abbate:** Writing – review & editing, Supervision, Resources.

## Declaration of Competing Interest

The authors declare no competing interests.

## Acknowledgements

The authors would like to acknowledge Agrim Gupta from the Centre for Biomolecular Spectroscopy, King's College London Guy's Campus, and Alexander Koering from Nanalysis Corp. for their support.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2026.112902.

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