Electronic Supplementary Material (ESI) for Sensors & Diagnostics.

Supporting information

Electrochemical methods for on-site multidrug detection at festivals

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Experimental section

Portable Raman measurements. A Bruker Bravo Handheld Raman spectrometer (Bruker Optik GmbH, Ettlingen, Germany) was used for all Raman measurements. The instrument uses a dual laser excitation feature with two laser diodes (wavelengths: 785 nm and 852 nm). Spectra were recorded from 170 cm^{-1} to 3200 cm^{-1}. OPUS 8.2.28 (Bruker Optik GmbH, Ettlingen, Germany) software was used for data acquisition and analysis. All seized samples were processed by the partnered institutes into powdered form and kept in transparent Eppendorf tubes. All measurements were performed by placing the Eppendorf tubes containing the sample on the measuring tip. The TICTAC Drug Library (TICTAC Communications Ltd., London, United Kingdom) was used for identification.

Tables

Table S1. Training set containing four drugs, eight adulterants and 21 binary mixtures.

Training set			
Cocaine	+ Benzocaine	MDMA	+ Amphetamine
	+ Caffeine		+ Caffeine
	+ Levamisole		+ Creatine
	+ Lidocaine		+ Ketamine
	+ Paracetamol		+ Paracetamol
	+ Procaine		+ Phenacetin
	+ Phenacetin		
Amphetamine	+ Caffeine	Ketamine	+ Amphetamine
	+ Creatine		+ Benzocaine
	+ Paracetamol		+ Caffeine
			+ Creatine
			+ Paracetamol
Codeine	Procaine	Caffeine	Paracetamol
Lidocaine	Benzocaine	Creatine	Phenacetin

Table S2. Overview of the peaks produced by each adulterant and the corresponding peak potential in the pH7F and pH12 measuring conditions.

	pH7F		pH12	
	Peak number	**Peak potential (V)**	**Peak number**	**Peak potential (V)**
Benzocaine	1	0.76	1	0.53
	2	0.93		
	3	1.00		
	4	1.14		
Caffeine	1	1.33	1	1.28
Codeine	1	0.91	1	0.77
	2	1.04	2	0.91
	3	1.27	3	1.10
Creatine	1	/	1	/
Lidocaine	1	0.82	1	0.66
	2	0.99		
	3	1.18		
Paracetamol	1	0.38	1	0.10
Phenacetin	1	0.76	1	0.54
	2	1.13		
Procaine	1	0.80	1	0.69

	2	1.08	
	3	1.26	

Table S3. Overview of the potentials of drug peaks in their binary mixtures in pH7F and pH12. Between brackets is the potential change of the characteristic drug peaks compared to those of the pure compound. Deviations of 50 mV and more are indicated in red.

	pH7F		pH12	
	Peak name	**Peak potential (V)**	**Peak name**	**Peak potential (V)**
Amphetamine + caffeine	A1	1.01 (+0.00)		
	A2	1.33 (+0.10)		
Amphetamine + creatine	A1	1.01 (+0.00)		
	A2	1.25 (+0.02)		
Amphetamine + paracetamol	A1	1.02 (+0.01)		
	A2	1.26 (+0.03)		
Cocaine + benzocaine	C1	0.94 (-0.04)	C2	0.92 (+0.09)
Cocaine + caffeine	C1	1.02 (+0.04)	C2	0.83 (+0.00)
Cocaine + levamisole	C1	0.96 (-0.02)	C2	0.87 (+0.04)
Cocaine + lidocaine	C1	1.04 (+0.06)	C2	0.85 (+0.02)
Cocaine + paracetamol	C1	1.03 (+0.05)	C2	0.82 (-0.01)
Cocaine + procaine	C1	0.97 (-0.01)	C2	0.90 (+0.07)
Cocaine + phenacetin	C1	1.02 (+0.04)	C2	0.83 (+0.04)
Ketamine + amphetamine	K1	1.04 (+0.05)	K2	1.01 (+0.03)
			K3	1.26 (+0.00)
Ketamine + benzocaine	K1	1.01 (+0.02)	K2	1.07 (+0.09)
			K3	/
Ketamine + caffeine	K1	1.03 (+0.04)	K2	0.94 (-0.04)
			K3	1.27 (+0.01)
Ketamine + creatine	K1	1.03 (+0.04)	K2	0.96 (-0.02)
			K3	1.24 (-0.02)
Ketamine + paracetamol	K1	1.04 (+0.05)	K2	0.96 (-0.02)
			K3	1.23 (-0.03)
MDMA + amphetamine	M1	0.80 (-0.01)	M3	/
	M2	1.00 (-0.03)	M4	0.93 (-0.02)
			M5	1.28 (+0.04)

MDMA + caffeine	M1	0.83 (+0.02)	M3	0.82 (+0.01)
	M2	1.02 (-0.01)	M4	0.93 (-0.02)
			M5	1.30 (+0.06)
MDMA + creatine	M1	0.82 (+0.01)	M3	0.82 (+0.01)
	M2	1.01 (-0.02)	M4	0.93 (-0.02)
			M5	1.24 (+0.00)
MDMA + ketamine	M1	0.79 (-0.02)	M3	/
	M2	0.98 (-0.05)	M4	0.92 (-0.03)
			M5	1.27 (+0.03)
MDMA + paracetamol	M1	0.84 (+0.03)	M3	0.82 (+0.01)
	M2	1.02 (-0.01)	M4	0.93 (-0.02)
			M5	1.24 (+0.00)
MDMA + phenacetin	M1	0.79 (-0.02)	M3	0.82 (+0.01)
	M2	0.99 (-0.04)	M4	0.94 (-0.01)
			M5	1.25 (+0.01)

Table S4. Overview of the composition and appearance of street samples. Identification and weight percentages were determined at NICC using GC-MS and GC-FID respectively.

Name	Sample nature (+ color)	Composition	wt.%
1A	Tablet (off-white)	**Amphetamine**	25.8
2A	Paste (orange)	**Amphetamine** Caffeine	52.2 29.2
3A	Tablet (red)	**Amphetamine** Caffeine Ketamine MDMA 3-Fluoroamphetamine	6.6 13.3 / 1.36 1.84
4A	Powder (yellow)	**Amphetamine** Caffeine	20.9 48.4
5A	Powder (white)	**Amphetamine** Caffeine	47.9 41.8
6A	Powder (white)	**Amphetamine** Caffeine	57.6 31.2
7A	Paste (yellow)	**Amphetamine** Caffeine	67.7 20.7
8A	Paste (yellow)	**Amphetamine** Caffeine	36.4 1.3
9A	Powder (white)	**Amphetamine** Caffeine	77.8 13.4
10A	Powder (yellow)	**Amphetamine**	62.1
1C	Powder (white)	**Cocaine**	97.5
2C	Powder (white)	**Cocaine**	57.0

		Levamisole	41.0
3C	Powder (white)	**Cocaine** Paracetamol Levamisole	19.2 73.2 1.6
4C	Powder (white)	**Cocaine** Phenacetin Levamisole	31.0 2.8 5.7
5C	Powder (white)	**Cocaine** Boric acid	29.6 /
6C	Powder (white)	**Cocaine** Phenacetin Caffeine Lidocaine Levamisole Benzocaine	22.0 8.3 15.5 12.0 2.2 25.7
7C	Powder (white)	**Cocaine** Caffeine Hydroxyzine Lidocaine	75.5 3.1 9.6 <1
8C	Powder (brown)	**Cocaine**	20.0
9C	Powder (white)	**Cocaine**	>90.0
10C	Powder (white)	**Cocaine** Levamisole	57.0 41.0

1K	Powder (off-white)	**Ketamine**	83.0
2K	Powder (off-white)	**Ketamine**	5.0
3K	Powder (white)	**Ketamine**	82.0
4K	Crystals (white)	**Ketamine**	72.0
5K	Powder (white)	**Ketamine**	100.0
6K	Powder (white)	**Ketamine**	84.0
7K	Powder (white)	**Ketamine**	99.0
8K	Crystals (white)	**Ketamine**	99.0
9K	Powder (white)	**Ketamine**	100.0
10K	Powder (white)	**Ketamine**	100.0

1M	Powder (white)	**MDMA**	93.7
2M	Powder (off-white)	**MDMA**	92.6
3M	Crystals (white)	**MDMA**	88.0
4M	Tablet (pink)	**MDMA**	40.4
5M	Tablet (grey)	**MDMA**	24.7
6M	Tablet (purple)	**MDMA**	57.2
7M	Tablet (grey)	**MDMA**	54.1
8M	Crystals (white)	**MDMA**	96.8

9M	Tablet (orange)	**MDMA**	39.5
10M	Tablet (yellow)	**MDMA**	54.4

Table S5. Potentials of the peaks detected in the voltammograms of the confiscated samples in pH7F and pH12, as well as the results of the peak recognition software and the portable Raman analysis. For the flowchart, the result after the first analysis (pH7F) and, if applicable, second analysis (pH12) are displayed. For the dual-sensor, the result of the double analysis (pH7F + pH12 in parallel) is shown. For the Raman results, the three main components resulting from the library search were considered. The result displayed in the table is the most relevant one according to the analysis by the standard method (**Table S4**). Incorrect results are indicated in red. ACK: joint interval amphetamine, cocaine and ketamine; AMP: amphetamine; COC: cocaine; COC(b): cocaine after activation of extended interval due to benzocaine detection (0.45 – 0.55 V in pH12); KET: ketamine.

	pH7F	**pH12**	**Flowchart result**		**Dual-sensor result**	**Raman result**
Name	**Peak potential (V)**	**Peak potential (V)**	**First analysis**	**Second analysis**	**Double analysis**	
1A	0.97 1.17	1.34	ACK	AMP	AMP	Nor-ephedrine
2A	0.99 1.18 1.34	1.34	ACK	AMP	AMP	Phenethyl-amine
3A	0.97 1.30	1.34	ACK	AMP	AMP	Caffeine
4A	0.96 1.33	1.34	ACK	AMP	AMP	AMP
5A	0.97 1.17 1.34	1.35	ACK	AMP	AMP	AMP
6A	0.99 1.18 1.34	1.34	ACK	AMP	AMP	AMP
7A	0.98 1.18 1.35	1.33	ACK	AMP	AMP	Nor-ephedrine
8A	0.96 1.17	1.34	ACK	AMP	AMP	Creatine
9A	0.98 1.18 1.33	1.34	ACK	AMP	AMP	Nor-ephedrine
	0.98	1.34				Nor-

10A	1.18		ACK	AMP	AMP	ephedrine
	1.32					

1C	1.09	0.83	No drug	/	No drug	COC
	1.30	1.10				
		1.34				
2C	1.05	0.84	ACK	COC	COC	Paracetamol
	1.26	1.07				
		1.41				
3C	0.39	0.15	ACK	COC	COC	COC
	1.02	0.85				
	1.19					
4C	0.78	0.51	ACK	COC	COC(b)	Unknown
	1.01	0.81				
	1.21	1.38				
5C	1.04	0.83	ACK	COC	COC	COC
		1.33				
6C	0.75	0.54	ACK	COC	COC(b)	Unknown
	1.02	0.92				
	1.33					
7C	0.76	0.69	ACK	COC	COC	Unknown
	0.98	0.84				
	1.30	1.31				
8C	1.03	0.83	ACK	COC	COC	COC
	1.22	1.37				
9C	1.09	0.83	No drug	/	No drug	COC
	1.34	1.12				
		1.35				
10C	1.05	0.86	ACK	COC	COC	COC
	1.26	1.08				
		1.29				

1K	0.83	1.01	MDMA	/	KET	KET
	1.01	1.38				
	1.28					
2K	1.06	1.00	ACK	KET	KET	KET
	1.31	1.35				
3K	0.84	1.00	MDMA	/	KET	KET
	1.03					
	1.29	1.37				
4K	0.83	0.99	MDMA	/	KET	COC
	1.05					
	1.28	1.35				
5K	0.83	1.00	MDMA	/	KET	KET
	0.99	1.36				
	1.36					
6K	0.83	1.01	ACK	KET	AMP	KET
	0.96	1.38				

	1.30					
7K	0.83	1.01	MDMA	/	KET	KET
	0.99	1.37				
	1.34					
8K	0.83	1.00	MDMA	/	KET	COC
	0.99	1.38				
	1.37					
9K	0.83	1.00	ACK	KET	KET	KET
	0.98	1.36				
	1.32					
10K	0.83	1.00	ACK	KET	KET	KET
	0.97	1.36				
	1.35					

1M	0.85	0.93	MDMA	/	MDMA	MDMA
	1.05	1.30				
2M	0.85	0.93	MDMA	/	MDMA	2-amino propane
	1.03	1.29				
3M	0.85	0.93	MDMA	/	MDMA	MDMA
	1.04	1.30				
4M	0.84	0.93	MDMA	/	MDMA	MDMA
	1.03	1.25				
		1.41				
5M	0.84	0.92	MDMA	/	KET	2-amino propane
	1.03	1.38				
6M	0.84	0.94	MDMA	/	MDMA	MDMA
	1.03	1.26				
	1.30					
7M	0.84	0.83	MDMA	/	MDMA	2-amino propane
	1.03	0.95				
	1.31	1.25				
8M	0.85	0.91	MDMA	/	KET	MDMA
	1.05	1.30				
9M	0.84	0.93	MDMA	/	MDMA	MDMA
	1.03	1.24				
		1.40				
10M	0.84	0.95	MDMA	/	MDMA	MDMA

Accuracy confiscated samples	32/40 (80.0%)	35/40 (87.5%)	24/40 (60.0%)

Figures

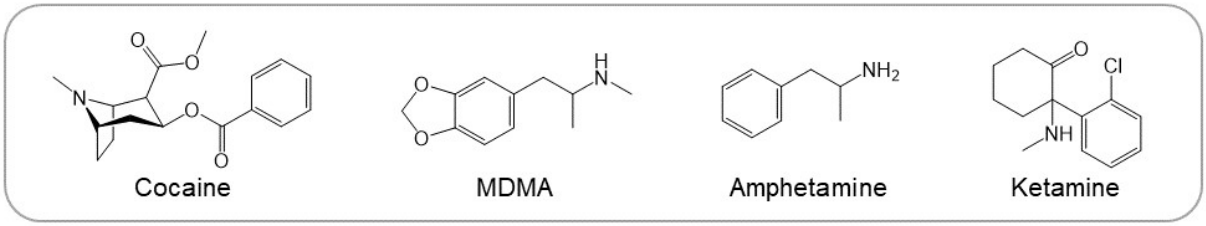


Figure S1. Chemical structures of the four target drugs.

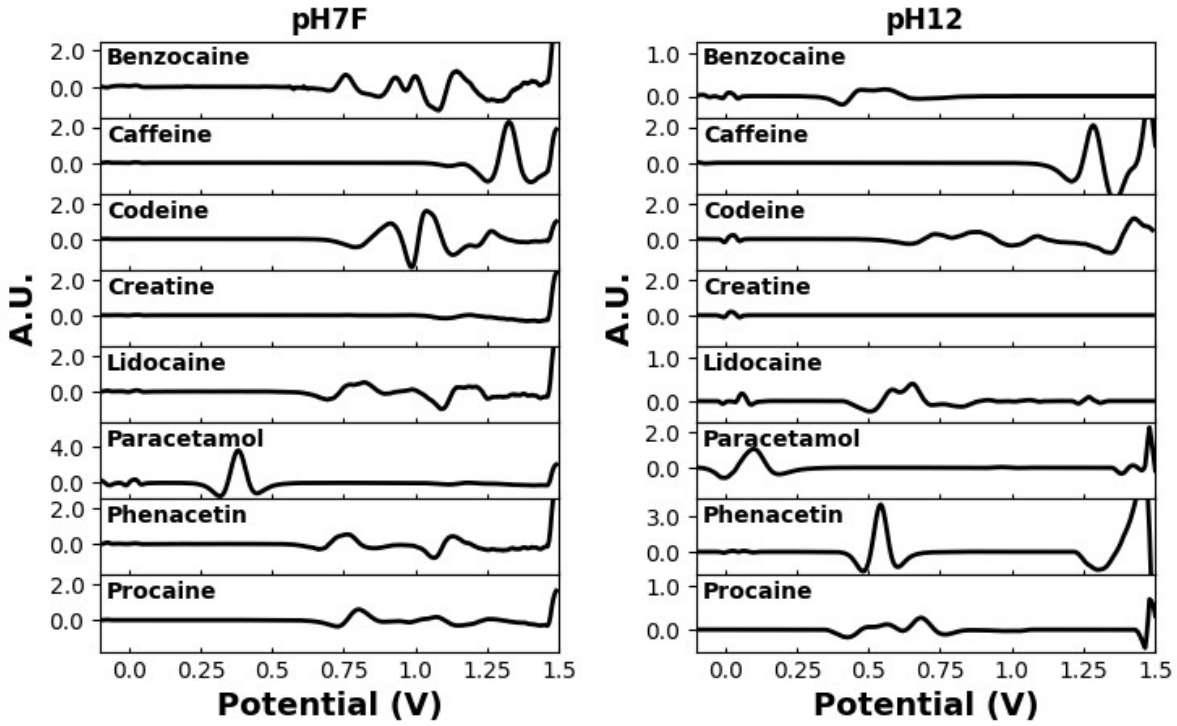


Figure S2. Overview of the pre-processed EPs of the adulterants in the training set, recorded in pH7F (left) and pH12 (right). Concentrations in pH7F: 1 mM. Concentrations in pH12: 0.5 mM.

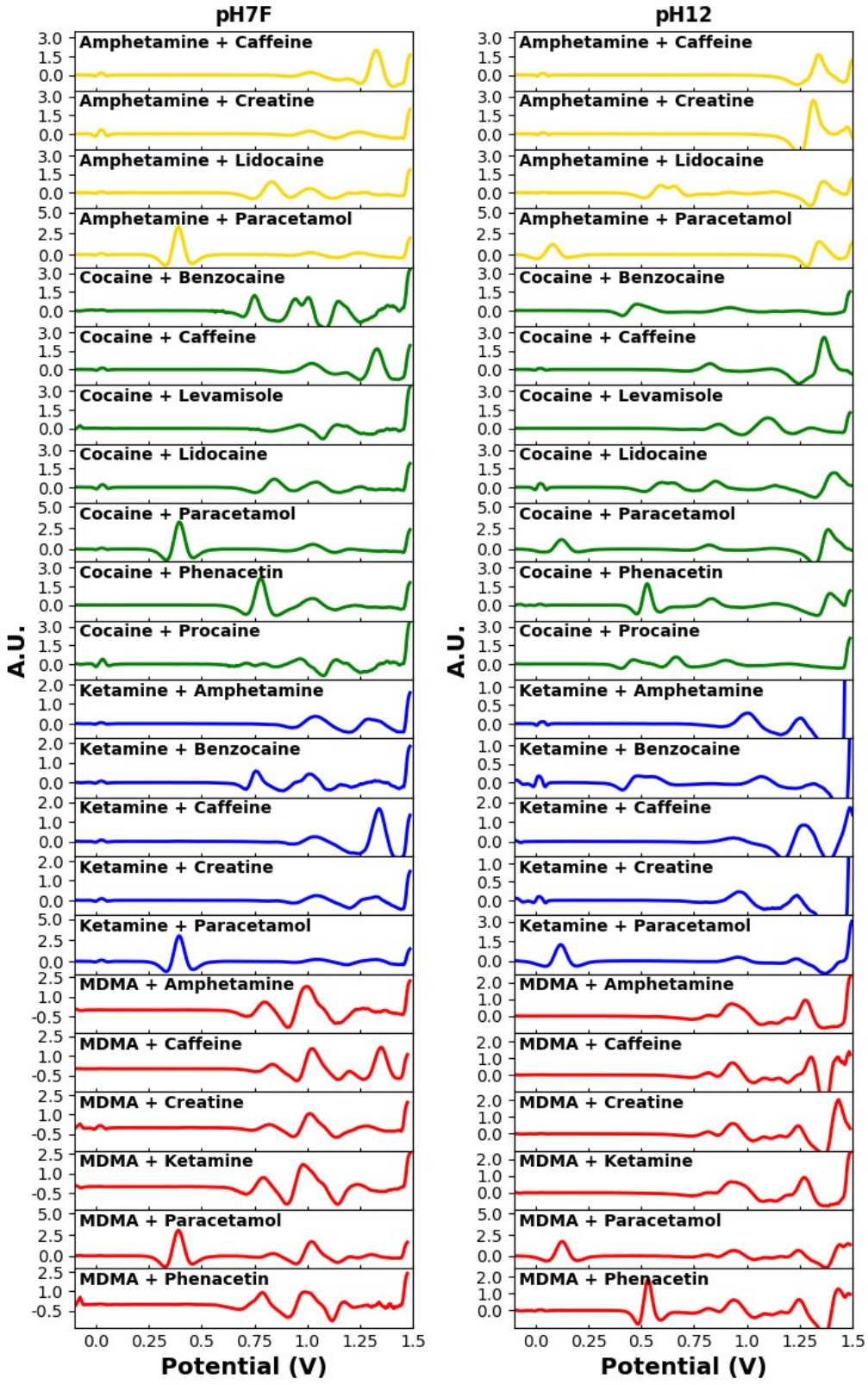


Figure S3. Overview of the pre-processed EPs of the binary mixtures in the training set, recorded in pH7F (left) and pH12 (right). Yellow: amphetamine mixtures, green: cocaine mixtures, blue: ketamine

mixtures, red: MDMA mixtures. Ratio in all mixtures: 1:1. Concentrations in pH7F: 1 mM. Concentrations in pH12: 0.5 mM.

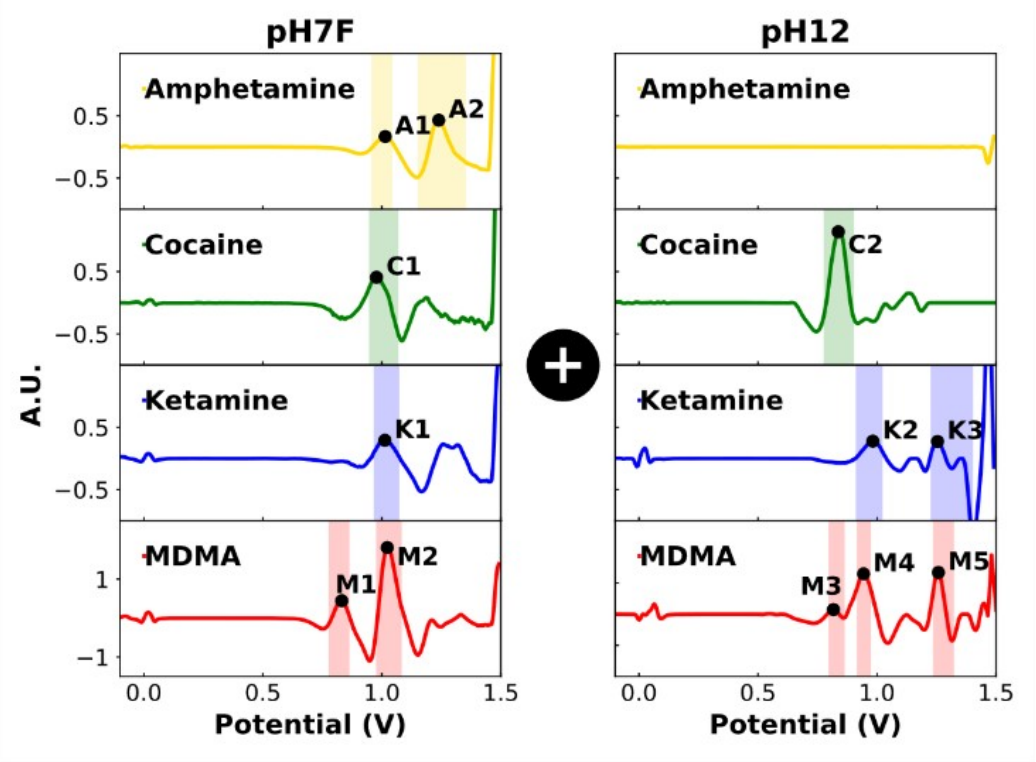
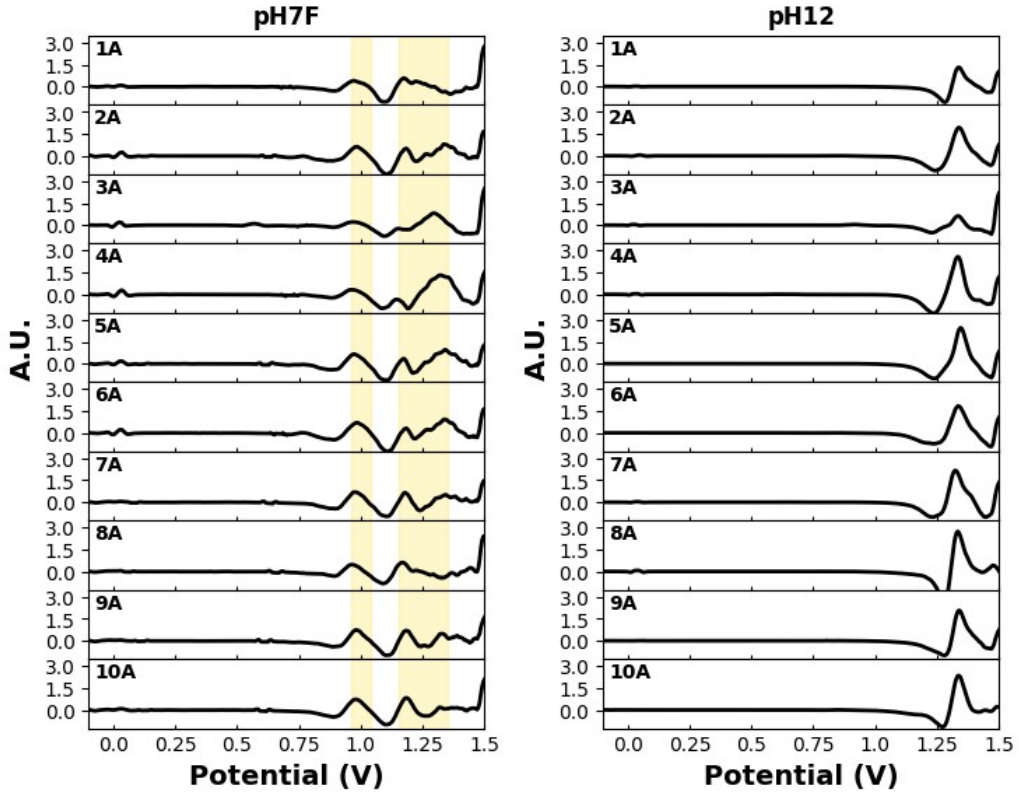
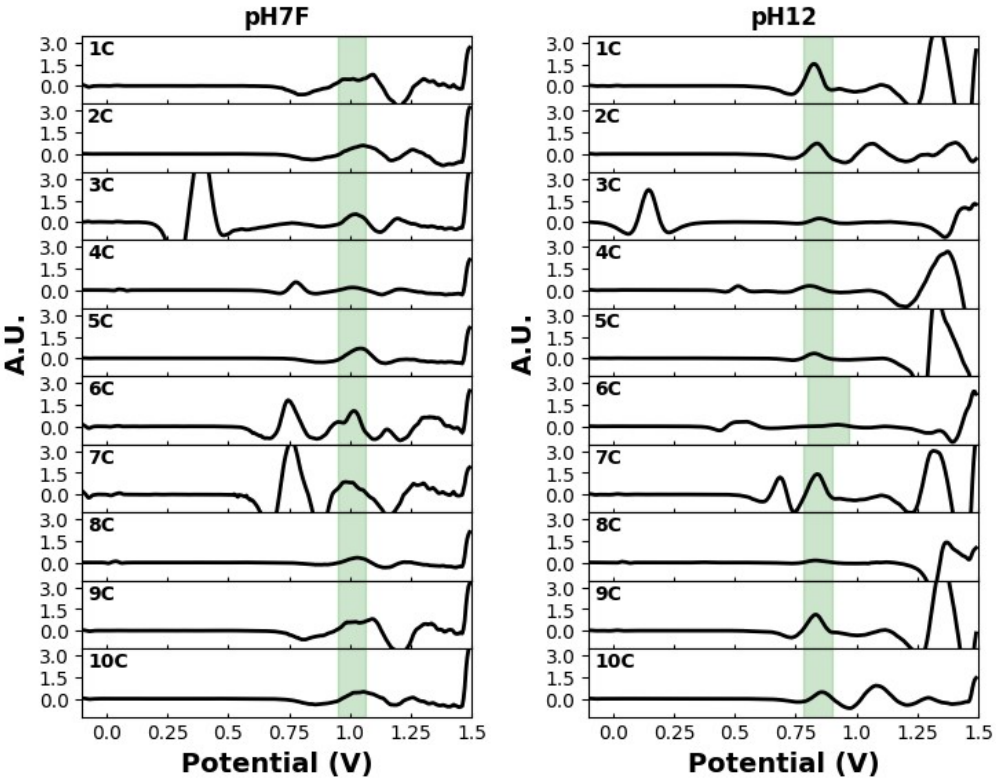
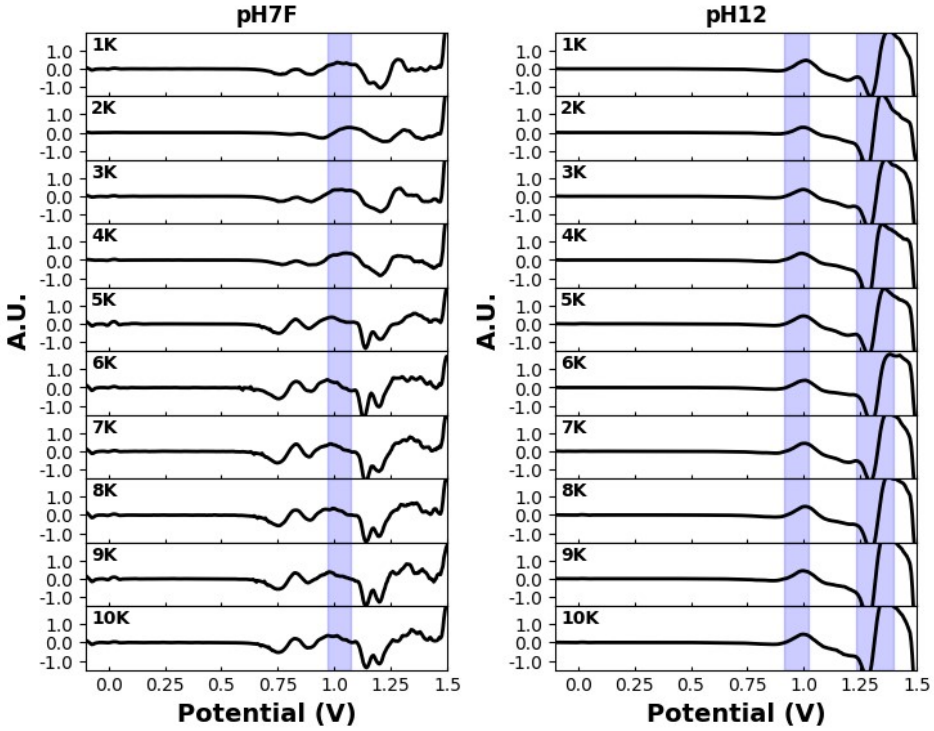


Figure S4. Representation of the database used in the dual-sensor method (pH7F + pH12).




pH7F
pH12
1C
2C
3C
4C
5C
6C
7C
8C
9C
10C
A.U.
Potential (V)


pH7F
pH12
1K
2K
3K
4K
5K
6K
7K
8K
9K
10K
A.U.
Potential (V)

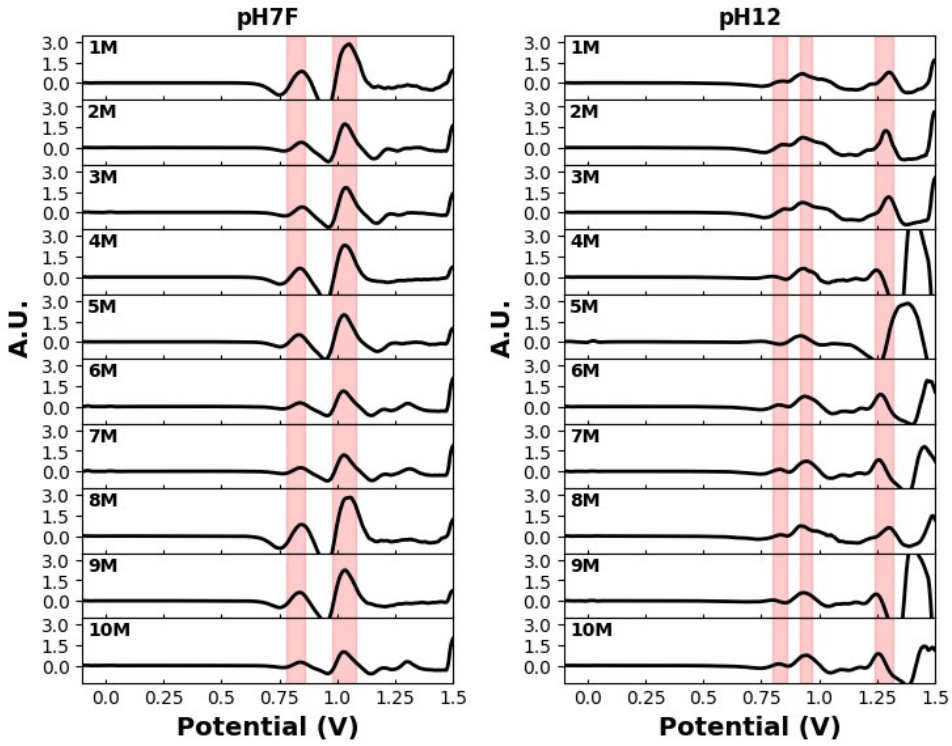


Figure S5. Overview of the pre-processed EPs of the confiscated samples, recorded in pH7F (left) and pH12 (right). The potential intervals defined for each drug's peaks are visually shown in the color assigned to each drug. Yellow: amphetamine samples, green: cocaine samples, blue: ketamine samples, red: MDMA samples. Concentrations in pH7F: 2.0 mg mL^{-1}. Concentrations in pH12: 0.3 mg mL^{-1}.