DSR_PORTAL_API

Umm Alqura University

Document Details

Submission ID

trn:oid:::3117:504418605

Submission Date

Sep 28, 2025, 8:35 AM GMT+3

Download Date

Sep 28, 2025, 3:14 PM GMT+3

File Name

plagiarismCheck_ca0fcd938eb4b8dbdec3ee2ce43a8019.pdf

File Size

769.2 KB

33 Pages

12,739 Words

74,602 Characters

4% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Quoted Text
- Small Matches (less than 12 words)

Match Groups

13 Not Cited or Quoted 3%
Matches with neither in-text citation nor quotation marks

7 Missing Quotations 1%
Matches that are still very similar to source material

0 Missing Citation 0%
Matches that have quotation marks, but no in-text citation

0 Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

4%	Internet sources
4%	Publications
0%	Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

No suspicious text manipulations found.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Match Groups

13 Not Cited or Quoted 3%
Matches with neither in-text citation nor quotation marks

7 Missing Quotations 1%
Matches that are still very similar to source material

0 Missing Citation 0%
Matches that have quotation marks, but no in-text citation

0 Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

4%	Internet sources
4%	Publications
0%	Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Internet	**openaccess.hku.edu.tr**	<1%
2	Publication	**Hussain Alessa, Nasser Algethami. "Up-to-date studies regarding the determinati...**	<1%
3	Publication	**Priyanka Das, Jegyasu Gupta, Debabrata Sikdar, Ratnajit Bhattacharjee. "A smart ...**	<1%
4	Internet	**www.mdpi.com**	<1%
5	Publication	**Qian Yang, Yangqing Wu, Shuaihua Zhang, Hongyu Xie, Dandan Han, Hongyuan Y...**	<1%
6	Internet	**pmc.ncbi.nlm.nih.gov**	<1%
7	Internet	**www.ncbi.nlm.nih.gov**	<1%
8	Internet	**www2.mdpi.com**	<1%
9	Publication	**Petr Samiec, Zuzana Navrátilová. "Electrochemical behaviour of bromazepam an...**	<1%
10	Internet	**hdl.handle.net**	<1%

11	Internet	
pubmed.ncbi.nlm.nih.gov		<1%
12	Internet	
www.intechopen.com		<1%
13	Publication	
"Sample Preparation in LC-MS Bioanalysis", Wiley, 2019		<1%
14	Publication	
Zeynab Khorablou, Faezeh Shahdost-fard, Habib Razmi, Mehmet Lütfi Yola, Hassa...		<1%
15	Internet	
www.electrochemsci.org		<1%
16	Internet	
pubs.rsc.org		<1%

Studies on the detection of methamphetamine by different sensors

Hussain Alessa[1,*], Sulafa J.M. Nassar[1]

15

[1] Chemistry Department, Faculty of Science, Umm Al-Qura University, Makkah, Saudi Arabia

Correspondence: hhessa@uqu.edu.sa

Abstract

Methamphetamine (MAPA) is one of illicit synthesized drugs that is fabricated in clandestine laboratories. It is considered as one of the most harmful drugs spreading among youths around the globe, which can cause unpleasant addiction strengthened by its euphoric feeling. However, it damages the brain cells and leads to death. In this review, the detection of MAPA in various samples, especially from the year 2012 onwards, with the focus on the last five years. The presented information is in relation to up-to-date optical or electrochemical sensors.

Keywords Methamphetamine. Sensors. Voltammetry.

1. Introduction

N-methyl-1-phenylpropane-2-amine compound, known as methamphetamine (MAPA), is one of the popular illegal drugs worldwide. It was synthesized from ephedrine [1, 2]. MAPA is represented by the chemical formula $C_{10}H_{15}N$ (Fig 1), with a molecular weight of 149.24 g/mol. MAPA is known by different nomenclature like meth, crystal meth and whiz. It has two isomers; dextro (*d*-) and levo (*l*-). MAPA is a basic drug with pKa of 9.9, so it is usually extracted in basic mediums by organic solvents [3]. Although MAPA had been used for the short-term treatment of extravagant obesity and hyper-activity disorder, it can cause unpleasant addiction strengthened by its euphoric feeling [4]. MAPA found popularity among young people as it stimulates their pleasure through rising the liberation of dopamine and serotonin, which worked by blocking some receptors in the brain. However, the consumption of higher MAPA amounts would result in high blood pressure, breathing difficulty, paranoia, uncontrollable violence and death [4-6, 7].

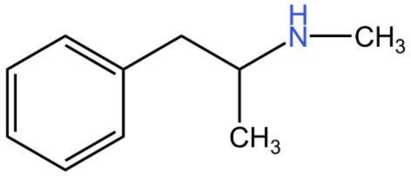

Fig 1. The structure of methamphetamine.

Although, transferring MAPA from mothers to their infants has not been proven yet, as it had no correlation with the maternal depression [8]. Some psychotropic effects would increase directly or indirectly by the use of MAPA, such as decreased driving ability leading to car accidents, extreme violence, spreading contagious diseases, simplify sexual assaults, air pollution by the released smoke, reduce the safe vegetation and converting it to illegal drug cultivation, the release of MAPA and its metabolites into the wastewater affect the water treatment processes and thereby the final water [6, 9, 10]. Although MAPA is produced by different approaches, such as Leukart and Nagai method [11,12], Phenyl-2-Propanone method [13], Red Phosphorus method [14], one pot method [15], it is said to be produced illegally and used via different routes; it can be injected, inhaled, smoked or even introduced orally to human body [16]. However, the detailed mechanisms of its effect are not well understood. Therefore, different studies were conducted to reveal these mechanisms and to allocate biomarkers for its possible determination [17]. It is worth noticing that some medications used for mitigating symptoms of Parkinson's disease like selegiline (SE) can produce *l*-MAPA as a metabolite upon ingestion. This metabolite should be distinguished from people who consume MAPA as illicit drug. Shin et al. studied this phenomenon in a urine sample and confirmed that observation by using headspace–solid phase microextraction (HS-SPME) coupled with gas chromatography–mass spectrometry (GC-MS) [18].

Sensors and chromatographic methods are among analytical methods utilized for isolating and detecting MAPA that are presented in bio and non-bio samples. These methods were used in many fields, including environmental analysis [19, 20], forensic studies and drug identification and quantification [21, 22]. Sensors are miniature analytical devices that can determine the presence of analyte species and measure their concentration in different media. There are different examples of chemical sensors, such as optical, magnetic, thermal and electrochemical sensors. They differ in the working mechanism and the type of the measured signal. Sensors consist mainly of a recognition element, a transduction element and a signal processor for recording the chemical concentration. Different sensors were used for MAPA quantification; all aimed at measuring MAPA with high selectivity and sensitivity. The improvement in validation parameters was done by modifying the biological receptors, like antibodies [23], DNA and enzymes, or by using nano-based materials for modifying electrodes' surfaces [24].

7 As they are instrumental methods, calibration curves are mandatory to study the relationship between different concentrations of MAPA, as standard solutions, and the physical properties that are measured by the instrument. From the calibration curve, different validation parameters can be extracted, such as the method linearity range, limit of detection (LOD) and limit of quantification (LOQ). The way to enhance these validation parameters would be through improving the response of the instruments or sensors. This could be achieved by better engineering the sensing electrodes, as for sensors, or better modification of the phases, as for chromatographic methods. Generally, the capability of these analytical methods to detect MAPA can be enhanced by the modification of their components; the materials that are employed for constructing the sensing electrodes in sensors.

Stemming from its problems, tremendous work published worldwide is focused on finding a reliable fast method for its on-site determination in solid samples and human bio-fluids. Among these methods are spectrophotometric, chromatographic and electroanalytical techniques. This review wraps together different sensors that have been employed for the analysis and quantification of methamphetamine since 2012.

Different search sources, such as Scopus, PubMed, Science Direct and Google Scholar, were used for the extraction of the review data that were published in English language within the time range 2012 until 2025. Almost all the paper types were included in the search. The articles were then read individually and added if they had relevant relation to the aim of this work, such as the effect of MAPA, MAPA extraction, MAPA detection or MAPA quantification. The search was done by using the keywords "methamphetamine", "meth", " methamphetamine determination" and " methamphetamine extraction".

2. Reported sample preparation methods

As the illegal substances enter the human body via different routes, they undergo different biological processes in the human organs before ejecting them. Therefore, they can be collected from human-based fluids and sewage water. The pharmacokinetics journey of MAPA starts from administrating it orally by eating and smoking or introducing it to the blood stream by injection. After that, the MAPA metabolites, which resulted from MAPA reaction with human organs, would be excreted as fluids. These fluids can be urine, oral fluid and blood plasma, from which the prominent MAPA-metabolite, or by-products known as amphetamine (APA), or the other metabolites like para-hydroxy-MAPA and para-hydroxylation should be detected [25,26].

The exposure to MAPA can be direct (as for the users), and indirect. The latter related to people who do not consume MAPA but take it from MAPA users or from the contaminated surfaces like ceilings or internal parts of cars [27 – 30]. MAPA could be synthesized in clandestine laboratories, and this of course has negative impact on the workers, children and their families [31]. Also, MAPA can be transferred by hands and clothing from one area to another, so the exposure to contaminated surfaces would be possible source for being affected by MAPA [32].

MAPA dissolves in some organic solvents like chloroform ($CHCl_3$), ethyl acetate ($CH_3COOC_2H_5$) and diethyl ether $(C_2H_5)_2O$. So, it is back-extracted without loss by using acidic medium. It should be noted that loss during its extraction can occur if the procedure includes evaporation due to MAPA volatility. However, the use of hydrochloric acid (HCl) or dimethyl formamide (DMF) can minimize or avoid the loss process [3]. As it is a volatile compound, gas chromatography (GC) is mostly suitable for its analysis [33,34].

Usually, MAPA and its metabolites are presented in trace amounts in human-based samples. The samples must not be directly subjected to analytical instruments due to their complex nature. They must be pretreated well for acquiring useful analysis data. The purpose of preparing samples is to choose an appropriate route for transporting the analyte of interest from the matrix to a suitable analytical technique for its analysis. Many factors influence the selection of the preparation method, namely, matrix type, properties of the analyte, analyte concentration in the sample, the chosen analytical method and the analysis time. The sample preparation has undergone persistent development which is mainly based on finding new materials or improving the methods used.

2.1. Extraction methods

5 Different techniques were used for MAPA sample pretreatment before the analysis by using various analytical methods. These preparation steps include the extraction, preconcentration and derivatization. Different extraction methods were reported for MAPA extraction, such as electro-membrane extraction (EME), liquid-

5 liquid extraction (LLE), liquid-liquid microextraction (LLME), dispersive liquid-liquid microextraction (DLLME), solid phase extraction (SPE), magnetic solid phase extraction (MSPE), capillary microextraction (CME), headspace solid phase microextraction (HS-SPME) and liquid-phase microextraction (LPME) [35].

Amongst the extraction methods, EME is simple, rapid, consumes very small amounts of solvents (in µL range) and is cost-effective. In EME, MAPA is extracted through vacuous membrane filled with an organic solvent that divides the donor phase (aqueous medium) from acceptor solution (inside the vacuous membrane) by applying electrical potential. Under the influence of the applied potential, charged analytes in the donor phase moved to the acceptor solution, then analyzed by gas chromatography (GC) or high-performance liquid chromatography (HPLC) [34].

As for LLE or LLME, samples are collected by fluid sampling tool, mixed with two different solvents to undergo partitioning and then the analyte is transferred to one of the solvents, dried from the extractable solvent, then reconstituted by dissolving the residue in a suitable solvent or the mobile phase (if chromatographic analysis is selected) [36]. The extraction efficiency is affected by the properties of MAPA (solubility and pKa), polarity of the solvent, solvent volume, number of extractions, H_2O: solvent ratio. Radwan et al. studied the extraction efficiency of MAPA by using different solvents and found that using alkaline solution having *tert*-butylmethyl ether (MTBE) for extracting MAPA from human urine, then using HCl spiked with propranolol, as internal standard, for back-extracting MAPA produced the highest extraction efficiency [37].

With regard to SPE, two phases are used named as solid phase and liquid phase. SPEs are made from different polymers, and has a commercial names like Oasis HLB, Isolute SLE+ and Extrabond EB2 cartridges, each of which is made of different polymers and has the ability of extracting different drugs at different pH values [38]. Sorbents in cartridges comprise the solid phase while the liquid phase is made of organic solvents. Different stages presented during SPE, conditioning the adsorbent, introducing the sample, the adsorbent wash, the adsorbent dry then eluting the analytes. Analytes are extracted with the sorbents then eluted by the liquid solvent. Different sorbents were employed in SPE, such as molecularly imprinted polymer [39], nano-carbonaceous material [40, 41], and magnetic nanoparticles [42, 43]. Although SPE is used by various research groups, its popularity is decreasing due to some drawbacks regarding the required high sample volume, time consumption and unsatisfactory reduction of matrix effect [44], although loss of MAPA amount may be encountered during evaporation process, 0.01% HNO_3 dissolved in methanol may be used to improve MAPA recovery [45]. However, it is important to select appropriate packing material, solvents for washing and elution that are suitable for MAPA, modify the SPE components for better extraction, like using 96-well plates [46, 47]. The final MAPA extract must be compatible with the applied analytical instrument.

A cationic exchanger of silica was used as a sorbent in SPE for extraction of MAPA from ground and river water samples. Suspended particulate was removed from the samples by membrane filter, then exposed to silica exchanger, that had been cleaned with alkaline water and placed inside SPE, then the analytes were passed through the cartridge and eluted with a mixture of acetone and ethyl acetate. The extract was then dried under a stream of nitrogen and reconstituted with 500 μL of the mobile phase before subjecting to HPLC-DAD [48]. It was found that when an adsorbent is bonded with a single molecule having double opposite charges would enhance the selectivity of separating MAPA and muscimol. This occurred during the interaction between the drugs and double-zwitterionic SP by using liquid chromatography [49]. Hair is used in forensic detection because it is easy to sample, has high stability and can contain drugs months after consumption. SPE could also extract MAPA from hair samples. The hair samples were acetone-washed, powdered, kept at 53 °C soaked in HCl solution overnight and extracted by SPE. Marfey's reagent was then used to derivatized the extract before the chromatographic analysis [50]. Recently, GO substrates were coated with different nano-adsorbents like polyaniline or Fe_3O_4/C-nanodots for extracting MAPA from urine samples prior to quantitative analysis by liquid chromatographic method [51]. The study illustrated that stacking carbon layers would close the active adsorption sites in GO, the problem can be overcome by dispersing carbon nanodots through the carbon layers.

MSPE, involving Fe_2O_3, used acid-oxidized multiwalled carbon nanotubes (MWCNTs) to extract MAPA and ketamine from biological samples. High affinity of the drugs towards MWCNTs was observed stemming from the bi-bi stacking interaction derived from the aromatic rings, also the functional groups of the drugs surfaces provided good chelating sites [52]. The magnetic adsorbent was further improved by carbon coating which was then used to extract MAPA from urine sample [53]. The combination of MSPE with bio-DLLME enhanced the extraction and pre-concentration of MAPA in human urine samples. The use of methanol and rhamnolipid biosurfactant as a binary part enables the extraction of MAPA. This binary part has several advantages, such as decreasing the interfacial tension and being environmentally friendly [54]. Additionally, MSPE was improved by coating the magnetic nanoparticles with poly(3-thienylboronic acid. The improved MSPE enables MAPA extraction from human urine [42]. Moreover, a nanocomposite of graphene oxide and Fe_2O_3 was utilized for extracting MAPA from human urine [55]. Recently, the nanocomposite was used for extracting MAPA from supplements of sport and weigh control. Sample solution was treated with tiny amounts of graphene oxide and Fe_2O_3 then shaken, MAPA was extracted withing 3 minutes [43].

The combination of different extraction methods would improve the preconcentration process. LLE and DLLME were combined. Urine and CH_3CN were mixed and passed through a column filled with NaCl which caused formation of CH_3CN droplets in a salting-out effect. These droplets had lower densities with regard to the mixture, hence were extracted easily by a syringe then mixed with 1-undecanol. The mixture was injected with potassium carbonate (K_2CO_3) then experienced DLLME. The combined extraction techniques had MAPA recoveries up to 108% [56]. Ionic liquids like 1-butyl-3-methylimidazolium bis (trifluoromethyl) imide were used for extracting MAPA yielding high recoveries [57]. Furthermore, ionic liquid, 1-Octyl-3-methylimidazolium hexafluorophosphate, and CH_3OH were used during the extraction process from human urine to eliminate health and environmentally related issues. The combination of the extraction method recovered by over 80%. The HPLC showed linearity range over very low MAPA concentrations with LOD of 1.7 µg/L [58].

As the use of LLE and SPE has some drawbacks, such as analyte loss, consuming large solvent volumes and having relatively low precision, the use of SPME can overcome these limitations. It also presents useful applications for the extraction of volatile compounds from biofluid specimen. The use of different polymeric fibers makes it suitable for a variety of biological samples. These fibers could be dodecyl sulfate-doped poly-pyrrole (PPy-DS) [59]. As the fibers are non-polar, SPME is mainly used with GC. The selectivity and sensitivity of SPME would be improved by derivatizing the analyzed compounds. SPME was used for extracting MAPA from the air samples. One of the methods used designed unit for generating MAPA vapors, which had flow controller and a syringe pump, was linked to a glass chamber. MAPA was dissolved in acetonitrile and injected into the system for creating the vapors. SPME, which had poly(dimethylsiloxane) (PDMS), was used for sampling MAPA vapors before using GC-MS. It was claimed that the recoveries would be enhanced if the sampling time was longer than 2 hours or if the pump rate was increased [60]. Another modification was adopted in which the holder of SPME fiber was attached to a tube, made of stainless steel then coupled to air sampling pump. This adaptation was success in collecting MAPA vapors from clandestine laboratories, then vapor were analyzed by GC-MS. No expensive tools were used, and the sampling time was short. This method was claimed to be suitable for sampling MAPA indoors, breath, vehicles and containers [61].

CME was proposed by Nair and Miskelly as useful extraction method for MAPA vapors produced by vapor dosing system. MAPA vapors in clandestine laboratories were collected onto glass filters, that had been coated with PDMS coating, before GC-MS analysis. It was claimed that the sensitivity of CME is better than SPME one under the same sampling conditions [62]. Later one, pentafluorobenzyl chloroformate was loaded before sampling to conserve the MAPA concentration for five days after sampling. Although the sensitivity of this method exceeded SPME by 60 times, it is not used for outdoor sampling yet [63]. Also, the MAPA vapors that are sampled by the glass fiber filter can be detected by using LC-MS, provided that samples are desorbed in methanol before the analysis.

2.2. Derivatization methods

Several chemicals have been used to derivatized MAPA during the sample preparation steps to enhance its detection when using chromatographic methods. For example, MAPA was derivatized by using a composite having 1,2-naphthoquinone-4-sulfonate and poly dimethylsiloxane/tetraethylorthosilicate/SiO_2 NPs, for spectroscopic measurements [64]. Also, MAPA in urine samples was individually derivatized by heptafluorobutyric anhydride, pentafluoropropionic anhydride, trifluoroacetic anhydride, acetic anhydride (AA) and N-methyl-bis(trifluoroacetamide), before the GC analysis [65, 66]. Oxidation and silylation were also used for derivatization [67]. The extract having MAPA may be evaporated then treated with trifluoroacetic anhydride alone [68], pentafluoropropionic anhydride [69], trifluoroacetic anhydride in ethyl-acetate [70], pentafluorobenzyl chloroformate or L-N-(trifluoroacetyl)prolyl chloride for derivatizing MAPA before GC-MS measurements [63, 71]. When using HPLC, the derivatization of MAPA is not usually used unless for the separation of MAPA enantiomers by using HPLC-tandem MS which may require derivatization of MAPA to reduce the analysis cost, by eliminating the use of chiral columns. In addition, some agents like Mosher reagent or Marfey’s reagent were each used for that purpose.

3. Detection methods

The scientific publications worldwide have shown huge amounts of work, based on using analytical methods, conducted to determine MAPA and its metabolites in various samples. Some scholars claimed the ability to determine MAPA in seized samples by using chloride test [72]. The current work focuses on the electroanalytical and chromatographic methods, their working mechanism would be briefly explained as well as the validation parameters like the method linearity range, limit of detection (LOD) and limit of quantification (LOQ).

3.1. Sensors

Sensors are relatively simple, easy, and consume relatively less amounts of reagents when compared to many analytical methods. Sensors found applications in drug detection in various sample types. Selecting a suitable sensor is influenced by some factors, such as selectivity (the prime importance), sensitivity level and the matrix nature. Analytes can bind to the recognition elements in biological receptors part of biosensors [73]. To achieve excellent selectivity, the sensor must be able to discriminate between the analyte and other chemicals present in the matrix. The selectivity can be enhanced by integrating molecularly imprinted polymer (MIP), or molecular recognition element, like aptamer, which is derived from DNA, that would create a signal upon binding with the analytes [74]. Also, the use of nanomaterials would improve the selectivity and sensitivity of the biosensors [75]. Sensors can be fabricated onto paper or flexible substrates at small scale which make them favorable for in-field detection process. In this instance, the concentrations of different drugs were determined by using colorimetric sessor fabricated onto test paper. The color's shade produced was processed by a digital camera, which facilitates its on-site analysis [64].

Nowadays, smartphones are equipped with large computing power and are capable to assist the on-site drug detection applications. In this instance, Krauss et al. used smartphones to identify the color changes of images taken during the detection process, for defining the threshold values of different chemicals like MAPA [76]. Although Guo et al. fabricated smartphone-based fluorescent sensor which relay on antibody-antigen binding for ketamine fluorescence [77], Fan et al. designed dyed nanobead matrix with oil soluble dyes, widely applied to prepare NPs-based lateral flow immunoassay strips that enable the MAPA sensing with naked eyes, and obtained LOD of 8 μg/L [78].

To simplify the flow of this work, these sensors are divided into optical and electrochemical ones. Optically, they can be fluorometric, colorimetric or chemiluminometric sensors. Electrochemically, MAPA was detected by using many electroanalytical methods based on voltammetry and its derivatives (Table 1 and Table 2).

3.1.1. Optical sensors

They operate by measuring the changes in optical features, like absorbance or fluorescence, that resulted from biochemical reactions between the discrimination element and the target analyte. These biosensors excel in remarkable sensibility and label-free sensing. The detection mechanism of optical sensors is based on the interaction between MAPA and the light from UV-Vis or fluorescent sources; light absorption is measured by UV-Vis spectrophotometry whereas the emitted light after excitation is measured by fluorescence spectroscopy.

3.1.1.1. Fluorometric sensors (FLS)

He et al. proposed the first fluorometric sensor for detecting MAPA in which the fluorescent (FL) probe composed of amine side of a polyfluorene was used. This produced LOD of 26.6 μg/L [79]. Three different polymers, (poly[(9,9-dioctylfluorenyl-2,7-diyl)-alt(2,1,3-benzothiadiazole-4,7-diyl)]), (poly[(9,9-dioctylfluorenyl-2,7-diyl)-alt(2,1,3-benzooxadiazole-4,7-diyl([(and (poly[(9,9-dioctylfluorenyl-2,7-diyl)-alt(quinoxaline-5,8-diyl)]) denoted as P1, P2 and P3, respectively, were used for studying MAPA vapors. The highest selectivity and sensitivity were observed when using P1 polymer, yielding 191 μg/L as LOD [80].

The use of nanotechnology has positively impacted the performance of these sensors. For instance, silica (SiO_2) nanoparticles (NPs) were used for doping 1,8-naphthalimide-thiophene before using the doped material for sensing MAPA. The thiophene part of the sensor binds to the amine part of MAPA, lowering the effect of internal heavy atom and improving the FL signal, this was confirmed in a linear concentration range of $0.99 \times 10^3 - 40.29 \times 10^3$ μg/L [81]. Moreover, quantum dots (QDs) were demonstrated to have viable properties, such as narrow emission, broad absorption wavelengths and biocompatibility [82-84]. Following that, MAPA was sensed by bioreceptor that is based on CdS QDs. An antibody of MAPA was immobilized onto a platform of CdS QDs as the receptor. The QDs were capped with mercapto-acetic acid with the assistance of coupling agents (N-ethyl-N0-(3-dimethylaminopropyl carbodiimide) and sulfo-*N*-hydroxysuccinimide. The improved immunosensor had high selectivity, even in the presence of other drugs, sensed MAPA with LOD of 118 μg/L [85]. Another example of QDs is graphene QDs which have remarkable optical features and biocompatibility [86].

Although the immunosensors showed remarkable advantages, they suffer from some drawbacks in terms of cost and durability. Hence, other receptors like molecularly imprinted polymers (MIP) were proposed as alternative binding sites template due to their lower cost, ease of fabrication, high selectivity and being reusable to eliminate the already mentioned problems [87]. Detecting MAPA in blood serum or plasma is challenging due to blood matrix effect that resulted from MAPA interaction with blood chemicals. Forensic and toxicology demand improving the sensors' selectivity and sensitivity, this to detect MAPA at low concentrations. In response to that, graphene QDs were combined with MIP to couple their advantages in terms of the enhanced surface area and the conductivity, this combination was used to amplify the MAPA sensing signal. The composite structure showed high selectivity towards MAPA, as MAPA was able to quench the FL signal whereas other presented drugs could not. MAPA was detected as low as 1.7 µg/L [88]. Following similar approach, carbon QDs were immobilized onto SiO_2 to fabricate a fluorescent probe which detected MAPA [89]. Another approach was reported by Goulding et al. who introduced a complex of nano-MIP beacons/aptamer for detecting MAPA in human urine and serum samples. The use of theses beacons showed remarkable quenching for MAPA that improved MAPA detection among other drugs presented in forensic samples [90].

Another solution to overcome the limitations of immunosensors is by adopting a single strand of DNA or RNA, known as aptamer which has high selectivity towards targeted analyte. The biosensor found applications in determining MAPA, carbon QDs were fabricated as donors whereas cobalt oxyhydroxide as acceptor. The FL of carbon dots was quenched upon the interaction of donor and acceptor [91]. Also, CdTe QDs were used in biosensors for MAPA detection with LOD down to $60.20 \pm 1.56 \times 10^{-4}$ µg/L [92]. Furthermore, a non-invasive optical sensor for detecting MAPA and cocaine by using rhodamine B-labelled polymer bodies was developed by Hichem et al. [93], and reported LOD of 0.37 ng/mL and 0.49 ng/mL for MAPA and cocaine, respectively from saliva samples.

Fluorescent sensors can also detect drugs, like MAPA, that are volatilized and presented in air as vapors, this facilitates non-invasive detection. Different optical approaches were adopted for detecting MAPA in vapors, like work reported by Li et al. [94] and Liu et al. [95]. In Li et al. work, a fluorescent polymer probe was attached to UV-ozone treated substrate which enabled the detection of methylphenethylamine with LOD of 25×10^{-2} µg/L [94]. Liu et al. utilized perylene bisimide derivatives for fluorescent sensing many illicit drugs. MAPA vapors were diluted thousand times by the air, and the sensor could still detect MAPA presence with little effect from the odorous substances [95]. Unlike previous approach, Zhang et al. followed a chemical approach for constructing a sensor based on conductivity. MAPA was detected by carbon nanotubes-functionalized Poly[3-(6-carboxyhexyl)thiophene-2,5-diyl)], that is sensitive to amine vapors, with LOD of 4 µg/L [96].

3.1.1.2. Colorimetric sensors (CS)

In colorimetry, the compounds of interest are made colorful by using specific reagents to make them easily detectable. These sensors are simple, cost-effective and use spectrometer for analytes' measurements [97]. However, the reliability of these sensors may be affected by the contamination and the interference of the matrices. Their performance can be advanced by different strategies, one of which is by employing nanostructures like metals nanoparticles (NPs). The manipulation of the NPs size can alter the optical properties. The surface plasmon band can be shifted by altering the interparticle plasmon coupling. The dispersion and aggregation of NPs influence the NPs color [98]. Another strategy is by using a mixture of 1,2-naphthoquinone-4-sulfonate and poly dimethylsiloxane/tetraethylorthosilicate/SiO_2 NPs as a composite for the MAPA detection and other drugs. All analytes were derivatized by the composite yielding colors that assisted their spectrophotometric determination in street samples [64].

Owing to their remarkable features, such as low LOD, specificity and good adaptability of DNA nucleic acid aptamer, colorimetric sensors used aptamer decorated with gold NPs in which the presence or absence of MAPA changed the aptamer structure. Also, the NPs' color was bleached based on the dispersion and aggregation processes. MAPA was quantified as low as µM range [99]. MAPA was determined in human urine by aptasensor linked to unmodified gold NPs. The aggregation of the unmodified NPs induced by salt resulted in changing the solution's color from red to blue, which was the basis of detecting MAPA as low as 122 µg/L [100].

Magnetic beads (MBs) were combined with aptasensor and NPs for detecting MAPA and cocaine simultaneously. Gold@silver NPs core shells were coated with a single stranded DNA as aptamer. The absence of the analytes did not cause a color change; however, their presence created a competition for the aptamer to bind with the analytes and emit a color accordingly [101]. In another strategy, MAPA and cocaine were simultaneously detected in spiked wastewater. Reporter probes (RPs) were fabricated by functionalizing the synthesized Au NPs and Au@Ag NPs with DNA. The two drugs were detected by two capture probes (CPs) that had been coupled with magnetic beads (MBs). The two drugs underwent DNA-DNA hybridization with individual RP and CP in folded structure, which then unfolded by applying external magnetic field. The presence of each drug, which has high affinity towards the aptamer, in the solution dismantles the structure and changes the supernatant color [102]. MAPA and APA were determined by DNA aptamer sensor modified with a combination of GO, cetyltrimethylammonium bromide (CTAB) gold NPs. Stemming from its catalytic properties, hemin was used for amplification. The method had LOD of 28.6 µg/L and 34.1 µg/L for MAPA and APA, respectively [103]. Bastami et al. showed that the addition of small amounts of Cu, during the ultrasonic irradiation, for the synthesis of Ag NPs improved the resulted chemosensor's sensitivity towards MAPA and morphine (MOR) in the analysis of street samples, this was seen by the color change from light yellow, in the absence of drugs, to dark orange color in their presence [104].

3.1.1.3. Chemiluminometric sensors (CLS)

Some oxidation-reduction reactions involve several steps, during which a luminescence emitted light is produced creating chemiluminescence (CL) process. The CLS differs from CS and FLS in having low background interferences [105, 106]. As MAPA would interact with the blood matrix, hence influencing analysis signals when working on blood serum or plasma, mitigating these interferences is vital for the analysis. A portable chemiluminescent fiber-based sensor is developed to enhance MAPA sensing in linear response range of 0.001 – 0.3 µg/mL with LOD to 5×10^{-4} µg/mL [107].

A combination of CTAB, rhodamine B (R-B), L-cysteine capped with QDs of CdS was used for fabricating a sensor established on FL and CL methods. The intensities of emission of both CL and FL, which resulted from the reaction between MAPA and RhoB-CTAB-$KMnO_4$, were monitored by CdS QDs. The CL emission and FL emission of CdS CQs were linear over 26.56 – 133 µg/L and 7.16 – 425 µg/L, respectively [108].

Table 1. A survey of some optical sensors employed for the determination of methamphetamine.

Detection method	Electrode	Sample	Linear range (µg/L)	Detection limit (µg/L)	Ref
Fluorimetry	SiO_2@CQDs@mesoporous-MIPs	Human urine and blood	746 – 37.31×10^3	238	89

Fluorimetry	Aptasensor	Human blood	0.746 –23	149	91
Fluorimetry	Modified aptasensor	Human blood plasma and urine	$1.99 \pm 0.37 \times 10^{-2}$ – 18.5 ± 1.0	$6.02 \pm 0.15 \times 10^{-3}$	92
Colorimetry	Modified aptasensor	Human urine	298 – 1.49×10^{3}	122	100
Colorimetry	Modified aptasensor	Human urine	0.07 – 29	0.014	101
Colorimetry			0 – 50 $\times 10^{3}$ (MOR) 0 – 100 $\times 10^{3}$ (MAPA)	0.21×10^{3} (MOR) 0.49×10^{3} (MAPA)	104
Chemiluminescence	NR	Human urine	6.7 – 400 (FLS) 25×10^{-2} – 125 (CLS)	86×10^{-3} (CLS)	108

Although optical sensors are non-invasive, have high sensitivity, able to detect low MAPA concentration, they are affected by complex sample matrices and need frequent calibrations. Moreover, delicate instrumentation is required for their operation, which needs cost consideration when utilizing these methods.

3.1.2. Electrochemical sensors

The detection of MAPA by electrochemical methods is mainly based on voltammetry-derived techniques. In voltammetry, a working electrode is subjected to a single or varied potential. This potential is to oxidize or reduce the analyte species which can be observed on a voltammogram. The electrochemical measurements are made in certain mediums that have electrolyte support. The choice of the used mediums is affected by some physical properties of the targeted drugs. The sensing property in this type of sensors is affected by the immobilization of the receptors onto the electrode surface. This is as the analyte would be attracted to the electrode surface hence electrode interface engineering is of prime importance. Some catching agents like MIP, aptamer and antibodies can sense the MAPA and they should be stable onto the sensing electrodes [109-112].

As already mentioned, MAPA can be detected by many electroanalytical sensors. These are voltametric, potentiometric, amperometric and impedimetric sensors. The voltametric sensors operate by cyclic voltammetry (CV), differential pulse voltammetry (DPV), square wave voltammetry (SWV), fourier-transform square-wave voltammetry (FFT-SWV), square wave stripping voltammetry (SWSV) techniques. Analytes were sensed by various modified and unmodified electrodes, such as glassy carbon electrode (GCE), carbon paste electrode (CPE), screen-printed electrode (SPE), screen-printed carbon electrode (SPCE), boron-doped diamond electrode (BDDE), carbon nanotubes (CNTs), pencil graphite electrode (PGE) and gold disk electrode (GDE). Samples of using these electrodes and electroanalytical methods are presented (Table 2.).

CV is a simple electrochemical technique which is usually used for studying oxidation-reduction reactions and kinetics parameters of the analytes' sensing electrodes. Although it provides useful information regarding redox reactions, it is not as sensitive as other electroanalytical methods [113, 114]. Gold NPs and chitosan were blended together to form a nanocomposite for aptasensor which is used for detecting MAPA. The NPs improved the chitosan stability. The CV measurement determined MAPA in which the peak current of the electrochemical probe, ferro/ferricyanide, changed indicating capability to determine MAPA with LOD of 1.49 µg/L [115]. Compared to CV, DPV is more sensitive due to lowered background current as the sensing current is measured at each applied pulse. DPV is derived from staircase voltammetry or linear sweep voltammetry. In DPV, a series of voltage pulses is superimposed onto increased potential of stairsteps or linear sweep voltage, then the produced current is measured just after or before every pulse. The literature witnessed the use of DPV more than the other electrochemical methods.

BDDE was employed for studying MAPA in basic medium of Britton-Robinson buffer (BRB) in which the MAPA oxidation peak, by DPV measurement, was observed at 1.23×10^3 mV against silver/silver chloride (Ag/AgCl) reference electrode. The MAPA oxidation mechanism was proposed as 2 protons/2 electrons [116].

Another electroanalytical sensor based on PGE was fabricated by Oghli et al. to determine MAPA. The presence of oxygen in the functional groups improved the PGE surface and enhanced the electrochemical activity of PGE, which was studied by DPV. MAPA was detected in human-based samples at very low concentrations [117].

SPCE was used for detecting MAPA due to its improved attributes over classical PGE and GCE like larger surface area and µL solution capacity. The determination process was run by SWV. Moreover, MAPA was determined in human saliva by SPCE, as sensing electrode, and N,N_0-(1,4-phenylene)-dibenzenesulfonamide, as intermediate. The SPCE surface experienced interaction between the oxidized mediator and MAPA. The SWV measurement detected MAPA within 60 seconds and had LOD of 192 µg/L [118].

The modification of CPE with MIP/multi walled (MW) CNTs composite was demonstrated as a good sensor for detecting MAPA. The FFT-SWV measurement showed an oxidation of the secondary amine of MAPA at 1 V. The sensor displayed large resistance to interference during π-π stacking interactions between the molecules of interest and the template molecules. The method showed a linear response for concentrations 1.49 – 14.92 × 10^3 µg/L [88]. This performance is due to remarkable properties of CNTs, such as large surface-to-volume ratio, high durability under thermal and chemical conditions and high electron transfer [119].

A sensor for detecting MAPA was fabricated by immobilizing antibody onto GCE that had been modified by fluorescent-labeled polypeptide. This sensor determined MAPA in spiked human samples by DPV with LOD of 13.91 × 10^3 µg/L [120]. Another modification of GCE was applied by using Nafion-$[Ru(bpy)_3]^{2+}$ for MAPA detection in oral fluids and obtained a LOD of 10 µM [121], whereas LOD of 20 nM was obtained by Xie et al. [122], and lower LOD down to 72 × 10^{-2} µg/L was achieved [123]. Conversely, the use of optical sensors for detecting MAPA produced low LODs like 9.7 µg/L [124] ,and 50 × 10^{-2} µg/L [107].

Moreover, MWCNTs amine-functionalized decorated with Au NPs were used in combination with $SiO_2@Fe_3O_4$ to modify GCE. This is to overcome weak oxidation of bare GCE surface and produce well-defined anodic peak. Electron transfer between MAPA and MWCNTs was assisted by the use of $SiO_2@Fe_3O_4$. The SWV measurement showed the electrochemical mechanism to be controlled by diffusion [125]. Reduced graphene oxide (rGO) was decorated with CeO_2 NPs, then used for modifying GCE. The sensor screened MAPA with minimized overpotential and had good peak current when compared to bare GCE. The oxidation process of MAPA was proposed to be 2 electrons/2 protons [126].

Riahifar et al. modified GCE by Fe_3O_4@poly pyrrole core-shell and rGO then used it to detect MAPA in urine and blood samples. The determination was conducted in slightly basic medium of Britton Robinson buffer solution [127].

The combination of flexible substrate and conductive Ag nanoparticles attracted the attention of Anzar et al. for fabricating a wearable glove-base sensor for on-site use [128]. Latex gloves were printed with methyl aptamers were immobilized onto AgNPs modified electrode. Operating the sensor at 30 °C showed the optimal signal amplitude, beyond that temperature the performance of the sensor decreases which may hinder its use in very hot areas. The same group used Ag and ZnO as nanocomposite for decorating paper-based electrodes [129]. A MAPA's binding aptamer with a sequence of ACG GTT GCA AGT GGG ACT CTG GTA GGC TGG GTT AAT TTG G was attached to the electrode surface with a mean of Ag and ZnO nanocomposite. The sensor, having the structure of MAPA/Aptamer/Ag-ZnO nanocomposite/paper-based substrate, showed optimal current response at 35 °C. Further improvement was shown in modifying a paper-based multiplex analytical device, used for detecting MAPA and other illicit drugs in beverages, with Ag NPs and specific-drug aptamer [130]. Duan et al. electropolymerized polyarginine membrane onto GCE to increase the reaction sites for MAPA, this improved the electrode's selectivity towards MAPA in human hair and urine samples [131].

3.1.2.1. Potentiometric and amperometric sensors

As for potentiometric sensors, there is no flow of current, zero current, and the working mechanism is affected by the electrode potential. Upon immersing indicator electrodes, like ion-selective electrodes ISEs, and reference electrodes in an analyte solution, the concentration of the ions that are presented in a solution is determined by the potential difference that exists between the two electrodes, so the potential difference is proportional to the ion concentration. The ISEs have a selective membrane which includes ionophore for sensing ions of interest, plasticizer and poly(vinyl chloride) (PVC). The modification of the ISEs components would improve the analytical performance. There is no study, up to our knowledge, published in the last ten years regarding this type of sensor, although it is a simple method and does not demand tricky sample preparation. A relatively old demonstration of this sensor for detecting MAPA dated back to 1993. In that work, PVC electrode was modified with an ion exchanger, sodium tetrak[3,5-bis(trifluoromethyl)phenyl]borate. The potentiometric study conducted on human urine showed MAPA's LOD of 1.492×10^3 μg/L [132].

Contrary to the potentiometric sensors, amperometric sensors operate at zero voltage while electrochemical reactions produce electric current. Thus, amperometry detects ions in solutions based on measuring the electrical current or the changes in the electrical current. Amperometric sensors have high sensitivity over wider linearity of concentration ranges [133]. There is limited publication associated with amperometric sensors for MAPA detection. Back to 2014, a gold electrode was modified by several components in the order of L-cystine (LC), Prussian blue (PB), nano-Au and (3-mercaptorpropyl) trimethoxysilane (MPS). The current signal was enhanced by PB as it reduced hydrogen peroxide (H_2O_2) [134].

3.1.2.2. Impedimetric sensors

Regarding impedimetric sensors, they are more complicated than the already mentioned sensors, however, they can provide very useful insights regarding the characterization of the electrode double layer, the transfer of charges and the electrodes' kinetics by employing impedance spectroscopy (EIS) [135]. Yeh et al. developed an impedimetric sensor for MAPA determination by constructing a bridge for the electron transfer between two electrodes. The bridge was made by coupling gold NPs with an antibody. This construction led to LOD of 100 µg/L for MAPA determination [136].

Ya et al. modified gold electrode by incorporating 3-mercaptopropionic acid, as self-assembly modifier, then activated by 1-ethyl-3-(3-dimethylaminoprophyl) carbodiimide /n-hydroxysulfsuccinimide. The sensor completed by immobilizing MAPA antibody onto the surface of modified electrode for determining MAPA in spiked human blood [137]. Gold electrodes were immobilized with different aptamer sequences through Au-thiol affinity. The composition was electrochemically evaluated by CV, DPV and EIS and the best sequence had the capability to determine MAPA as low as 467 × 10^{-3} µg/L [23].

By combining the properties of nanotechnology and aptamer-detection, an impedimetric sensor is developed for determining MAPA. The MAPA was captured by the aptamer that had been adhered onto GCE by gold NPs [138]. Interferences during charge transfer were minimized due to the incubation of MAPA onto the surface of the aptasensor, which improved the MAPA detection [138]. Recently, Anvari et al. decorated rGO with CeO_2 NPs then used it to modify GCE for MAPA detection in spiked urine samples. The aptasensor performance is evaluated by EIS measurement in the presence of ferro/ferricyanide redox probe which exhibited LOD of 0.023 µg/L [139]. Khorablou et al. decorated carbon nano-onions with Ag nano-dendrites then coated it onto GCE for MAPA in human urine and blood samples. The use of this nano-shape of C or Ag would elevate catalytic efficiency and well-adhered onto GCE surface enabling coating more layers, this created more efficient sensing interface [140].

Another impedimetric sensor was made by modifying SPE electrode with MWCNTs-nafion and gold NPs. MAPA was adsorbed onto the modified electrode, and the electrochemical study was conducted by using EIS and SWSV which exhibited LOD down to nM [141]. The surface of SPE electrode was modified by iono-gel (mixture of hydrogel and ionic liquid) and particular antibodies for the determination of MAPA in human saliva with LOD of 72×10^{-2} µg/L [123]. A 3-sensor array made of different carbon-based SPEs, modified with MWCNTs and graphite and graphene, was employed for qualitative analysis of some illicit drugs, among which is MAPA. The SWV analysis for each modified electrode showed a single oxidation peak when used for each individual drug, i.e. MAPA had oxidation peaks of 700 mV, 900 mV and 650 mV when using electrodes modified with MWCNTs and graphite and graphene, respectively, against a pseudo-silver reference electrode [142]. This allows their fast qualitative analysis in street samples.

The use of aptamers as recognition units, alone or doped, in biosensors for binding target molecules is widely reported. A study claimed the detection of MAPA by using aptamer sensor without exogenous reagents. The aptamer sequence was truncated to be in unfolded state. A conformation change occurred upon binding MAPA on the aptamer which lowered the electrical signal. MAPA was detected in different biofluids, and the method had LOD of 7.46 µg/L of MAPA in urine sample [122]. The signal of the aptamer sensor could be amplified by atom transfer radical polymerization. In this, the sensing electrode was coated with azide-modified DNA and MAPA aptamer. The MAPA was detected in urine and blood samples. The method showed linearity in 0.149×10^{-3} – 14 µg/L with 2.54×10^{-6} µg/L as LOD [143]. Moreover, graphene electrode was used for MAPA determination in human saliva and in household surfaces. The graphene electrode was induced by CO_2 laser, in which a laminating film of polyethylene terephthalate (PET) was used for extracting carbon from Kapton tape. The fabricated modified graphene electrode was used for detecting MAPA in a portable sensor [144]. Another study reported the use of modified electrodes for residual MAPA contamination on different household surfaces, like glass, wood and plastic. GCEs were modified by different carbon-based material, among which electrodes modified with GO were applied for the MAPA determination in household. The DPV showed LOD of 45 µg/L [145]. Liu reported that modifying GCEs with GO-Au NPs composite could detect MAPA in spiked urine samples down to 22.38×10^{-3} µg/L [146]. Liu showed that modifying GCE with GO reduced the peak current, due to the repulsion between negatively-charged GO sheets and the redox solution. Therefore, GO were decorated with Au NPs to assist transferring electrons between the electrode surface and the redox solution, which enhanced the peak current. The aptasensor showed 90% recovery of its response after being stored at 4 °C for 30 days.

Melo et al. illustrates the benefits of combining colorimetric and electrochemical methods for detecting MAPA in forensic samples. MAPA was proven by Simons's test, in which the MAPA color changed from pink to purple, this is followed by subsequent electrochemical confirmation [147].

Table 2. A survey of some electroanalytical techniques employed for the determination of methamphetamine.

Detection method	Electrode	Sample	Linear range (µg/L)	LOD (µg/L)	Ref.
DPV	BDDE	Human urine and serum	10 – 11.93 × 10^3	7	116
DPV	PGE	Human urine and blood	11 – 8.06 × 10^3	7	117
DPV	Modified GCE	Human saliva, urine and blood	10.64 × 10^6 – 106.42 × 10^6	13.91 × 10^3	120
FFT-SWV	Modified CPE	Human urine and serum	1.49 – 14.92 × 10^3	0.12	87
SWV	Modified GCE	Human urine	7.46 – 7.46 × 10^3	2.38	125
SWV	Modified GCE	Human plasma	3.73 × 10^3 – 24.77 × 10^3	1.29 × 10^3	126
SWV	Modified GCE	Human urine and blood	0.746 – 29.85 × 10^3	0.1	127
Amperometry	Modified gold electrode	Spiked bovine serum	1.49 – 0.74 × 10^3	1.12	134
SWSV	Modified SPE	NR	2.98 – 14.9 and 0.44 × 10^3 – 7.46 × 10^3	0.895	141
EIS	Modified SPE	NR	1.72 – 4.01	4.48 × 10^{-2}	141
EIS	Modified GCE	Spiked urine samples	7.46 × 10^{-2} – 40	2.39 × 10^{-2}	139
Electrochemical	Modified aptamer sensor	Human urine and blood	1.49 × 10^{-4} – 10	2.54 × 10^{-6}	143

Electrochemical	Modified graphene electrode	Saliva and household surfaces	0.14×10^{3} – 4.48×10^{3}	40	144
DPV	Gold SPE	Human saliva	5 – 1000	0.56	123
SWV	Graphite SPE	On-site analysis of cargos	7.46×10^{3} – 373×10^{3}	2.49×10^{3}	148
DPV	Modified gold electrode	Spiked urine	0.1 – 50	467×10^{-3}	23
DPV	Modified GCE	Household surfaces	0.14×10^{3} – 5.96×10^{3} and 5.96×10^{3} – 17.91×10^{3}	50	145
DPV	Modified GCE	Human urine and blood	14.77 – 1120 and 1120 – 8940	4.48	140
Electrochemical	Glove substrate modified with Ag nanoparticles	Spiked beverages	0.01×10^{3} – 5×10^{3}	0.1×10^{3}	128
Electrochemical	Paper substrate modified with Ag and ZnO nanocomposite	Spiked beverages	0.01×10^{3} – 6×10^{3}	0.1×10^{3}	129
CV and EIS	GCE modified with	Spiked urine	0.074 – 74.62	1.5×10^{-4}	146
AdSDPV	3D-printed graphite/polylactic acid electrode	Forensic samples	149.24 – 11.19	14.92	147
CV	Modified GCE	Human hair and urine	1.49×10^{2} – 5.22×10^{2}	5.22	131

Despite having various inherent advantages, such as high specificity and sensitivity, cost-effective, wide measuring range, easy to transport, are ideal for real-time monitoring, electrochemical methods may suffer from interferences from complex matrices, and the need for meticulous calibration of the electrodes frequently due to electrodes' fouling problems. Moreover, selective receptors are required for modifying the sensing electrodes to enhance specificity towards the analyte of interest. Following this, a layer of complication is added to their utility.

4. Conclusion and future viewpoint

For many decades, there have been tremendous number of articles in relation to MAPA spread, effect and its determination and quantification. The methamphetamine was proven to badly affect the world communities due to its ease synthesis which makes locating its manufacturing sites difficult. Also, this drug causes serious health and social problems. Due to its presence with other street drugs, its determination in various samples found interest by using different analytical methods. The current work emphasized the use of different optical and electrochemical sensors and some chromatographic methods for its analysis. Chromatographic methods are preferable over other methods due to their ability to quantify very trace concentrations of the analytes but they are bulky, require tedious sample preparation, use large amounts of solvents; that are usually not environmentally friendly, time consuming and need special care and maintenance. Also, they cannot be easily converted into portable kits which may not attract the investment companies. On the other hand, sensors would be suitable for the methamphetamine determination due to their simple fabrication, relatively lower cost, minimum solvent usage and easily made portable. The analysis of MAPA by GC can be enhanced by the use of graphene oxide (GO) in SPE or EME, this is as GO's surface can interact directly with MAPA. Sensors are relatively new compared to chromatographic methods, so there is still room for their improvement by manipulating the properties of the constituents of the sensing electrodes by coupling the nanomaterials with the receptors, also by further reduction of sensors' cost through lab-on-chip technology. Additionally, the utilization of some environmentally friendly products like paper and cotton, as sorptive phases or in SPME, would conserve the environment.

Overall, there still a need for developing reliable, portable or wearable analytical devices for on-site determination of MAPA alone or in combination with other street drugs, particularly if they presented in liquid phase.

Authors' contribution statement

Hussain Alessa initiated the idea, collected the references and wrote the manuscript. **Sulafa Nassar** revised the manuscript and drew the figures.

Funding This research is not funded.

Data availability The data will be made available on reasonable request.

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

References

[1] Shakeri, J., Farnia, V., Davarinejad, O., Salemi, S., Golshani, S., Rahami, B., Alikhani, M., Hookari, S., 2020, Distress tolerance in methamphetamine and opium abusers with non-drug abuser (A comparative analysis), *CEGH*., 8, 513-518,

[2] Rusyniak, DE., 2013, Neurologic manifestations of chronic methamphetamine abuse. *Psychiatr. Clin.,* 36:261-275.

[3] Logan, BK., 2002, Methamphetamine-effects on human performance and behavior. *Forensic Sci. Rev*., 14:133-151.

[4] Prakash, MD., Tangalakis, K., Antonipillai, J., Stojanovska, L., Nurgali, K., Apostolopoulos, V., 2017, Methamphetamine: effects on the brain, gut and immune system. *Pharmacol. Res*., 120:60-67.

[5] Wearne, TA., Cornish, JL., 2018, A comparison of methamphetamine-induced psychosis and schizophrenia: a review of positive, negative, and cognitive symptomatology. *Front. Psychiatry*., 9:491.

[6] Rawson, RA., 2013, Current research on the epidemiology, medical and psychiatric effects, and treatment of methamphetamine use. *J. Food. Drug. Anal.*, 21:S77-S81.

[7] Akhgari, M., Mobaraki, H., Etemadi-Aleagha, A., 2017, Histopathological study of cardiac lesions in methamphetamine poisoning-related deaths. *DARU. J. Pharm. Sci*., 25:5.

[8] Smith, LM., Paz, MS., LaGasse, LL., Derauf, C., Newman, E., Shah, R., Arria, A., Huestis, MA., Haning, W., Strauss, A., Della Grotta, S., 2012, Maternal depression and prenatal exposure to methamphetamine: neurodevelopmental findings from the infant development, environment, and lifestyle (ideal) study. Depression and anxiety 29:515-522.

[9] UNODC (United Nations Office on Drugs and Crime): World drug report 2022. United Nations publication. https://www.unodc.org/unodc/data-and-analysis/world-drug-report-2022.html Accessed 15 April 2025

[10] Pietsch, J., Paulick, T., Schulz, K., Flössel, U., Engel, A., Schmitter, S., Schmidt, U., 2013, Escalation of methamphetamine-related crime and fatalities in the Dresden region, Germany, between 2005 and 2011. *Forensic. Sci. Int*., 233:51-54.

[11] Frank, RS., 1983, The clandestine drug laboratory situation in the United States. *J. Forensic. Sci*., 28:18-31.

[12] Shekari, A., Akhgari, M., Jokar, F., Mousavi, Z., 2016, Impurity characteristics of street methamphetamine crystals seized in Tehran, Iran. *J. Subst. Use*., 21:501-505.

[13] Skinner, HF., 1993, Methamphetamine synthesis via reductive alkylation hydrogenolysis of phenyl-2-propanone with N-benzylmethylamine. *Forensic. Sci. Int*., 60:155-162.

[14] Skinner, HF., 1990, Methamphetamine synthesis via hydriodic acid/red phosphorus reduction of ephedrine. *Forensic. Sci. Int*., 48:123-134.

[15] Ciesielski, AL., Green, MK., Wagner, JR., 2020, Characterization of One Pot methamphetamine laboratories using GC-MS and LC-MS/MS. *Forensic. Chem*., 19:100244.

[16] Karila, L., Weinstein, A., Aubin, HJ., Benyamina, A., Reynaud, M., Batki, SL., 2010, Pharmacological approaches to methamphetamine dependence: a focused review. *Br. J. Clin. Pharmacol*., 69:578-592.

[17] Wang, T., Xu, C., Xu, S., Gao, L., Blaženović, I., Ji, J., Wang, J., Sun, X., 2021, Untargeted metabolomics analysis by gas chromatography/time-of-flight mass spectrometry of human serum from methamphetamine abusers. *Addict. Biol*., 26:e13062.

[18] Shin, I., Choi, H., Kang, S., Kim, J., Park, Y., Yang, W., 2021, Detection of l-Methamphetamine and l-Amphetamine as Selegiline Metabolites. *J. Anal. Toxicol*., 45:99-104.

[19] Pérez-Fernández, V., Rocca, LM., Tomai, P., Fanali, S., Gentili, A., 2017, Recent advancements and future trends in environmental analysis: Sample preparation, liquid chromatography and mass spectrometry. *Anal. Chim. Acta*., 983:9-41.

[20] Péron, O., Rinnert, E., Toury, T., De La Chapelle, ML., Compere, C., 2011, Quantitative SERS sensors for environmental analysis of naphthalene. *Analyst*., 136:1018-1022.

[21] Shaw, L., and Dennany, L., 2017, Applications of electrochemical sensors: Forensic drug analysis. *Curr. Opin. Electrochem.*, 3:23-28.

[22] Farah, S., Tsach, T., Bentolila, A., Domb, AJ., 2014, Morphological, spectral and chromatography analysis and forensic comparison of PET fibers. *Talanta*., 123:54-62.

[23] Bor, G., Bulut, U., Man, E., Hanoglu, SB., Evran, S., Timur, S., 2022, Synthetic antibodies for methamphetamine analysis: Design of high affinity aptamers and their use in electrochemical biosensors. J. Electroanal. Chem., 921:116686.

[24] Khorablou, Z., Shahdost-Fard, F., Razmi, H., 2023, High sensitive detection of methamphetamine by high-performance aptasensing platform based on nickel oxide nanoparticles anchored on mxene. *Microchem. J.,* 109216.

[25] Johannessen, SI., Tomson, T., 2006, Pharmacokinetic variability of newer antiepileptic drugs: when is monitoring needed?. *Clin. Pharmacokinet*., 45:1061-1075.

[26] Mager, DE., Jusko, WJ., 2001, General pharmacokinetic model for drugs exhibiting target-mediated drug disposition. *J. Pharmacokinet. Pharmacodyn*., 28:507-532.

[27] Wright, J., Kenneally, M., Ross, K., Walker, S., 2020, Environmental methamphetamine exposures and health effects in 25 case studies. *Toxics*., 8:61.

[28] McFadden, D., Kub, J., Fitzgerald, S., 2006, Occupational health hazards to first responders from clandestine methamphetamine labs. *J. Addict. Nurs*., 17:169-173.

[29] Gao, J., Culshaw, P., Ngo, H., Howell, J., Le, H., Yang, M., Thai, P., 2023, Methamphetamine contamination in residential properties and their remediation in Queensland, Australia. *Forensic. Sci. Int. Rep*., 7: 100311.

[30] Kerry, G.L., Ross, K., Walker, G., Wright, J., 2025, Determining extent and distribution of methamphetamine in cars: Air vs. surface vs. fabrics, *Forensic. Chem*., 42: 100628.

[31] Farst, K., Bolden, BB., 2012, Substance-exposed infants and children: forensic approach. *Clin. Pediatr. Emerg. Med.*, 13:221-228.

[32] Morrison, G., Shakila, NV., Parker, K., 2015, Accumulation of gas-phase methamphetamine on clothing, toy fabrics, and skin oil. *Indoor Air.*, 25:405-414.

[33] Miyaguchi, H., Iwata, YT., Kanamori, T., Tsujikawa, K., Kuwayama, K., Inoue, H., 2009, Rapid identification and quantification of methamphetamine and amphetamine in hair by gas chromatography/mass spectrometry coupled with micropulverized extraction, aqueous acetylation and microextraction by packed sorbent. *J. Chromatogr. A.*, 1216:4063-4070.

[34] Bagheri, H., Zavareh, AF., Koruni, MH., 2016, Graphene oxide assisted electromembrane extraction with gas chromatography for the determination of methamphetamine as a model analyte in hair and urine samples. *J. Sep. Sci.*, 39:1182-1188.

[35] Darvish, M., Qomi, M., Akhgari, M., Raoufi, P., 2015, Determination of trace amounts of methamphetamine in biological samples by hollow fiber liquid-phase microextraction followed by high performance liquid chromatography. *Biosci. Biotechnol. Res. Asia.*, 12:587-597.

[36] Bahmanabadi, L., Akhgari, M., Jokar, F., Sadeghi, HB., 2017, Quantitative determination of methamphetamine in oral fluid by liquid–liquid extraction and gas chromatography/mass spectrometry. *Hum. Exp. Toxicol.*, 36:195-202.

[37] Radwan, R., Abouzied, N., Mora, A., Hassan, A., Elkader, M., 2025, Study Of Methamphetamine Abuse Among Drug Abuse Positive Cases Attending Sohag Clinical Toxicology Laboratory By New Validated HPLC-DAD Method, *AJFM.*, 44: 100-118.

[38] Gracia-Lor, E., Pérez-Valenciano, A., Oro-Carretero, P., Ramírez-García, L., Sanz-Landaluze, J., Martín-Gutiérrez, M., 2024, Consumption of illicit drugs and benzodiazepines in six Spanish cities during different periods of the COVID-19 pandemic, *Sci. Total. Environ.*, 935: 173356.

[39] Kumazawa, T., Hasegawa, C., Hara, K., Uchigasaki, S., Lee, XP., Seno, H., Suzuki, O., Sato, K., 2012, Molecularly imprinted solid-phase extraction for the selective determination of methamphetamine, amphetamine, and methylenedioxyphenylalkylamine designer drugs in human whole blood by gas chromatography-mass spectrometry. *J. Sep. Sci.*, 35:726-733.

[40] Rezazadeh, M., Yamini, Y., Seidi, S., 2015, Application of a new nanocarbonaceous sorbent in electromembrane surrounded solid phase microextraction for analysis of amphetamine and methamphetamine in human urine and whole blood. *J. Chromatogr. A.*, 1396:1-6.

[41] Kala, KL., Anbuchezhiyan, G., Pingili, K., Singh, PK., Vel, VM., Yusuf, K., Aljuwayid, AM., Islam, MA., Christopher, D., 2023, Employing a Carbon-Based Nanocomposite as a Diffusive Solid-Phase Extraction Adsorbent for Methamphetamine for Therapeutic Purposes. *Adsorp. Sci. Technol.*

[42] Farasati, Far, B., Naimi-Jamal, MR., Jahanbakhshi, M., Mohammed, HT., Altimari, US., Ansari, J., 2022, Poly (3-thienylboronic acid) coated magnetic nanoparticles as a magnetic solid-phase adsorbent for extraction of methamphetamine from urine samples. *J. Dispers. Sci. Technol.*, 1-11.

[43] Ghalebi, M., Hamidi, S., Nemati, M., Sheykizadeh, S., Lotfipour, F., Alipour, Ghorbani, N., Farjami, A., 2022, Development of an Efficient and Sensitive Magnetic

Dispersive Solid-phase Extraction Technique for Preconcentration of Amphetamine and Methamphetamine Determined by High-performance Liquid Chromatography and Liquid Chromatography-Tandem Mass Spectrometry in Sports Supplements. *Anal. Bioanal. Chem. Res.*, 9:431-442.

[44] Simarro-Gimeno, C., Garlito, B., Pitarch, E., Hernández, F., 2023, Evaluation of direct sample injection as a fast, no-sample handling, approach for the LC-MS/MS monitoring of pharmaceuticals in different water matrices. *Microchem. J.*, 193: 108985.

[45] Jørgenrud, B., McQuade, T., Maria, M., Nilsson, G., Berg, T., 2025, Buffer-free high pH mobile phase LC-MS/MS for determination of the alcohol biomarker phosphatidylethanol 16: 0/18: 1 and 20 drugs and metabolites in whole blood, *Talanta.*, 282: 126964.

[46] Baz-Lomba, A., Löve, ASC., Reid, MJ., Ólafsdóttir, K., Thomas, KV., 2018, A high-throughput solid-phase microextraction and post-loop mixing large volume injection method for water samples. *J. Chromatogr.. A.*, 1531: 32-38.

[47] Boogaerts, T., Quireyns, M., Maes, F., Laimou-Geraniou, M., Wichelen, N., Heath, E., Pussig, B., Aertgeerts, B., Covaci, A., Nuijs, A., 2023, Optimization, validation and application of a high-throughput 96-well elution protocol for the quantification of psychoactive substances in influent wastewater. *DTA*. 15(2): 240-246.

[48] Vosough, M., Mohamedian, H., Salemi, A., Baheri, T., 2015, Multivariate curve resolution-assisted determination of pseudoephedrine and methamphetamine by HPLC-DAD in water samples. *J. Chromatogr. Sci.*, 53:233-239.

[49] Abdulrahman, SK., Qassim, AW., Rasheed, AS., 2022, The evaluation of Two Zwitterionic Hydrophilic Interaction Liquid Chromatography Materials for the Rapid Separation of Methamphetamine and Muscimol Pharmaceuticals.

[50] Shu, I., et al., 2016, Determination of methamphetamine enantiomer composition in human hair by non-chiral liquid chromatography–tandem mass spectrometry method. *J. Chromatogr. B.*, 1028,145-152.

[51] Nourani, N., Javadzadeh, Y., Shayanfar, A., Taghvimi, A., Bavili-Tabrizi, A., Dastmalchi, S., 2024, Extraction of methamphetamine and pseudoephedrine by modified graphene oxide solid phase extraction method coupled to HPLC-UV in urine sample. *BMC Chem.*, 18(1): 216.

[52] Zhang, S., Cui, Y., Sun, J., Xi, Y., Zhang, C., Tang, J., 2015, Sensitive magnetic solid-phase microextraction based on oxide multi-walled carbon-nanotubes for the determination of methylamphetamine and ketamine in human urine and blood. *Anal. Methods.*, 7: 4209-4215.

[53] Taghvimi, A., Hamishehkar, H., 2017, Carbon coated magnetic nanoparticles as a novel magnetic solid phase extraction adsorbent for simultaneous extraction of methamphetamine and ephedrine from urine samples. *J. Chromatogr. B.*, 1041:113-119.

[54] Haeri, S., Abbasi, S., Sajjadifar, S., 2017, Bio-dispersive liquid liquid microextraction based on nano rhaminolipid aggregates combined with magnetic solid phase extraction using Fe_3O_4@ PPy magnetic nanoparticles for the determination of methamphetamine in human urine. *J. Chromatogr. B.*, 1063: 101-106.

[55] Lu, Q., Guo, H., Zhang, Y., Tang, X., Lei, W., Qi, R., Chu, J., Li, D., Zhao, Q., 2020, Graphene oxide-Fe_3O_4 nanocomposite magnetic solid phase extraction followed by UHPLC-MS/MS for highly sensitive determination of eight psychoactive drugs in urine samples. *Talanta.*, 206: 120212.

[56] Akramipour, R., Fattahi, N., Pirsaheb, M., Gheini, S., 2016, Combination of counter current salting-out homogenous liquid–liquid extraction and dispersive liquid–liquid microextraction as a novel microextraction of drugs in urine samples. *J. Chromatogr. B.*, 1012:162-168.

[57] Chen, X., 2015, Analysis of Methamphetamine in Human Urine Using Ionic Liquid Dispersive Liquid-Phase Microextraction Combined with HPLC. *Chromatographia.*, 78:515–520.

[58] Wang, R., Qi, X., Zhao, L., Liu, S., Gao, S., Ma, X., Deng, Y., 2016, Ionic-liquid-based dispersive liquid–liquid microextraction coupled with high-performance liquid chromatography for the forensic determination of methamphetamine in human urine. *J. Sep. Sci.*, 39:2444-2450.

[59] Alizadeh, N., Jafari, M., Mohammadi, A., 2009, Headspace-solid-phase microextraction using a dodecylsulfate-doped polypyrrole film coupled to ion mobility spectrometry for analysis methyl tert-butyl ether in water and gasoline. *J. Hazard. Mater.*, 169:861-867.

[60] McKenzie, EJ., Miskelly, GM., Butler, PA., 2013, Dynamic solid phase microextraction analysis for airborne methamphetamine: quantitation using isotopically substituted methamphetamine. *Anal. Methods.*, 5:4391-4396.

[61] McKenzie, EJ., Miskelly, GM., Butler, PA., 2013, Detection of methamphetamine in indoor air using dynamic solid phase microextraction: a supplementary method to surface wipe sampling. *Anal. Methods.*, 5:5418-5424.

[62] Nair, MV., Miskelly, GM., 2016, Capillary microextraction: A new method for sampling methamphetamine vapour. *Forensic. Sci. Int.*, 268:131-138.

[63] Nair, MV., Miskelly, GM., 2019, Determination of airborne methamphetamine via capillary microextraction of volatiles (CMV) with on-sorbent derivatisation using o-pentafluorobenzyl chloroformate. *Forensic. Chem.*, 14:100161.

[64] Argente-García, A., Jornet-Martínez, N., Herráez-Hernández, R., Campíns-Falcó, P., 2016, A solid colorimetric sensor for the analysis of amphetamine-like street samples. *Anal. Chim. Acta.*, 943:123-130.

[65] Dobos, A., Hidvégi, E., Somogyi, GP., 2012, Comparison of five derivatizing agents for the determination of amphetamine-type stimulants in Human urine by extractive acylation and gas chromatography–mass spectrometry. *J. anal. Toxicol.*, 36:340-344.

[66] Pires, B., Simão, A., Rosado, T., Barroso, M., Gallardo, E., 2024, Determination of amphetamines in hair samples using microextraction by packed sorbent and gas chromatography–mass spectrometry. *DTA.*, 17 (6): 761-771.

[67] Djozan, D., Farajzadeh, MA., Sorouraddin, SM., et al. 2012, Determination of methamphetamine, amphetamine and ecstasy by inside-needle adsorption trap based on molecularly imprinted polymer followed by GC-FID determination. *Microchim. Acta.*, 179:209–217.

[68] Kumazawa, T., Hasegawa, C., Hara, K., Uchigasaki, S., Lee, XP., Seno, H., Suzuki, O., Sato, K., 2012, Molecularly imprinted solid-phase extraction for the

selective determination of methamphetamine, amphetamine, and methylenedioxyphenylalkylamine designer drugs in human whole blood by gas chromatography-mass spectrometry. *J. Sep. Sci.*, 35:726-733.

[69] Kwon, NH., Lee, YR., Kim, HS., Cheong, JC., Kim, JY., 2019, Hybrid solid-phase extraction for selective determination of methamphetamine and amphetamine in dyed hair by using gas chromatography–mass spectrometry. *Molecules*., 24:2501.

[70] Han, E., Yang, H., Seol, I., et al. 2013, Segmental hair analysis and estimation of methamphetamine use pattern. *Int. J. Legal. Med.*, 127:405–411.

[71] Alawi A., Dhabbah AM., Morrison C., Ben-Jaber S., AlAngari WA., Bin Jassas M., Badjah-Hadj-Ahmed, Y., 2022, Indirect chiral separation of crystal methamphetamine seized in Saudi Arabia using GC-MS. *Aust. J. Forensic. Sci.,* 1-14.

[72] Khajeamiri, AR., Faizi, M., Sohani, F., Baheri, T., Kobarfard, F., 2012, Determination of impurities in illicit methamphetamine samples seized in Iran. *Forensic. Sci. Int.,* 217:204-206.

[73] Hart, JP., Crew, A., Crouch, E., Honeychurch, KC., Pemberton, RM., 2004, Some recent designs and developments of screen-printed carbon electrochemical sensors/biosensors for biomedical, environmental, and industrial analyses. *Anal. Lett.*, 37:789-830.

[74] Al-Hetlani, E., 2013, Forensic drug analysis and microfluidics. *Electrophor.*, 34:1262-1272.

[75] Mao, K., Zhang, H., Wang, Z., Cao, H., Zhang, K., Li, X., Yang, Z., 2020, Nanomaterial-based aptamer sensors for arsenic detection., *Biosens. Bioelectron*., 148:111785.

[76] Krauss, ST.,, Remcho, TP., Lipes, SM., Aranda, R., Maynard, HP., Shukla, N., Li, J., Tontarski, RE., Landers, JP., 2016, Objective method for presumptive field-testing of illicit drug possession using centrifugal microdevices and smartphone analysis. *Anal. Chem.*, 88(17):8689-8697.

[77] Guo, J., Tian, S., Liu, K., Guo, J., 2020, IoT-enabled fluorescence sensor for quantitative KET detection and anti-drug situational awareness. *IEEE Transactions on NanoBiosci*., 20(1): 2-8.

[78] Fan, L., Yang, J., Wu, J., Li, F., Yan, W., Tan, F., Zhang, P., 2022, Deeply-dyed nanobead system for rapid lateral flow assay testing of drugs at point-of-care. *Sens. Actuators. B-Chem.*, 362: 131829.

[79] Cheng Q, Tang J, Ma J, Zhang H, Shinya N, Qin LC (2011) Polyaniline-coated electro-etched carbon fiber cloth electrodes for supercapacitors. *J. Phys. Chem. C.* 115:23584-23590.

[80] Wen D, Fu YY, Shi LQ, He C, Dong L, Zhu DF, He QG, Cao HM, Cheng JG (2012) Fine structural tuning of fluorescent copolymer sensors for methamphetamine vapor detection. *Sens. Actuators. B-Chem.*, 168:283-288.

[81] Rouhani, S., Haghgoo, S., 2015, A novel fluorescence nanosensor based on 1, 8-naphthalimide-thiophene doped silica nanoparticles, and its application to the determination of methamphetamine. *Sens. Actuators. B-Chem.*, 209:957-965.

[82] Dennis, AM., Rhee, WJ., Sotto, D., Dublin, SN., Bao, G., 2012, Quantum dot–fluorescent protein FRET probes for sensing intracellular pH. *ACS nano.*, 6:2917-2924.

[83] Mohammad-Rezaei, R., Razmi, H., 2012, Reduced Graphene Oxide| Carbon Ceramic Electrode Modified with CdS-Hemoglobin as a Sensitive Hydrogen Peroxide Biosensor. *Electroanalysis*., 24:2094-2101.

[84] Roushani, M., Shahdost-Fard, F., 2017, Ultra-sensitive detection of ibuprofen (IBP) by electrochemical aptasensor using the dendrimer-quantum dot (Den-QD) bioconjugate as an immobilization platform with special features. *Mater. Sci. Eng. C.*, 75:1091-1096.

[85] Masteri-Farahani, M., Mosleh, N., 2019, Modified CdS quantum dots as selective turn-on fluorescent nanosensor for detection and determination of methamphetamine. *J. Mater. Sci. Mater. Electron.*, 30:21170-21176.

[86] Shen, J., Zhu, Y., Yang, X., Li, C., 2012, Graphene quantum dots: emergent nanolights for bioimaging, sensors, catalysis and photovoltaic devices. *ChemComm*., 48:3686-3699.

[87] Akhoundian, M., Alizadeh, T., Ganjali, MR., Norouzi, P., 2019, Ultra-trace detection of methamphetamine in biological samples using FFT-square wave voltammetry and nano-sized imprinted polymer/MWCNTs-modified electrode. *Talanta*., 200:115-123.

[88] Masteri-Farahani, M., Mashhadi-Ramezani, S., Mosleh, N., 2020, Molecularly imprinted polymer containing fluorescent graphene quantum dots as a new fluorescent nanosensor for detection of methamphetamine. *Spectrochim. Acta. A. Mol. Biomol. Spectrosc.*, 229:118021.

[89] Mandani, S., Rezaei, B., Ensafi, AA., 2020, Sensitive imprinted optical sensor based on mesoporous structure and green nanoparticles for the detection of methamphetamine in plasma and urine. *Spectrochim. Acta. A. Mol. Biomol. Spectrosc.*, 231:118077.

[90] Goulding, W., Sun, Y., Ashley, J., 2025, NanoMIP beacons with a co-operative binding mechanism for the all-in-one detection of methamphetamine aptamer complexes, *Biosens. Bioelectron*., 267: 116856.

[91] Saberi, Z., Rezaei, B., Faroukhpour, H., Ensafi, AA., 2018, A fluorometric aptasensor for methamphetamine based on fluorescence resonance energy transfer using cobalt oxyhydroxide nanosheets and carbon dots. *Microchim. Acta.*, 185:1-10.

[92] Elmizadeh, H., Bardajee, GR., Moaddeli, A., 2023, Ultrasensitive and rapid detection of methamphetamine in forensic biological fluids using fluorescent apta-nanobiosensors based on CdTe quantum dots, *Microchem. J.*, 189: 108519.

[93] Ghorbanizamani, F., Moulahoum, H., Timur, S., 2021, Noninvasive optical sensor for the detection of cocaine and methamphetamine in saliva using rhodamine B-labeled polymersomes. *IEEE Sens. J.,* 22(2): 1146-1153.

[94] Li, B., Li, K., Xu, W., Yan, M., Zhao, J., Zhang, W., Yuan, M., Fu, Y., He, Q., Cheng, J., 2023, Micro-interfaces modulation by UV—ozone substrate treatment for MPEA vapor fluorescence detection. *Nano. Res.*, 16: 4055–4060.

[95] Liu, K., Shang, C., Wang, Z., Qi, Y., Miao, R., Liu, K., Liu, T., Fang, Y., 2018, Non-contact identification and differentiation of illicit drugs using fluorescent films. *Nat. Commun.*, 9: 1695.

[96] Zhang, Y., Bunes, BR., Wu, N., Ansari, A., Rajabali, S., Zang, L., 2018, Sensing methamphetamine with chemiresistive sensors based on polythiophene-blended single-walled carbon nanotubes. *Sens. Actuators. B-Chem.*, 255: 1814-1818.

[97] Xiao, R., Wang, D., Lin, Z., Qiu, B., Liu, M., Guo, L., Chen, G., 2015, Disassembly of gold nanoparticle dimers for colorimetric detection of ochratoxin A. *Anal. Methods.*, 7: 842-845.

[98] Petryayeva, E., Krull, UJ., 2011, Localized surface plasmon resonance: Nanostructures, bioassays and biosensing—A review. *Anal. Chim. Acta.*, 706: 8-24.

[99] Yarbakht, M., Nikkhah, M., 2016, Unmodified gold nanoparticles as a colorimetric probe for visual methamphetamine detection. *J. Exp. Nanosci.*, 11: 593-601.

[100] Shi Q., Shi, Y., Pan, Y., Yue, Z., Zhang, H., Yi, C., 2015, Colorimetric and bare eye determination of urinary methylamphetamine based on the use of aptamers and the salt-induced aggregation of unmodified gold nanoparticles. *Microchim. Acta*., 182: 505-511.

[101] Mao, K., Yang, Z., Li, J., Zhou, X., Li, X., Hu, J., 2017, A novel colorimetric biosensor based on non-aggregated Au@ Ag core–shell nanoparticles for methamphetamine and cocaine detection. *Talanta*., 175:338-346.

[102] Mao, K., Ma, J., Li, X., Yang, Z., 2019, Rapid duplexed detection of illicit drugs in wastewater using gold nanoparticle conjugated aptamer sensors. *Sci. Total. Environ.*, 688:771-779.

[103] Adegoke, O., Zolotovskaya, S., Abdolvand, A., Daeid, NN., 2020, Biomimetic graphene oxide-cationic multi-shaped gold nanoparticle-hemin hybrid nanozyme: Tuning enhanced catalytic activity for the rapid colorimetric apta-biosensing of amphetamine-type stimulants. *Talanta*., 216:120990.

[104] Bastami, TR., Ghamari, Y., Khadempir, S., Khorasani, ME., Paolesse, R., Bayat, M., 2024, Discriminative detection of morphine and methamphetamine-like street samples by label-free Cu doped-silver nanoparticles chemosensor. *J. Ind. Eng. Chem.*, 131: 459-469.

[105] Zagatto, EA., Oliveira, CC., Townshend, A., Worsfold, P., 2012, Flow analysis with spectrophotometric and luminometric detection. Elsevier.

[106] Wang, Z., Dong, B., Feng, G., Shan, H., Huan, Y., Fei, Q., 2019, Water-soluble hemin-mPEG-enhanced luminol chemiluminescence for sensitive detection of hydrogen peroxide and glucose. *Anal. Sci.*, 35:1135-1140.

[107] Zhao, S., Chen, X., Huang, J., Zhang, X., Sun, J., Yang, L., 2022, Point-of-care testing of methylamphetamine with a portable optical fiber immunosensor. *Analytica. Chimica. Acta.*, 1192: 339345.

[108] Hassanzadeh, J., Khataee, A., Lotfi, R., 2017, Sensitive fluorescence and chemiluminescence procedures for methamphetamine detection based on CdS quantum dots. *Microchem. J.*, 132:371-377.

[109] Yadav, SK., Agrawal, B., Oyama, M., Goyal, RN., 2014, Graphene modified Palladium sensor for electrochemical analysis of norepinephrine in pharmaceuticals and biological fluids. *Electrochim. Acta.*, 125:622-629.

[110] Roushani, M., Dizajdizi, BZ., Salimi, A., Azadbakht, A., 2019, Preparation of modified glassy carbon electrode by the use of titanium oxide, copper and palladium nanoparticles and its application for the electrocatalytic and photelectrocatalytic reduction of hydrogen peroxide. *J. Mater. Sci. Mater. Electron.*, 30:5212-5221.

[111] Razmi, H., Ezzati, L., Khorablou, Z., 2019, Direct electrochemical synthesis of graphene oxide/cobalt oxide nanocomposite on pencil graphite electrode for highly

sensitive and selective detection of insulin in pharmaceutical samples. *J. Electrochem. Soc.*, 166:B961.

[112] Karim-Nezhad, G., Khorablou, Z., Dorraji, PS., 2016, Modification of glassy carbon electrode with a bilayer of multiwalled carbon nanotube/poly (l-Arginine) in the presence of surfactant: Application to discrimination and simultaneous electrochemical determination of dihydroxybenzene isomers. *J. Electrochem. Soc.*, 163:B358.

[113] Baghbamidi, SE., Beitollahi, H., Tajik, S., Hosseinzadeh, R., 2016, Voltammetric sensor based on 1-benzyl-4-ferrocenyl-1H-[1, 2, 3]-triazole/carbon nanotube modified glassy carbon electrode; detection of hydrochlorothiazide in the presence of propranolol. *Int. J. Electrochem. Sci.*, 11:10874-10883.

[114] Rezaei, B., Irannejad, N., 2019, Electrochemical detection techniques in biosensor applications. In Electrochemical biosensors (pp. 11-43). Elsevier.

[115] Kohzadi, R., Molaeirad, A., Alijanianzadeh, M., Kamali, N., Mohtashamifar, M., 2016, Designing a label free aptasensor for detection of methamphetamine. *Biomacromolecular. J.*, 2:28-33.

[116] Švorc, Ľ., Vojs, M., Michniak, P., Marton, M., Rievaj, M., Bustin, D., 2014, Electrochemical behavior of methamphetamine and its voltammetric determination in biological samples using self-assembled boron-doped diamond electrode. *J. Electroanal. Chem.*, 717:34-40.

[117] Oghli, AH., Alipour, E., Asadzadeh, M., 2015, Development of a novel voltammetric sensor for the determination of methamphetamine in biological samples on the pretreated pencil graphite electrode. *RSC. Adv.*, 5:9674-9682.

[118] Bartlett, CA., Taylor, S., Fernandez, C., Wanklyn, C., Burton, D., Enston, E., Raniczkowska, A., Black, M., Murphy, L., 2016, Disposable screen printed sensor for the electrochemical detection of methamphetamine in undiluted saliva. *Chem. Cent. J.*, 10:1-9.

[119] Razmi, H., Sarhang-Zadeh, K., Mohammad-Rezaei, R., 2013, Electrochemical behavior and voltammetric determination of diclofenac at a multi-walled carbon nanotube-ionic liquid composite modified carbon ceramic electrode. *Anal. Lett.*, 46:1885-1896.

[120] Demir, B., Yilmaz, T., Guler, E., Gumus, ZP., Akbulut, H., Aldemir, E., Coskunol, H., Colak, DG., Cianga, I., Yamada, S., Timur, S., 2016, Polypeptide with electroactive endgroups as sensing platform for the abused drug 'methamphetamine'by bioelectrochemical method. *Talanta.*, 161:789-796.

[121] Dokuzparmak, E., Brown, K., Dennany, L., 2021, Electrochemiluminescent screening for methamphetamine metabolites. *Analyst.*, 146(10): 3336-3345.

[122] Xie, Y., Wu, S., Chen, Z., Jiang, J., Sun, J., 2022, Rapid nanomolar detection of methamphetamine in biofluids via a reagentless electrochemical aptamer-based biosensor. *Anal. Chim. Acta.*, 1207:339742.

[123] Ghorbanizamani, F., Moulahoum, H., Celik, EG., Timur, S., 2022, Ionic liquid-hydrogel hybrid material for enhanced electron transfer and sensitivity towards electrochemical detection of methamphetamine. *J. Mol. Liq.*, 361:119627.

[124] Beduk, D., Beduk, T., de Oliveira Filho, JI., Lahcen, A., Aldemir, E., Celik, E., Salama, K., Timur, S., 2023, Smart multiplex point-of-care platform for simultaneous drug monitoring. *ACS. Appl. Mater. Interfaces.*, 15(31): 37247-37258.

[125] Haghighi, M., Shahlaei, M., Irandoust, M., Hassanpour, A., 2020, New and sensitive sensor for voltammetry determination of Methamphetamine in biological samples. *J. Mater. Sci. Mater. Electron.*, 31:10989-11000.

[126] Anvari, L., Ghoreishi, SM., Faridbod, F., Ganjali, MR., 2021, Electrochemical determination of methamphetamine in human plasma on a nanoceria nanoparticle decorated reduced graphene oxide (rGO) glassy carbon electrode (GCE). *Anal. Lett.*, 54:2509-2522.

[127] Riahifar, V., Haghnazari, N., Keshavarzi, F., Ahmadi, E., 2021, A sensitive voltammetric sensor for methamphetamine determination based on modified glassy carbon electrode using Fe3O4@ poly pyrrole core-shell and graphene oxide. *Microchem. J.*, 170:106748.

[128] N. Anzar, et al., 2023, Wearable Electrochemical Glove-Based Analytical Device (eGAD) for the Detection of Methamphetamine Employing Silver Nanoparticles, *Biosens.*, 13(10): 934

[129] Anzar, N., Suleman, S., Bano, H., Parvez, S., Khanuja, M., Pilloton, R., Narang, J., 2023, Based Electrodes Decorated with Silver and Zinc Oxide Nanocomposite for Electro-Chemical Sensing of Methamphetamine. *Sensors*., 23(12), 5519.

[130] Suleman, S.; Anzar, N.; Patil, S.; Ansari, S.; Jahan, F.; Narang, J., 2025, Development of an electrochemical paper based multiplex analytical device for the detection of “illicit drugs” employing silver nanoparticles. *Mater. Chem. Phys.*, 338, 130649.

[131] Duan, S., Chen, H., Xu, A., He, Y., Li, M., Zhang, R., Zhnag, R., Bai, H., 2024, A simple polyarginine membrane electrochemical sensor for the determination of MDMA and MDA. *Anal. Biochem.*, 688, 115478.

[132] Watanabe, K., Okada, K., Katsu, T., 1993, Determination of methamphetamine in urine in situ using a methamphetamine-sensitive membrane electrode. *Analytica. Chimica. Acta.*, 274:59-63.

[133] Hayat, A., Catanante, G., Marty JL., (2014) Current trends in nanomaterial-based amperometric biosensors. Sensors 14:23439-23461.

[134] Zhang, LY., Liu, YJ., 2014, Label-free amperometric immunosensor based on prussian blue as artificial peroxidase for the detection of methamphetamine. *Analytica. Chimica. Acta*., 806, 204-209.

[135] Randviir, EP., Banks, CE., 2013, Electrochemical impedance spectroscopy: an overview of bioanalytical applications. *Anal. Methods*., 5, 1098-1115.

[136] Yeh, CH., Wang, WT., Shen, PL., Lin, YC., 2012, A developed competitive immunoassay based on impedance measurements for methamphetamine detection. *Microfluid*., 13, 319-329.

[137] Yang, Y., Pan, J., Hua, W., Tu, Y., 2014, An approach for the preparation of highly sensitive electrochemical impedimetric immunosensors for the detection of illicit drugs. *J. Electroanal. Chem*., 726, 1-6.

[138] Ebrahimi, M., Johari-Ahar, M., Hamzeiy, H., Barar, J., Mashinchian, O., Omidi, Y., 2012, Electrochemical impedance spectroscopic sensing of methamphetamine by a specific aptamer. *BioImpacts: BI*., 2, 91.

[139] Anvari, L., Ghoreishi, SM., Khoshnevisan, K., Ganjali, MR., Faridbod, F., 2023, Methamphetamine determination using label-free impedimetric aptasensor based on ceria nanocomposite. *J. Appl. Electrochem*., 1-9.

[140] Khorablou, Z., Shahdost-fard, F., Razmi, H., 2022, Nanodiamond-derived carbon nano-onions decorated with silver nanodendrites as an effective sensing platform for methamphetamine detection. *Surf. Interfaces.*, 31:102061.

[141] Rafiee, B., Fakhari, AR., Ghaffarzadeh, M., 2015, Impedimetric and stripping voltammetric determination of methamphetamine at gold nanoparticles-multiwalled carbon nanotubes modified screen printed electrode. *Sens. Actuators. B. Chem.*, 218:271-279.

[142] Ceto, X., Truta, FM., Dragan, AM., Rodríguez-Franch, E., Tertis, M., Sánchez-Pereña, Á., Comellas-Tena, S., Cristea, C., del Valle, M., 2025, Towards the development of a portable device based on modified-voltammetric sensors for the detection of illicit drugs and seized samples. *Talanta*., 282: 127055.

[143] Sun, H., Liu, J., Qiu, Y., Kong, J., Zhang, X., 2022, High sensitive electrochemical methamphetamine detection in serum and urine via atom transfer radical polymerization signal amplification. *Talanta*., 238:123026.

[144] Saisahas, K., Soleh, A., Somsiri, S., Senglan, P., Promsuwan, K., Saichanapan, J., Kanatharana, P., Thavarungkul, P., Lee, K., Chang, KH., Abdullah, AFL., 2022, Electrochemical Sensor for Methamphetamine Detection Using Laser-Induced Porous Graphene Electrode. *Nanomater*., 12:73.

[145] Lee, K., Saisahas, K., Soleh, A., Kunalan, V., Chang, KH., Limbut, W., Abdullah, AFL., 2022, Forensic electrochemistry: electrochemical analysis of trace methamphetamine residues on household surfaces. *J. Electrochem. Soc.*, 169: 056514.

[146] Liu, H., 2024, Highly selective detection of methamphetamine in urine using biosynthesized graphene oxide-gold nanoparticle composite modified electrodes. *Int. J. Electrochem. Sci*. 19(11): 100851.

[147] Melo, L. M., de Faria, L.V., Arantes, L.C., Richter, E.M., Munoz, R.A., dos Santos, W.T., 2024, Combined colorimetric and electrochemical screening method using 3D printed devices: Towards the selective detection of MDMA in forensic samples. *Electrochimica. Acta*., 483, 144041.

[148] Dragan, AM., Parrilla, M., Sleegers, N., Slosse, A., Van Durme, F., van Nuijs, A., Oprean, R., Cristea, C., De Wael, K., 2023, Investigating the electrochemical profile of methamphetamine to enable fast on-site detection in forensic analysis. *Talanta*., 124208.