European Monitoring Centre
for Drugs and Drug Addiction

Environmental impact of synthetic drug production: analysis of groundwater samples for contaminants derived from illicit synthetic drug production waste

Background paper commissioned by the EMCDDA

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2023

This paper was commissioned by the European Monitoring Centre for Drugs and Drug Addiction (EMCDDA), to provide background material to inform and contribute to the analysis of EU Drug Markets. This background paper was produced under contract no CT.21.SAS.0107.1.0 and we are grateful for the authors' valuable contributions. The paper is available online for those who would like further information on the topic. The views, interpretations and conclusions set out are those of the authors and are not necessarily those of the EMCDDA or its partners, any EU Member State or any agency or institution of the European Union.

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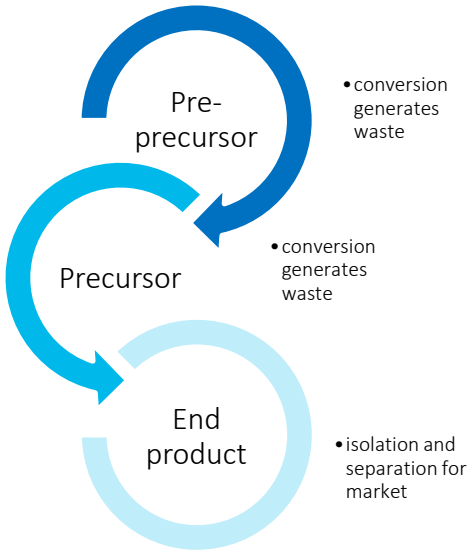
Executive summary

The Netherlands and Belgium are known major producers of synthetic psychoactive drugs such as MDMA, amphetamine and, more recently, methamphetamine. The present study shows that as a result of the illicit production of these synthetic drugs, large volumes of chemical waste are generated and encountered in the environment after disposal. It is estimated that between 25 and 43 kilograms of (liquid) drug production waste is generated per kilogram of produced drug. Knowledge on the composition and the emission of synthetic drug production waste is limited. However, emissions onto or into soil and surface water pose a particular environmental risk. In a field study that was performed as part of the current project, residues of drug production waste, including the produced MDMA, amphetamine and methamphetamine as well as several known by-products, were encountered in the surface water and sediment of a former, remediated drug production waste dump location. Concentration patterns followed a trend, with the highest concentrations in the sediment and water near the former point of emission and lower concentrations found further away from this location. The current literature review and field study illustrate that knowledge on the occurrence and fate of drug production waste residues in surface waters, soils, sediments and groundwater remains limited, and that field research of dump locations is hampered by restrictions to site accessibility. The current remediation strategies applied by local authorities when drug production waste is encountered may overlook the environmental aspects and risks associated with the emission of such residues.

Introduction and objectives

Large quantities of synthetic drugs are produced in the Netherlands and Belgium (EMCDDA and Europol, 2019). MDMA (3,4-methylenedioxy-methamphetamine) and amphetamine have been produced in the Netherlands for four decades (Tops et al., 2018). More recently, large-scale methamphetamine production has also been observed in the Netherlands, and many other synthetic illicit drugs are produced on a smaller scale (Dutch National Police, 2022). The most used precursor for MDMA synthesis in the Netherlands is piperonyl methyl ketone (PMK), while benzyl methyl ketone (BMK) is the main precursor for amphetamine. With the banning of the trade in PMK and BMK, the pre-precursors of PMK and BMK subsequently became controlled substances, resulting in a continuous cycle of banning and finding alternative pre-precursors (Ter Laak and Mehlbaum, 2022) (Figure 1).

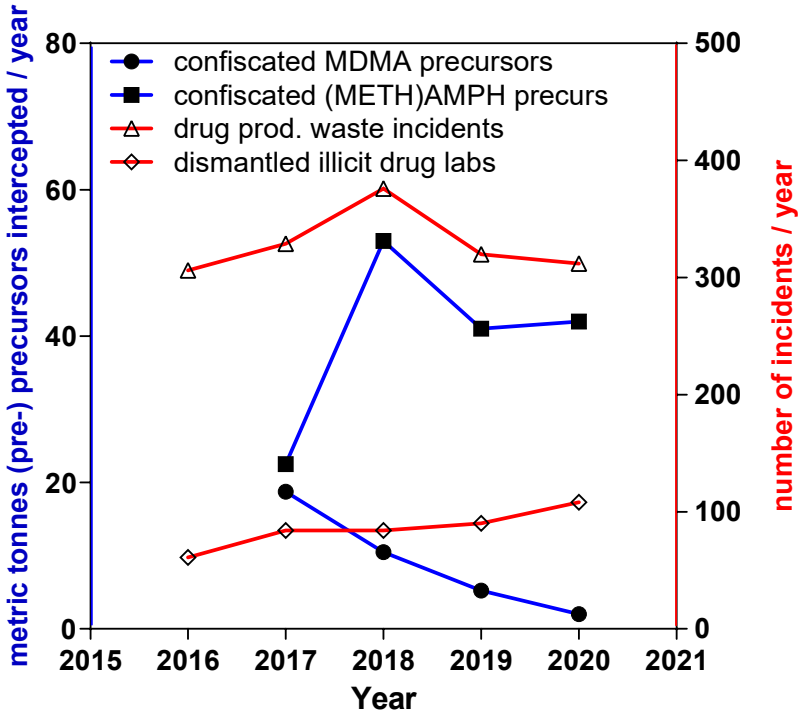
FIGURE 1
Conceptual picture of synthesis of synthetic drugs such as MDMA, amphetamine and methamphetamine



Between 2017 and 2020 the amount of confiscated precursors and pre-precursors of MDMA dropped from 19 to 2 metric tonnes per year in the Netherlands, while the volume of amphetamine/methamphetamine pre-precursors seized ranged from over 20 to over 53 tonnes per year, with no clear trend apparent over this period (Dutch National Police, 2022). However, within these four years confiscated pre-precursors showed that the MDMA precursors PMK and safrole ceased to appear after 2018, while between 2017 and 2020 alpha-phenylacetoacetamide (APAA) largely replaced alpha-phenylacetoacetonitrile (APAAN) for making BMK to produce amphetamine (Dutch National Police, 2022). This highlights the

dynamic character of the import, use and interception of pre-precursors. While the amount of confiscated MDMA (pre-)precursors dropped, the number of dismantled laboratories dedicated to MDMA production and other synthetic drugs remained static (Figure 2).

FIGURE 2
Trends in (pre-)precursor interceptions for MDMA amphetamine and methamphetamine (left y-axis) (Dutch National Police, 2022) and number of drug production waste dump incidents (Ter Laak and Mehlbaum, 2022) and dismantled illicit laboratories (Dutch National Police, 2022) in the Netherlands (right y-axis)



Recent discoveries of methyl alpha-phenylacetoacetate (MAPA) and ethyl alpha-phenylacetoacetate (EAPA) by customs agencies illustrate the ever-changing precursor market (personal communication, Dutch Customs, 2022). Furthermore, the number of waste dumps linked to illicit drug production registered by Dutch authorities showed a steady increase between 2010 and 2018 (Dutch National Police, 2022).

Chemical drug production waste is found at production sites, stored in buildings, dumped in the environment, discharged on land or in surface waters, and mixed with (waste) materials such as manure, municipal wastewater or industrial waste (Schoenmakers et al., 2016). The most frequently observed form of waste disposal is the dumping of barrels on the street, in nature, in ditches or in vehicles or trailers. However, this does not necessarily mean that these methods also account for the greatest fraction of waste disposal because other routes for the fly-tipping of waste are less easily discovered (Ter Laak and Mehlbaum, 2022). Discharging waste into sewers, soil or surface water, or mixing it with other waste streams are infrequently detected methods of waste disposal and are less well understood and quantified.

Direct emissions onto or into soil and surface waters can have an especially large impact on the environment, while mixing these products with waste streams can have an indirect impact (Emke, 2020; Emke et al., 2018; Pronk, 2020). The aim of this study is to investigate the potential environmental impact of waste generated by illicit drug production. To this end, we characterise the composition of drug production waste based on commonly applied procedures in the Netherlands and Belgium and discuss the emission and fate of the constituents of drug production waste in the soil and water environment. We also provide a case study of a drug production dump site that had discharged waste into surface water, examining residues of the production waste found in the environment after the site was remediated. Finally, we conclude with our research findings, pinpoint knowledge gaps and offer recommendations for research and mitigation.

Review of previous research on synthetic drug production waste in the environment

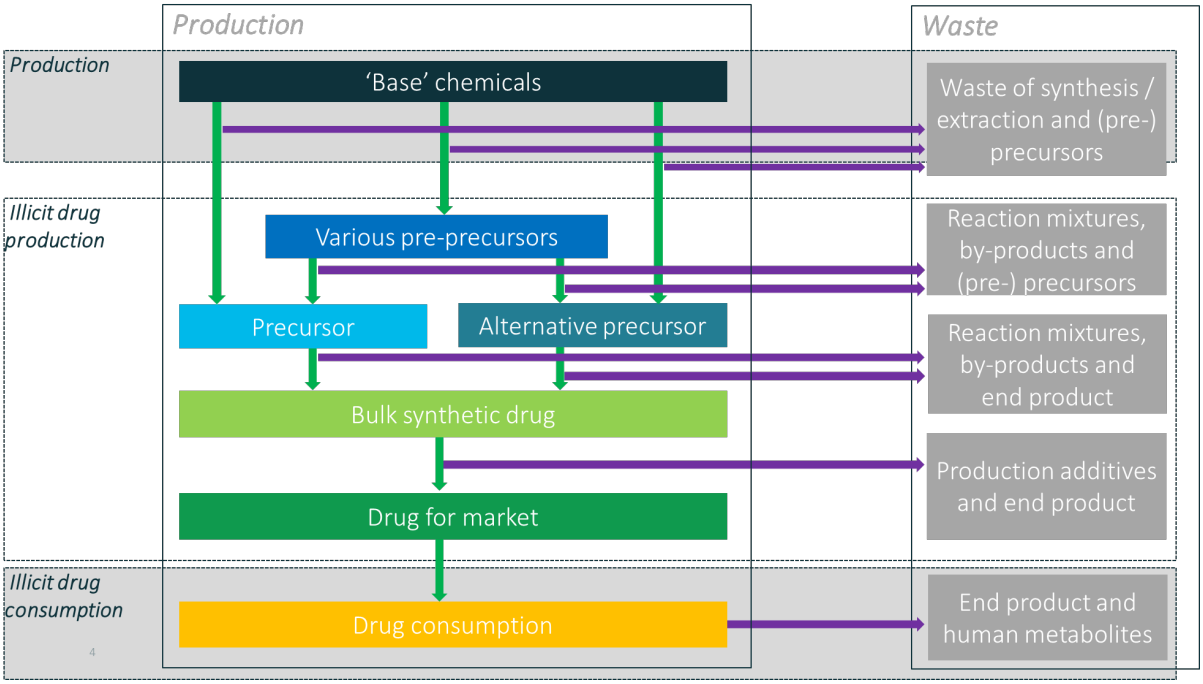
Production of synthetic drugs

All synthetic drug production processes require raw materials, reagents and excipients. Reagents and auxiliary agents are in most cases simple generic chemicals such as organic solvents, acids and bases that are readily available. They have many different applications, so while their environmental occurrence might indicate the emission of drug production waste, it is not conclusive. Furthermore, these substances are often replaceable by similar chemicals. For example, a range of acids, bases and solvents can be used to achieve the same end product.

The raw materials of drug production, also called precursors or pre-precursors, are the most important substances because they form the basis for the drug's production. Often, they are very similar to the final product in terms of chemical structure. These substances are more difficult to obtain due to legal restrictions in their trade. When a raw material is controlled producers often look for alternatives, or find ways to make the desired raw material (precursor) themselves from another raw material (pre-precursor). As a result, banning a precursor can generate more chemical waste than before, due to the modification of the production process requiring additional synthesis steps and raw materials.

At the end of the production process, the final product can be separated from the reaction mixture in various ways. Conversion steps and final isolation of the end product are never 100 % efficient, so the waste consists of a plethora of chemicals such as reagents, raw materials, catalysts, reaction intermediates, by-products and the final product — the drug itself (Figure 3). The current study focuses on the middle part of Figure 3, i.e., illicit drug production and its corresponding waste, with a focus on Europe, and especially the Netherlands and Belgium, as this is a prominent area for the production of synthetic drugs (EMCDDA and Europol, 2019).

FIGURE 3
Life-cycle of illicit drug production and waste materials



Note: Often the bulk chemical production takes place outside Europe, mostly China, and consumption occurs within and outside of Europe.

Volume and composition of drug production waste

A recent study estimated the composition and volume of drug production waste for amphetamine and MDMA synthesis and the production yields from pre-precursors to the end product (Ter Laak and Mehlbaum, 2022). Estimates were based on recipes found in clandestine laboratories over the past 25 years for the conversion of PMK to MDMA and BMK to amphetamine, and over the past 10 years for the synthesis of PMK and BMK from various pre-precursors, as well as looking at the relevant literature and experimental work by the Dutch National Forensic Institute. Despite the fact that these recipes come from Dutch laboratories, they are thought to be representative of production sites in Belgium and Germany, near the Dutch border, as the same organisations are active in this cross-border region. Table 1 lists the estimated volumes of waste generated for amphetamine and MDMA. With regard to methamphetamine, insufficient information was found to estimate the amounts of waste produced in its production. But as amphetamine and methamphetamine share the same precursor (in the commonly applied synthesis route) and further processing from BMK to methamphetamine involves some additional steps, it is likely that similar volumes of waste are generated for methamphetamine production.

TABLE 1
Volumes and composition of drug production waste for MDMA and amphetamine synthesis

Drug	pre-precursor	Kg pre-precursor / kg end product	Volume liquid waste (litre per kg produced drug)
Amphetamine	APAA(N)	3.4	26 (19-39)
MDMA	PMK-glycide acid-methylester	2.6 (High pressure method)	25 (21-31)
		3.1 (Cold method)	43 (29-58)

Data from reference (Ter Laak and Mehlbaum, 2022)

The volume and composition of chemical waste will vary, depending on the (pre)-precursors used, the drug produced and the synthesis route, the reaction conditions and duration, the installations and equipment employed, and the experience of the cook (UNODC, 2022). In general, the major part of the waste is highly acidic. Acids such as formic acid, hydrochloric acid and acetic acid are commonly applied. A smaller yet relevant fraction of the waste (of amphetamine production) consists of basic solutions. Furthermore, organic solvents such as acetone and methanol are commonly applied and can also end up as waste (Ter Laak and Mehlbaum, 2022), although solvents may be recycled as well. All these waste solutions contain residues of (pre-)precursors, by-products, catalysts, reactants and the end-product — the drug itself.

Emission of drug production waste to groundwater

The dumping of drug production waste onto soil or its infiltration into soil is observed occasionally at production sites and at hidden locations in the field. Furthermore ‘accidental’ spills can occur when waste stored in barrels or containers leaks onto the soil. However, the actual volume of both these emissions remains unclear as they are poorly registered and actual quantitative estimates of emissions are often impossible to reconstruct when a site/incident is discovered (Ter Laak and Mehlbaum, 2022).

Scenario studies can reliably illustrate that a sizable emission of drug production waste from a large illicit laboratory can affect groundwater quality in the area and last for decades. In particular, emissions of waste containing MDMA can contaminate groundwater. According to modelling exercises, if groundwater is abstracted near sites where drug production waste has infiltrated, it is expected that residues of MDMA may be found after 16 years if emissions were at a distance of 300 metres from the abstraction well and 154 years if this distance was 1500 metres (Emke, 2020). These scenario studies pinpoint the environmental risks of drug production waste infiltration over longer time scales and significant distances. The current remediation strategy focuses on mitigating direct human health risks, and restoring soil and water systems guided by deviating pH levels and the presence of volatile solvents. This approach is not focused on the precursors, end products and by-products, which are generally more persistent and have the ability to pollute groundwater and surface water. Furthermore,

timely remediation is often hampered by legal and financial constraints. As soil contamination/infiltration usually poses no direct threat to human health, there have been various occasions when the time between discovery and remediation has stretched to years. In the meantime, landowners and local authorities argue over who is responsible and who foots the bill. This does not help in protecting groundwater and the environment. However, recent legal changes in the Netherlands allow for action to be taken more swiftly, with the national government covering the bill if polluters can't be traced or landowners are unable to pay (Dutch Government, 2022).

Emission of drug production waste into surface water and wastewater

The dumping of drug production waste directly into surface waters or indirectly via the sewer and wastewater treatment infrastructure can affect surface water quality (Emke et al., 2018). When assessing drug production waste residues in surface water or wastewater, it is important to distinguish between residues from consumption and those from production. While monitoring the wastewater for the city of Eindhoven region has demonstrated that drug production waste emissions through surface water occur frequently (Reymond et al., 2022), this form of emission is hardly registered (Ter Laak and Mehlbaum, 2022).

Plausible scenario studies making use of hydrological modelling illustrate that a large emission of drug production waste from a sizable laboratory into a sewer (or directly into surface water) can affect surface water quality temporarily over long distances (Pronk, 2020). Emissions into sewer systems are in practical terms impossible to remediate as wastewater treatment is a continuous process that cannot be stopped. Emissions into surface water can be remediated when the water is (rather) stagnant such as in lakes or ditches, and the response time is short. However, this is in practical terms impossible in large rivers and fast-flowing streams.

A well-documented incident showed that a large volume of drug production waste (multiple cubic meters of liquid waste) emitted to a relatively small wastewater treatment plant (with a capacity of 15 000 inhabitant equivalents) can lead to the complete malfunctioning of the activated sludge system (Emke et al., 2018). When the treatment plant malfunctions, all the wastewater gathered from the catchment area will not be treated properly until the functioning of the activated sludge system is re-established by transferring activated sludge from other wastewater treatment plants. This leads to additional contamination of the aqueous environment with communal wastewater and incurs a huge cost.

Illicit drug production locations and waste incidents

Data on illicit laboratories that produce/process (precursors of) synthetic drugs are registered by the Dutch National Police. From 2017 to 2020 362 laboratories were discovered in the Netherlands (Dutch National Police, 2022) and 1631 drug production waste dumps were registered between 2016 and 2020 (Dutch National Police, 2022; Ter Laak and Mehlbaum,

2022) (see Figure 4). Such seized laboratories are investigated by national authorities and the precursors encountered and drugs produced are identified, but the encountered drug production waste is rarely chemically profiled due to limited forensic research capacity.

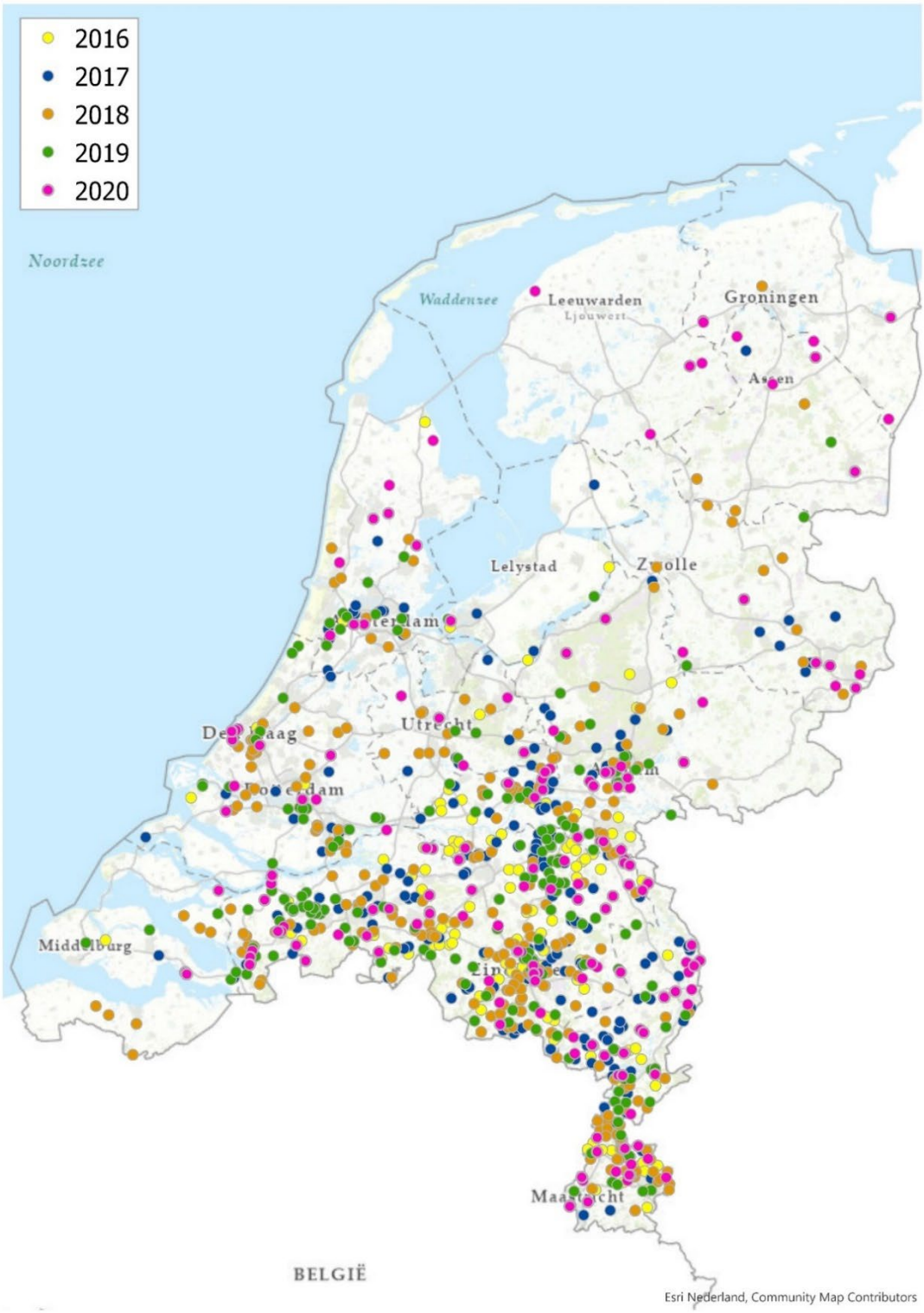
Remediation

When drug production waste is encountered several organisations become involved. The first response and primary aim is to remove the waste from (often) public places to protect people's health. The police and associated research institutes have limited capacities to characterise and document the waste incidents. The focus is on looking for direct evidence related to potential prosecutions, such as fingerprints, DNA on cigarette butts, and labels from containers or other evidence from the crime scene. Furthermore, different police regions and countries have different protocols for the administration of these incidents, making the characterisation and categorisation of waste incidents more complicated. The development of a common protocol for administration in this area is ongoing in the Netherlands (Dutch National Police, 2021).

Drug production waste directly dumped in containers is usually easy to recover. Greater problems can occur when leaking containers are disposed of or waste from drug production is purposely infiltrated into the soil. Then the cost for remediation includes the excavation of contaminated soil, and can increase up to hundreds of thousands of euros. Intentional infiltration of drug production waste is often encountered on private property or in remote locations, which makes it more difficult to identify. Furthermore, the time between emission and discovery is often longer than for container dumps. In addition, more complex and costly remediation efforts can extend the time taken between discovery and remediation.

FIGURE 4

Dump locations of drug production waste in the Netherlands between 2016 and 2020 (adopted from ter Laak and Mehlbaum, 2022).



Methodology of the field study

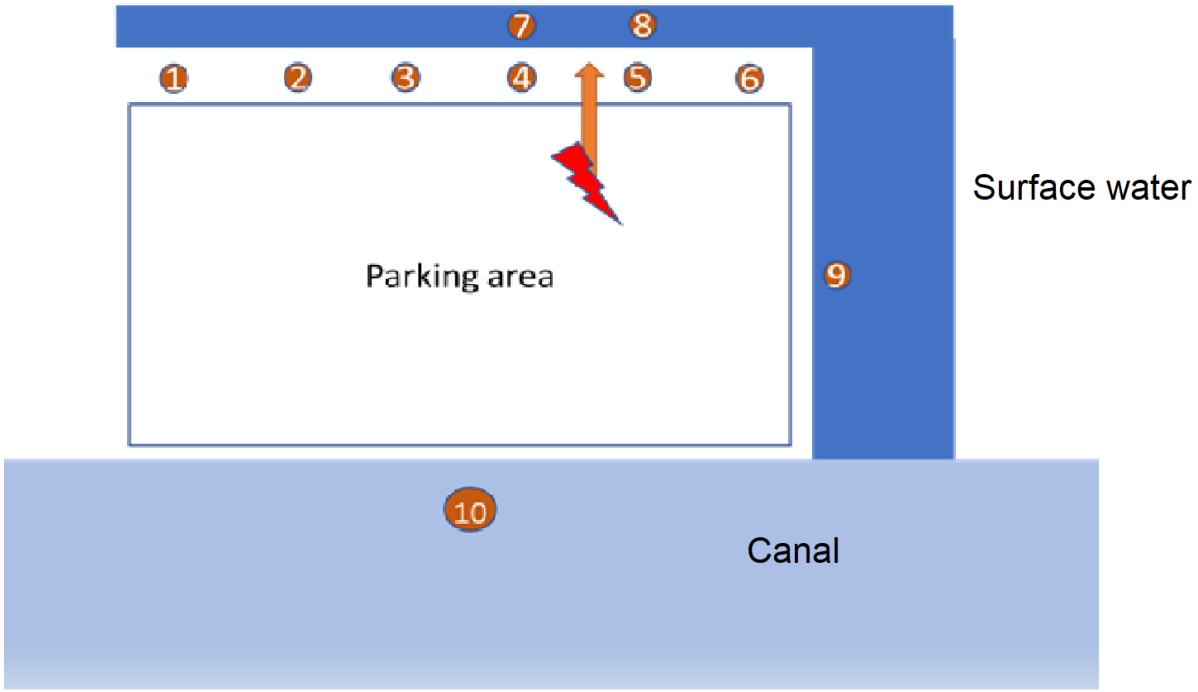
Gaining access to a contaminated site

Eight candidate locations for the field study were identified, including sites where drug waste had been disposed of in the environment. However, accessing contaminated sites presented a number of challenges due to ongoing (legal) discussions on remediation, costs, responsibilities and eligibility. For example, research at remediated sites might lead to finding residues that could require additional remediation for which, potentially, no funding was available, while research at active (non-remediated) sites turned out to be impossible, as this could complicate ongoing legal and financial debates on responsibility and the costs of remediation. Within the given timeframe and resources, out of the eight locations initially identified, just one could be accessed to conduct the field research for the present study. The results are presented below.

Description of location

At this location, drug production waste was emitted on two consecutive occasions into the drainage of a parking lot that was directly connected to a small area of surface water (a ditch of ~2 meters wide). This ditch was about 30 metres long and joined to a wider area of surface water (~10 metres wide, ~30 metres long), which, in turn, was connected to a canal (~15 metres wide) that was openly linked to the drainage infrastructure of the region. The ditches are designed for draining water from the land, so infiltration from surface water into the soil and groundwater is not expected, as the flow of seepage water moves in the opposite direction (Figure 5).

FIGURE 5
Schematic map of the sampling locations, the red lightning bolt indicates the point of emission into a drainage pipe discharging into the small ditch (orange arrow)



Location history and initial findings

The location was contaminated with drug production waste twice within a few days in 2021. Shortly after the first disposal was discovered the ditch was isolated. After this action was taken, a second discharge occurred, most likely during the night. Subsequently, the ditch and adjacent water were completely drained to remove the drug production waste and prevent emissions into the local and regional water system. Initial chemical analysis on volatile organic chemicals and acids showed the presence of solvents such as acetonitrile and tetrahydrofuran and exceptionally low pH. Furthermore, residues of amphetamine, methamphetamine and MDMA were detected in the water, but no quantitative results were reported on the drugs and their by-products. The contaminated ditch was remediated by isolating the small ditch from the surrounding water and removing all the water and the top layer of sediment. Remediation was guided by measurements taken with a handheld photo ionisation detector (PID), which detects residues of volatile organic chemicals such as solvents in air.

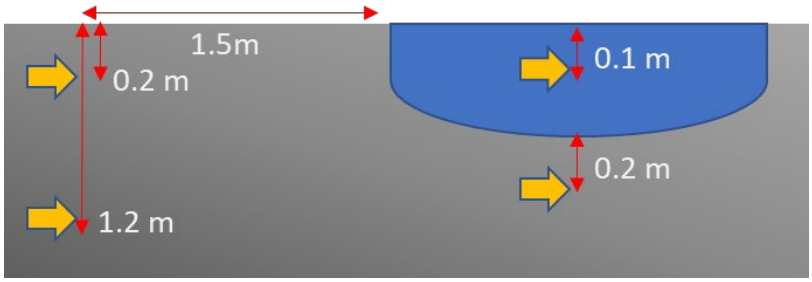
Sampling strategy

At the sampling site, the sediment and water of the small ditch were sampled at two locations near the outlet of the drainage pipe (Figure 5, locations 7 & 8), while the large ditch was sampled at one location (location 9), and the canal was also sampled at one location (location 10). In addition, samples of soil and groundwater were taken at six locations along the stretch of

the small ditch about 3–4 metres apart (Figure 5, locations 1–6) and 1.5 metres away from the ditch. These soil and groundwater samples were taken to establish whether drug production waste residues had infiltrated into the banks of the ditch and local groundwater.

Figures 5 and 6 present the sampling strategy in more detail. Numbers 1–6 in Figure 5 indicate the locations of the soil samples taken at 0.2 and 1.2 m depth above and below the groundwater table (see Figure 6 for a cross-section). Numbers 7 and 8 in Figure 5 represent the locations in the small ditch, number 9 in the wider surface water and number 10 in the canal where surface water and sediment samples were taken. Surface water samples were taken before sediment sampling to prevent disturbing the integrity of the water column by sediment sampling. Samples were taken about one year after the incident(s) and subsequent remediation.

FIGURE 6
Cross-section of where samples were taken



Chemical analysis

The water samples were extracted according to a methodology described in detail elsewhere (Bijlsma et al., 2013; de Voogt et al., 2011). In short, deuterated analogues are added to 500 ml of sample, filtered, and extracted with solid phase extraction. Extracts are then concentrated to 0.5 ml and analysed. The sediment and soil samples were extracted using an experimental (not fully validated) method, taking a QuEChERS approach (González-Curbelo et al., 2022; Lehotay, 2007). This analysis was based on the AOAC official method 2007.1, which was developed to extract pesticides from food items (Schreiber et al., 2013) and slightly adapted for sediment and soil application, following a search of the literature. In short, 15 g of a wet soil or sediment sample was taken and 5 ml of pure water was added to make a slurry. Subsequently, 15 ml of extraction solvent spiked with deuterated analogues of the illicit drugs was added before the first salting-out step was performed; after centrifugation, 8 ml of supernatant was transferred to a vial for a second salting-out treatment/clean-up step. After another centrifugation step, 6 ml of supernatant was sampled, concentrated to 0.5 ml by evaporation of the solvent, and analysed.

All samples were analysed with high-resolution mass spectrometry after liquid chromatography separation (HPLC-Orbitrap-FUSION-MS-MS) at a resolution of 100 000. This technique allows

for the quantification and screening of residues of illicit drugs to nanogram/litre levels, as well as of organic contaminants associated with the production waste from these drugs (Emke et al., 2018).

Results of analysis of groundwater samples

Table 2 shows the concentrations of parent drug residues in the samples taken.

TABLE 2
Drug residues in water, soil and sediment near the drug production waste dump location

Sample	MDMA		Amphetamine		Methamphetamine	
	Water (ng/L)	Solid (µg/kg dry weight)	Water (ng/L)	Solid (µg/kg dry weight)	Water (ng/L)	Solid (µg/kg dry weight)
Small ditch water (location 7)	19	26	143	32	273	179
Small ditch water (location 8)	19	96	*2225*[1]	246	1095([1])	311
Large ditch water (location 9)	4	2	21	4	18	14
Canal water (location 10)	3	7	< 1	0.4	7	5
Soil/groundwater (location 1 - 0.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil/groundwater (location 1 - 1.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil/groundwater (location 2 - 0.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil / groundwater (location 2 - 1.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil / groundwater (location 3 - 0.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil / groundwater (location 3 - 1.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil / groundwater (location 4 – 0.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	1.0
Soil / groundwater (location 4 – 1.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil / groundwater (location 5 - 0.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1([2])
Soil / groundwater (location 5 - 1.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil / groundwater (location 6 – 0.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1
Soil / groundwater (location 6 – 1.2 m depth)	n.a.	< 1	n.a.	< 1	n.a.	< 1

([1]) Concentrations were measured a factor 8 or less above the highest concentration in the calibration curve, so observed concentrations are extrapolated and might therefore be less accurate.
([2]) Present in the sample above limit of detection but below limit of quantification.
n.a.: not applicable.

In addition to MDMA, amphetamine and methamphetamine, the analysis screened for the presence of 60 precursors, intermediates, reactants and by-products in the samples using so-called suspect screening analysis. The 60 suspects were based on a list of products identified in

previous research on drug production waste residues (Reymond et al., 2022). As these precursors could not be fully identified, stringent criteria were applied to evaluate their potential presence. These criteria were a clear peak shape and integration, and a high mzLogic score (>75 %), which is a score that defines the chance that the identification is correct. The complete identities and quantitative concentrations of these chemicals could not be established as no reference standards were available for them. Subsequently, the responses of locations 7, 8 (small ditch) and 9 (larger ditch) were normalised to those of the canal water, which was considered a reference. Those chemicals that showed significant differences between one or more sampling locations were listed. This resulted in the selection of six out of the 60 chemicals in the suspect list that could be indicatively determined (identification level 4 on the Schymanski scale (Schymanski et al., 2014)).

Table 3 lists the ratios of responses in the water of locations 7, 8 (small ditch) and 9 (larger ditch) relative to the appointed reference location 10 (canal). The actual concentrations of the precursors could not be quantified as no reference standards for these chemicals were available.

TABLE 3
Suspect screening of drugs and drug-production-related compounds such as precursors, intermediates, by-products and reactants

Chemicals observed by suspect screening	Small ditch water (location 7): canal water (location 10)	Small ditch water (location 8): canal water (location 10)	Large ditch water (location 9): canal water (location 10)
MDMA	6.3	6.3	1.3
Amphetamine	>143	>2225	>21
Methamphetamine	36	62	2.8
2-norpinene, 2,6-dimethyl-6-(4-methyl-3-pentenyl) [1]	42	90	7.9
Oleic acid[1]	11	8.1	1.0
5-(3,4-methylenedioxyphenyl)-4-methylpent-4-en-2-one ([1])	1.9	5.9	1.0
N-formylamphetamine ([1])	1.3	2.5	0.8
Ephedrine ([1])	0.2	0.1	1.1
Norephedrine ([1])	0.9	56	1.2

([1]) Data were used to indicate the level as the ratio of each location (7, 8 and 9) to location 10. The ratios in this table carry a high degree of uncertainty and are therefore indicative. The values are not quantitative as they have not been normalised/corrected for internal standards.

It can be observed that 2-norpinene, 2,6-dimethyl-6-(4-methyl-3-pentenyl), oleic acid, 5-(3,4-methylenedioxyphenyl)-4-methylpent-4-en-2-one, *N*-formylamphetamine and norephedrine show elevated levels in locations 7 and 8 that more or less correspond to the trends observed for the three parent drugs (see Table 2), while the opposite is observed for ephedrine. Location 9 appears to be highly similar to the canal water, since most relative response factors, with the exception of that of 2-norpinene (2,6-dimethyl-6-(4-methyl-3-pentenyl)), are close to 1.

The results show that the drug production waste dumped in the ditch presumably came from the manufacture of amphetamine, MDMA and methamphetamine, since all three compounds were found to be present in samples from the ditch (Table 2). Furthermore, the presence of various precursors, intermediates and by-products observed by suspect screening demonstrates that there was a drug production waste dump. Despite the remediation that was performed shortly after (the discovery of) the contamination, residues of the produced drugs (Table 2) and production-related compounds could still be found in the water (Table 3) and sediment, with the highest concentrations recorded near the emission point (7 and especially 8) and (much) lower concentrations further away from the point of emission (locations 9 and 10).

The soil samples did not show any illicit drug residues above the limits of quantification, apart from a concentration of methamphetamine at or just below the limit of quantification close to the emission point (locations 4 and 5, cf. Table 2) at a depth of 0.2 metres. This demonstrates that there was no relevant transport of the illicit drugs from the sediment and water phase to the soil, which was expected as the water generally does not flow from the ditch towards the soil (i.e. infiltration) but in the opposite direction (i.e. drainage). The fact that a minute residue was found near the soil surface might be attributable to remediation activities that included isolating the ditch followed by the removal and proper disposal of the contaminated water and sediment. This activity potentially resulted in some transfer of contaminated water or sediment onto the bank of the ditch, close to the point of entry, at locations 4 and 5. This also explains why the drug was only observed near the surface of the soil in the unsaturated zone and not deeper, in the saturated zone.

The differences in concentrations between the sampling locations 7, 8, 9 and 10 span almost one order of magnitude for MDMA, almost two for methamphetamine and more than three for amphetamine, with a similar trend (location 8 > 7 > 9 > 10) for the different locations of all drugs in both the aqueous phase and the sediments. This illustrates that the contaminants are not homogeneously mixed within the water system, even one year after emission. Therefore, the contaminated sediment potentially acts as a source of contamination, while residue concentrations further from the source are lower due to dilution, degradation, and/or sorption processes in the water system.

Discussion

Drug production waste emissions

The Netherlands and the border region with Belgium have been a hot spot for the production of synthetic illicit drugs such as MDMA and amphetamine for four decades (EMCDDA and Europol, 2019; Tops et al., 2018). More recently, methamphetamine synthesis has also been detected in this area (Dutch National Police, 2022; UNODC, 2021). This drug production generates chemical waste. The banning of the trade in precursors during the past decades has led to the production, trading and use of pre-precursors. This has resulted in extended synthesis routes and generated more concomitant waste. Commonly applied synthesis procedures for amphetamine and MDMA require on average 3.4 and 2.6–3.1 kilograms of pre-precursors and generate 26 and 43 litres of liquid waste per kilogram of end-product, respectively (Ter Laak and Mehlbaum, 2022).

Chemical waste from illicit drug production can be found at production sites, stored in buildings, dumped in the environment in (leaking, burning) containers (in vehicles or trailers), discharged onto land or roads or in surface waters, or mixed with (waste) materials such as manure, wastewater or industrial waste. Out of 1631 listed incidents in the Netherlands registered between 2016 and 2020, 1036 (64 %) were not clearly characterised, and 568 (35 %) were characterised as some form of container dump. Infrequently, leakage from these containers was explicitly mentioned (16.1 %) or could be suspected due to the burning of the waste (36.2 %). Furthermore, the residual registered 27 (~2 %) incidents involved a direct emission to soil, mixing with manure or wastewater and miscellaneous incidents, such as emissions on the road, in car wash facilities or at municipal waste stations.

Contrastingly, wastewater analysis in the Eindhoven region indicates frequent discharges of drug production waste residues in wastewater, with peaks of such waste encountered on a weekly basis (de Voogt et al., 2018; Reymond et al., 2022). This reveals that the current registration of drug production waste incidents is biased towards the dumping of containers, while leakage and other forms of disposal, (e.g., discharges into wastewater, mixing with other waste streams such as manure and industrial waste, emissions into surface waters, or infiltration into the soil) are underrepresented in the statistics.

Additionally, there is a discrepancy between the remediation procedures used when waste containers are encountered and those applied to locations where drug production waste has been discharged. To the best of our knowledge there is no analysis of the time lag between the discovery of drug production waste incidents and clean-up activities taking place. However, the rapid removal of containers dumped in outdoor public areas, buildings, or vehicles and trailers is common practice, as it protects public health, while the removal or on-site clean-up of soil

contaminated with drug production waste can take up to five years (undisclosed cases in the Netherlands). Furthermore, one can assume that the infiltration of (liquid) waste into soil is less likely to be discovered, adding to the length of time that the soil environment is exposed to this waste. Discharges into sewer systems are generally not registered and usually cannot be stopped since wastewater treatment plants operate continuously. However, the wastewater treatment enables dilution and partial removal of the constituents of the drug production waste before the effluents are discharged into receiving surface waters.

Potential impacts on the environment

This qualitative analysis reveals that the emission routes that have the largest environmental impact (i.e. direct emissions into soil or surface waters and, to a lesser extent, indirect emissions into surface waters via wastewater treatment) are those that may often remain unnoticed, are the most difficult to remediate when encountered, and are therefore often subject to extended timeframes from emission to remediation.

The environmental impact of dumping chemical waste from illegal drug production can be significant. Drug production waste consists of organic solvents, acids, bases and chemicals, such as raw materials, finished products, intermediates, by-products and catalysts. The behaviour of acids, bases and organic solvents in the environment depends on the emission pathway and the receiving soil or water system (Shin et al., 2018). Acids, bases and organic solvents often pose a local and acute risk to the soil or water onto or into which they are discharged. In the long term and at a greater distance from the emission, the effect will be much more limited because acids and bases are neutralised in soil and water and solvents degrade over time. However, the ecosystem will still take some time to recover from a dump or discharge. Acids, bases and solvents can also locally mobilise other contaminants already present in the soil or sediment, which can promote the dispersal of substances such as heavy metals or organic micropollutants.

Several studies have examined the occurrence and effects on different organisms of various drugs, (pre-)precursors and by-products. Typical (exposure) concentrations of illicit drugs in wastewater and surface waters are below one microgram per litre. Based on measurements taken in the Netherlands, van der Aa and colleagues concluded that, in general, the risk of contamination from the consumption of illicit drugs in Dutch surface waters was negligible (van der Aa, 2010). However, large discharges or dumps of drug production waste can lead to significantly higher concentrations in water (temporarily or locally), causing safe concentration levels to be temporarily exceeded (Bongers, 2021). In addition, dumping and discharging drug production waste can lead to groundwater contamination. Once groundwater becomes contaminated, and the substances are not degraded (persistent), recovery is often difficult or impossible.

The dumping of chemical waste from illicit drug synthesis has led to several local environmental incidents in the Netherlands. For example, in 2016, amphetamine production waste in sewers shut down the operation of the receiving sewage treatment plant of Baarle Nassau in the south of the Netherlands (Emke et al., 2018).

Future monitoring possibilities for contamination analysis

There are almost no previous studies that have assessed the emissions, fate and effects of drug production waste residues. This study demonstrates that the residues of drug production waste, even after remediation of the receiving aqueous environmental system, can be observed in both the aqueous phase and sediments. The present study suggests that more refined and elaborate monitoring of surface waters contaminated by chemical waste from illicit drug production is required before, during and after remediation activities, in order to better assess the environmental impact of such contamination. This monitoring would have to include not only the illicit drugs themselves but also their precursors, by-products, intermediates and reactants.

The measurement of these chemicals at the point of discharge/dumping, either in surface water systems or in the soil, calls for risk-based thresholds, such as water quality standards, to better assess whether observed concentrations in aqueous and sediment phases actually pose an environmental threat (Davey et al., 2022) and could endanger drinking water sources (Emke, 2020; Pronk, 2020).

Conclusions and recommendations

- Investigating the dump sites of illicit drug production waste is challenging in terms of obtaining permission for sample collection. It was not possible to access and sample a non-remediated contaminated site within the timeframe of this project.
- The remediation and administration of illicit drug production waste dump sites is not focused on evaluating the potential impacts on the environment.
- Residues of synthetic drugs may be retrieved from the surface water and sediment of a remediated drug production waste dump location.
- Suspect screening identified chemicals associated with drug production waste that coincided with the presence of drug production residues.
- Better data collection and analysis of the volume and characteristics of drug production waste incidents and environmental research on the fate of the associated chemicals in the environment are required to enable evaluation of their environmental impact.

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