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# Estimating illicit production of MDMA from its production waste, a Dutch case study

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ABSTRACT

The Netherlands plays a key role in the global production of the synthetic illicit drug MDMA. However, the actual Dutch production of MDMA is difficult to quantify. The illicit production of MDMA results in large amounts of waste. This study uses amounts of waste found in the environment and production-related MDMA residues in wastewater to estimate the amount of MDMA that is produced. The MDMA produced, associated to the amount of waste found in the environment is 4.2 and 5.8 tons per year for two common synthesis routes. The MDMA produced, associated to production-related residues in wastewater is significantly larger, with 39.2 tons per year. The estimated MDMA production associated to waste in the environment and wastewater analysis is 43.4 and 45.0 tons per year for two common synthesis routes. Even though these estimates are difficult to validate, they are feasible when compared to prevalence-based consumption estimates or production estimates based on interceptions of precursors. The current study illustrates that waste of an illicit industry can shed light on its production volumes, thereby, complementing other efforts to estimate production, trade and use of synthetically produced illicit substances.

## 1. Introduction

The local and global production, market and consumption of illicit psychoactive substances is difficult to assess due to the hidden nature of production, trade and consumption [1]. The production of Illicit substances derived from plants (mostly) grown outside, such as cocaine and heroin, can be estimated from the land surface used to produce these substances [2]. The global production, market and consumption of substances that are mainly produced from synthetic chemicals are more difficult to estimate due to a lack of information on illegal trade of precursors and reliable consumption data. However, the production of synthetic drugs also leaves traces in the environment. Illicit laboratories are occasionally dismantled by authorities and chemical waste of the production of synthetic drugs are regularly encountered [3–5].

The current study focuses on the production of 3,4-Methyl enedioxy methamphetamine (MDMA) in the Netherlands. MDMA also goes by various street names such as Ecstasy, Molly and Mandy. It is sold in tablets, as crystalline powder, or in capsules [6]. The Netherlands is a major global producer of MDMA, but the actual market share is unknown [7]. Between 2002 and 2006, 42 % of the global seizures of MDMA occurred in the Netherlands [8] and the vast majority of the encountered Illicit laboratories in Europe are located in the Netherlands or just across the border in Belgium or Germany [1].

MDMA synthesis entails multiple reaction steps followed by an isolation step. Before 2008, the most used precursor for MDMA synthesis in the Netherlands was piperonyl methyl ketone (PMK). PMK was either imported from Asia or was synthesized from safrole or isosafrole. Around 2008 PMK became more difficult to obtain and new precursors for PMK started to appear in drug laboratories such as the synthetically produced salts of PMK-glycidic acid, PMK methyl glycidate, and more recently PMK ethyl glycidate and methyl 3-oxo-2- (3,4-methylenedioxyphenyl)butanoate (MAMDPA). These are used because they are easily converted into PMK. Most recently also isopropylidene (2-(3,4-methylenedioxyphenyl)acetyl)malonate (IMDPAM) has emerged [9].

The amounts of confiscated precursors, number of dismantled laboratories and volumes of dumped waste are indicators for the production

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volume of illicit drugs. Waste volumes encountered at dump locations or at illicit production sites represent a production volume. Most of the observed and registered waste incidents involve various forms of dumping of waste such as in barrels, jerrycans and intermediate bulk containers on the street, in the country side, in surface waters or leaving waste in vehicles or trailers. Occasionally, incidents of direct discharges on soil or in surface water or mixing with waste streams such as wastewater, manure or industrial waste have been reported [10]. It is thought that the volume of waste dumped trough the latter routes exceeds the often encountered dumping of various types of containers. However, this 'hunch' cannot be supported by quantitative data, as dumps though these routes often remain unnoticed [11].

The current study evaluates if and how drug production waste might lift the veil over the production volume of MDMA in the Netherlands. MDMA production processes are evaluated to determine the volume and composition of the generated waste. Furthermore, available data on drug production waste incidents and residues of MDMA in wastewater are collected to estimate associated production volumes. Subsequently, these data are used to estimate the associated MDMA production in the Netherlands. Finally, these estimates are compared with available trade- and consumption prevalence-based estimates of (inter)national MDMA production and markets.

## 2. Materials and methods

### 2.1. MDMA production waste

Waste incidents associated with illicit drug production of MDMA in the Netherlands often are encountered in the environment [1] whereas sometimes residues are observed in wastewater [4,5].

#### 2.1.1. Drug waste incidents

Data on drug waste incidents were collected for the period 2016–2021. Dutch data from the ERISSP (European Reporting on Illicit Synthetic Substance Production sites) database of Europol and the European Union Drugs Agency (EUDA) were provided by the Dutch police [12], complemented with data from regional divisions of the police 'Oost-Nederland' and 'Zeeland-West Brabant', various regional environmental services such as 'Omgevinsdienst Rivierenland' and 'Omgevingsdienst Zuid-Oost Brabant', records of drug waste clean-up (requests) at the provinces of 'Noord Brabant' and 'Gelderland' and 'Structon Milieutechniek', a major contractor for clean-up and remediation, and national public media sources. To avoid double reporting, all data were evaluated using the location (address, postal code) as unique identifier and a secondary evaluation of the incident date [13]. Available information was merged to provide the most complete dataset possible.

Volumes or masses of the waste were retrieved trough incident reporting (mostly in litres) [12], or records of clean-up by provinces or contractors (mostly in kilograms). Occasionally, reporting in media enabled to retrieve missing indicators for volumes through either photographs or reporting of numbers and types of containers. Incidents with known volumes were used to estimate volumes of registered incidents with missing volumes.

#### 2.1.2. MDMA production residues in wastewater

MDMA production waste volumes emitted into sewers cannot be traced back and quantified. Therefore, residues of the produced MDMA were used to estimate its production volume based on data of MDMA residues in waste that was studied by the Netherlands Forensic Institute in legal cases. MDMA residues were analysed in the raw wastewater (influent) of wastewater treatment plant (WWTP) Eindhoven. Samples were collected at 4 °C in the auto sampler for a maximum of 24 h and frozen (−20 °C) immediately after collection and stored for a maximum of 15 weeks. Analysis was performed according to Emke et. al. [14]. The catchment of WWTP Eindhoven serves 457,215 inhabitants from the city of Eindhoven and nine surrounding municipalities [15], covering 2.6 % of the Dutch population (01–01–2021). Within this treatment plant, daily loads of MDMA were monitored for 235 d in 2016 (88 d), 2017 (50 d) and 2018 (97 d), respectively [4,16].

The end-product, MDMA, is selected as production indicator as it is stable in sewer systems [17] and its presence in production waste is less dependent of production routes then that of (pre) precursors and impurities [4]. However, in contrast to most precursors, MDMA in wastewater can originate both from human consumption and illicit production waste emissions. Therefore, production residues in the wastewater are determined by subtracting MDMA loads originating from consumption from total MDMA loads by appointing daily loads exceeding 0.25 g of MDMA per 1000 inhabitants per d as production waste residues. This threshold is the upper limit of the daily MDMA consumption in the Eindhoven catchment observed in four sampling campaigns of seven consecutive days in the early spring of 2016, 2017, 2019 and 2020 that did not contain non-consumed MDMA [18].

#### 2.1.3. MDMA synthesis

In the Netherlands (and Belgium) MDMA is mainly produced from the masked-precursors PMK methyl glycidate or PMK glycidic acid sodium salt. This is reflected in the intercepted (pre)precursors between 2017 and 2020. While in 2017 rather large volumes PMK oil and safrole oil were intercepted in two unique incidents in the Netherlands and smaller amounts were intercepted outside of the Netherlands in 2018, the interceptions of 2019 and 2020 were dominated by PMK methyl glycidate or PMK glycidic acid sodium salt [11].

In-house information of the Netherlands Forensic Institute based on studied illegal production locations, obtained recipes and laboratory experiments revealed common MDMA production procedures from PMK methyl glycidate and PMK glycidic acid salts. PMK methyl glycidate is converted to PMK glycidic acid sodium salt by heating in a sodium hydroxide solution (Step 1). Subsequently, the PMK glycidic acid sodium salt is converted to PMK by the addition of an acid such as hydrochloric acid, citric acid or acetic acid (Step 2) [19]. The PMK is poorly soluble in water and separates from the acidic aqueous solution and sinks to the bottom. Subsequently, PMK oil is collected by separation, sometimes followed by vacuum distillation, and transformed into MDMA base by reductive amination (Step 3). This is done by mixing the PMK with methylamine in an organic solvent (e.g. methanol), adding a catalyst (e.g. platinum), and adding either hydrogen gas under high pressure or sodium borohydride under cold conditions [20]. The 'pressure method' and 'cold method' both lead to the formation of the oily liquid MDMA base. This oil is isolated from the reaction mixture by distillation that evaporates the solvent, water and surplus of methylamine. The distillate consists of MDMA base (oil) and non-volatile reaction by-products. Subsequently, the MDMA base oil is mixed with an organic solvent (e.g. acetone) and hydrochloric acid, either as gas (anhydrous) or as concentrated aqueous solution (37 %) and put into a freezer (Step 4). This leads to the crystallization of the MDMA as MDMA-HCl salt. The formed MDMA-HCl crystals grow and are collected by filtration or decanting and air-dried to remove residual solvent. The obtained crystals are distributed and sold as crystals, powder or processed in tablets/capsules solutions.

#### 2.1.4. MDMA synthesis waste

Table 1 lists the solvents reactants and their applied volumes as observed in recipes for the synthesis of PMK and recipes of the reductive amination using both the 'cold' and 'pressure' method. It also lists average conversion yields of the various reaction steps based on notes from laboratories and experiments and analysis performed by the Netherlands Forensic Institute.

#### 2.1.5. Calculating yield of the MDMA production

The volumes of reactants and reaction yields per reaction step are used to calculate the overall reaction yield and the total volume of waste

**Table 1**
Synthesis, reactants and conversion yields of MDMA synthesis applied in illicit laboratories in the Netherlands.

| Step | Conversion | | Reaction chemicals[a] | Average volume of reaction solution (L)[b] | Standard Deviation of reaction solution (L)[b] | Conversion yield %[c] |
|---|---|---|---|---|---|---|
| 1a | PMK methyl glycidate (solid) | PMK glycidic acid-sodium (solid) | Sodium hydroxide<br>Phosphoric Acid | 1.28[d] | 0.57 | Near 100 % |
| 1b | | | Sodium hydroxide<br>Hydrochloric acid | 1.85[d] | | |
| 2 | PMK glycidic acid-sodium (solid) | PMK oil (liquid) | Hydrochloric acid | 4.2[e] | n.a.[f] | 53 %[g] |
| 3a<br>Pressure method | PMK oil (liquid) | MDMA base[f] (liquid) | $H_2$ gas<br>Methanol<br>Methylamine (reactant)<br>Pt (catalyst) | 1.49[h] | 0.48 | 77 % |
| 3b<br>Cold method | | | Sodium borohydride<br>Methanol<br>Methylamine (reactant) | 4.57[i] | 1.87 | 64 % |
| 4 | MDMA base (liquid) | MDMA hydrochloride (solid salt) | Acetone<br>Hydrochloric acid | 3.28 | 1.15 | n.a.[j] |
| | | | | Cumulative volume of reaction solution (L) | Cumulative Standard Deviation of reaction solution (L) | Total conversion yield %[c] |
| Total cumulative reaction waste volume per kg MDMA within the isolated end product MDMA-HCl: Pressure method | | | | 22.8 | 5.1 | 41 % |
| Total cumulative reaction waste volume per kg MDMA within the isolated end product MDMA-HCl: Cold method | | | | 31.2 | 6.2 | 34 % |

[a] Water added to the reaction mixtures is not explicitly mentioned
[b] Volumes are expressed based on 1 kg precursor
[c] Yield based on a molar basis, corrected for mass differences between precursors and products
[d] Based on two recipes with phosphoric acid and two recipes with hydrochloric acid, standard deviation covers both treatments
[e] Based on one recipe listing hydrochloric acid, but multiple acids have been found in laboratories
[f] Not applicable due to insufficient data. For the cumulative calculation of the Standard Deviation of the full procedure, the average relative Standard Deviation of the conversion steps 1, 3 and 4 (being 36 %), is imputed on Step 2, resulting in a Standard Deviation of 1.5 L.
[g] Based on experiments by the Netherlands Forensic Institute
[h] Based on 13 recipes collected over the past 25 years
[i] Based on 8 recipes collected over the past 25 years
[j] Not applicable, as yields listed under 3a and 3b account for both the conversion from PMK to MDMA oil in Step 3 and the subsequent crystallisation and isolation of Step 4.

per kg of produced and isolated MDMA under the assumption that reactants are used once and there are no losses due to evaporation. The volumes of reactants with their standard deviations and reaction yields are used to calculate total waste volumes for the cold and high pressure method separately.

On a molar basis, the yield from the pre-precursor PMK glycidic acid-sodium to MDMA-HCl is 41 % for the pressure method and 34 % for the cold method (Table 1). These yields are at the low end of the 41–53 % yield observed by Nair et al., 2022 [20] in a validated multi-kilogram MDMA synthesis. Standard deviations could not be obtained for the yields.

### 2.1.6. *Calculating the waste volume per kg of produced MDMA*

The volume of waste generated per kg of isolated MDMA in form of MDMA-HCl salt was 22.8 (Standard Deviation ± 5.1) L of waste for the pressure method and 31.2 (Standard Deviation ± 6.2) L of waste for the cold method. The standard deviations of these volumes were derived from the standard deviations of the individual conversion steps. The standard deviation of the conversion of PMK glycidic acid into PMK could not be obtained. Therefore it was assumed to be equal to the average of the standard deviations of the other conversion steps relative to the average reaction volume. The calculation of the combined standard deviation takes the reaction yields into account, thereby correcting for the larger volumes that were required in the initial conversion steps to retrieve 1 kg of MDMA in the end product.

The estimated waste volume is larger than what is often listed in literature [21]. The discrepancy can be explained by the fact that most studies presume MDMA production from PMK and not from masked precursors that require additional reagents to produce PMK. Furthermore, these estimations do not always account for incomplete conversions, (*i.e.* lower reaction yields) that increase cumulative waste volumes when expressed per kg of isolated end product.

### 2.1.7. *Calculating the MDMA production volume from residues in wastewater*

In three separate studies conducted by the Netherlands Forensic Institute, 14.6, 9.2 and 8.2 % (average 10.7 %) of the produced MDMA was recovered in the supernatant of the crystallization solutions found in illicit laboratories. When these solutions are emitted via the sewer the nett production volume can be calculated from the *mass found in wastewater* and the *fraction* that ends up *in waste*:

$$nett\ prodution\ volume(kg) = \frac{mass\ in\ wastewater(kg)}{fraction\ in\ waste} - mass\ in\ wastewater(kg) \quad \text{Eq.n 1)}$$

## 3. Results and discussion

### 3.1. *Estimating MDMA production volume from waste incident data*

The recipes and production yields enable one to estimate the volume and composition of production waste per kg of produced MDMA. These figures can be used to reconstruct production volume from the drug production waste encountered in the environment. Ideally, this requires complete records of the origin (i.e. produced type of drug) and volume of drug production waste (in L or kg). This was not the case. Therefore, it was assumed that the fraction of seized laboratories involved in MDMA production also represents the fraction of the waste associated to MDMA production and that the waste of all conversion steps listed above is dumped in a similar way. Reductive amination uses organic solvents that easily evaporate or can be burned or reused after distillation. This reduces the total waste volume. Therefore, the assumption that all liquid waste is dumped likely results in a conservative estimate of the production volume associated with the encountered waste volume.

The volume of waste could be retrieved or deduced from available data for 26 % of the collected drug waste incidents between 2016 and 2020 (Table 2). The retrieved volumes were either listed in litres or in kilograms.

### *3.2. Projecting Dutch MDMA production volume from waste incident data*

Data on illicit laboratories that produce or process (precursors of) synthetic drugs are registered by the Dutch National Police. From 2017 to 2020, 362 clandestine laboratories were dismantled. 88 of these laboratories produced MDMA, 10 laboratories produced PMK (MDMA precursor) and 16 laboratories produced both MDMA and another synthetic drug [11]. Adding up the MDMA-linked laboratories and half of those laboratories that produced MDMA together with another synthetic drug results in 106 laboratories. This number represents 29 % of the 362 dismantled laboratories between 2017 and 2020. Therefore 29 % of the waste is assigned to MDMA production (*i.e.*, 131 of the 447 tons).

If we consider the production of MDMA from PMK methyl glycidate using both the pressure and cold method, 22.8 and 31.2 L of waste is generated per kg produced pure MDMA (within the MDMA-HCl salt end product). Therefore, conservatively estimated, the 131 tons of waste represent 5.8 (Standard Deviation range 4.7–7.4) or 4.2 (Standard Deviation range 3.5–5.3) tons of pure MDMA for the pressure and cold method, respectively.

### *3.3. Estimating MDMA production volume from emissions into wastewater*

Only 2 out of 1036 reported drug production waste incidents from the 2016–2020 period explicitly list emissions into sewers [13]. However, experts expect that a relevant fraction of drug production waste ends up in sewers (personal communication Dutch National Police). This is supported by reporting of residues of non-consumed MDMA in wastewater [5] and one well-documented incident where a wastewater treatment plant malfunctioned because of a large emission of amphetamine production waste [14].

**Table 2**
Extrapolation of drug production waste volumes in the Netherlands.

| | *2016* | *2017* | *2018* | *2019* | *2020* | *Annual average (relative standard deviation)* |
|---|---|---|---|---|---|---|
| Number of drug waste incidents | 306 | 329 | 376 | 320 | 312 | 329 (8 %) |
| Number of drug waste incidents with registered volume | 70 | 58 | 90 | 126 | 80 | 85 (31 %) |
| % of drug waste incidents with registered volume | 33 % | 18 % | 24 % | 39 % | 26 % | 26 % |
| Total registered drug waste in tons | 90 | 18 | 49 | 46 | 65 | 54 (49 %) |
| Total registered drug waste in $m^3$ | 18 | 78 | 37 | 120 | 48 | 60 (66 %) |
| Extrapolated total waste (tons and/or $m^3$)[a] | 470 | 544 | 359 | 423 | 441 | 447 (15 %) |

[a] It is assumed that one L of waste represents one kg of waste. Water based solutions (acids or bases) are slightly heavier than one kg per L while organic solvents (acetone and methanol) are slightly lighter than one kg per L. This suggests that average weights in kg and volumes in L are comparable.

MDMA production residues in urban wastewater of WWTP Eindhoven are used to estimate the associated MDMA production volume according to Eq. 1. 270.6 kg of MDMA was in the wastewater influent during two to three month periods in 2016, 2017 and 2018, totalling 235 sampling days. 255.8 kg (95 %) of this load exceeded the selected threshold of 0.25 g per 1000 inhabitants per day, and was considered non-consumed, while the residual 14.8 kg (5 %) was considered to originate from human consumption. Extrapolating these data to a full year results in an estimated non-consumed load of 397.3 kg. Fig. 1 illustrates MDMA loads per 1000 inhabitants per d sorted from the lowest to the highest load. Note that the load is presented on a log scale. It indicates which parts are considered consumed and non-consumed. It can be observed that over half of all daily samples were considered to contain also non-consumed MDMA.

The MDMA production volume associated with the MDMA residues in wastewater were estimated by evaluating the final steps in the production process: distillation and isolation of the MDMA base oil and crystallisation and subsequent filtration of the MDMA salt. The isolation of MDMA oil after reductive amination is not expected to lead to significant losses of MDMA to waste as the boiling point of the MDMA base is much higher than that of the solvent and methylamine. However, the conversion of MDMA oil into MDMA salt by crystallisation is incomplete. Crystallisation reactions always strive towards a dynamic equilibrium between dissolved (i.e. MDMA) species and crystals (i.e. MDMA-HCl), leading to dissolved MDMA-residue in the medium. In addition, the isolation of the MDMA-HCl crystals likely has no 100 % yield [20]. Therefore, the waste will always contain residues of MDMA. This residue is indicative of the nett production volume. Using the obtained residues of MDMA in crystallization waste (average 10.7 %), the 397.3 kg MDMA in wastewater of WWTP Eindhoven represents a nett production volume of 3.6 (Standard Deviation ± 1.1) tons of MDMA per year, using Eq. 1.

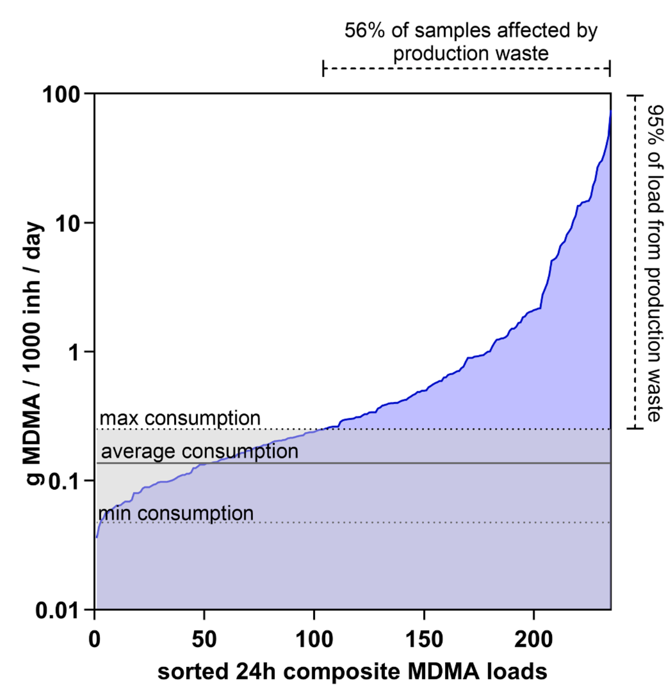


**Fig. 1.** All 235 measured daily MDMA loads in the wastewater samples of Eindhoven region, sorted from low to high. The horizontal lines indicate the minimum, average and maximum values of the daily MDMA consumption in the Eindhoven catchment observed in four sampling campaigns of seven consecutive days in the early spring of 2016, 2017, 2018 and 2019 that did not contain non-consumed MDMA [18]. The maximum consumption is the applied threshold of 0.25 g per 1000 inhabitants per d.

### 3.4. Projecting Dutch MDMA production volume from emissions into wastewater

The Eindhoven WWTP catchment lies in a region that has a relatively large Illicit synthetic drug production industry [22]. This is supported by the fact that 8 out of the 88 (9.1 %) Dutch MDMA laboratories were confiscated within the Eindhoven catchment between 2016 and 2020 [11]. If we assume that the percentage of the MDMA laboratories within the catchment is representative for the fraction of MDMA produced within this catchment, the Dutch national production would be 11 times the estimate for the Eindhoven region. This equals 39.2 (Standard Deviation ± 12.2) tons per year.

### 3.5. Do waste incidents and wastewater residues cover the total MDMA production volume?

We distinguish multiple ways of dumping drug production waste: (a) contained in the environment, (b) stored in buildings, (c) mixing with other waste streams or materials such as wastewater, manure, or industrial waste and (d) directly emitted into water or on/in soil.

The national MDMA production volume calculated with encountered waste incidents in the Netherlands is 4.2 tons or 5.8 tons of pure MDMA for the cold and pressure method, respectively. This presumably covers a major fraction of the waste dumped in containers in the environment (a), encountered in buildings or vehicles (b). Furthermore, some direct environmental emissions (d) are listed, but these are likely 'the tip of the iceberg'. The extrapolated national MDMA production volume extrapolated from residues of MDMA in wastewater is 39.2 tons per year. This volume presumably covers a relevant fraction of 'mixing with other waste streams' (c), although it does not include the mixing of illicit drug waste with industrial waste or manure, and lacks waste exported outside the Netherlands.

### 3.6. Uncertainties and biases of MDMA production estimates

The MDMA production estimates from waste streams shown above are provided with standard deviations, however the analysis is built upon assumptions with various margins of uncertainty and potential biases that are not all included in these standard deviations. Therefore, the possible impact of the assumptions are evaluated qualitatively below.

*Waste incidents:* The production estimate from waste incidents is extrapolated from recorded waste volumes of 26 % of the total number of waste incidents. These were dominated by the data from environmental services 'Omgevingsdienst Zuid-Oost Brabant'. Better recording of dumps would improve the accuracy of the estimation of the total waste volume. The attribution of 29 % of the waste to MDMA production, based on dismantled laboratories, intrinsically assumes that encountered illicit laboratories for different drugs produce the same volume of waste. This 29 % presumably is a conservative estimate as laboratories producing MDMA (as well as amphetamine, and more recently methamphetamine) generally have a larger production capacity than laboratories producing or processing other illicit such as anabolic steroid hormones, gamma-hydroxybutyric acid (GHB) and a wide share of new psychoactive substances that were also encountered among the dismantled laboratories. Finally, the production of MDMA generates rather large volumes of waste per kg of end product.

*Wastewater residues:* The extrapolation of illicit drug production volumes from wastewater residues in the Netherlands might be biased by the applied threshold 0.25 g of MDMA per 1000 inhabitants per d that distinguishes the consumption and production related MDMA in wastewater (Fig. 1). With this threshold 95 % of the total measured MDMA load is considered non-consumed (production waste), while 5 % is considered consumed. Using a lower threshold, based on average consumption, would only marginally affect the non-consumed fraction to 98 %. However, as the party-drug MDMA might peak with events [23], a higher threshold might be appropriate. Using a threshold of 1.0 g per 1000 inhabitants per d, which exceeds the maximum consumption recorded in 30 Dutch wastewater treatment plants based on 364 individual samples collected and analysed between 2015 and 2022 [24], only marginally reduces the waste attributed MDMA load to 84 %. Therefore, the impact of the applied threshold to obtain production-related MDMA residues is limited.

The nine highest daily loads in the wastewater out of the 235 daily samples over 2016, 2017 and 2018 ranged from 9 to 34 kg of pure MDMA and represent over 50 % of the total MDMA production-associated load in wastewater. These excessive loads might not be residues from regular production procedures, but a result of a malfunctioning production processes or an intentional dumping of MDMA to get rid of evidence during police raids, as was observed in 2011 in another large Dutch wastewater treatment plant [5]. Such artifacts lead to an overestimation of the MDMA production and market. Earlier work specifically studied these peak emissions of MDMA (and amphetamine) [4] and showed co-occurrence of various synthesis markers with these peak emissions. This contradicts the hypothesis of direct dumping of the final product (that presumably does not contain as much synthesis markers), but does not exclude emissions of waste from malfunctioning production processes. Unfortunately, it is not possible to verify this hypothesis. Additionally, the waste based estimate of the national MDMA nett production volume is extrapolated from a relatively small Dutch region covered by a single wastewater treatment plant. This introduces significant uncertainty that cannot be verified nor quantified.

The issues above introduce uncertainties of the MDMA production calculated from MDMA residues in wastewater. This means that obtained estimates are indicative. Better (field) data on MDMA residues in production waste and more extensive monitoring data of wastewater from multiple wastewater treatment plants will significantly improve these estimates.

### 3.7. Triangulating MDMA production estimates

The combined estimated annual MDMA production (tons) associated to waste incident data and wastewater analysis is 43.4 (Standard Deviation ranges from 31.2 to 55.7) for the cold method or 45.0 (Standard Deviation ranges from 32.8 to 57.2) for the high pressure method.

As discussed earlier, the production calculated from waste incidents is likely a conservative estimate, while the production calculated from observed residues in wastewater is potentially overestimated. Even though these assessments of residues from MDMA production do not cover all potential emission routes, the combined estimated MDMA production might still be an overestimate because it is dominated by the wastewater analysis based production estimate. Keeping this in mind, these results are compared to independent information about the MDMA market.

Tops et al. calculated that the Netherlands produced 152.5 tons of MDMA-HCl in 2017 [22]. This equals 128.3 tons of pure MDMA in the MDMA-HCl end product. Tops' estimate is based on a 20 % interception of PMK Methyl Glycidate and PMK oil. Tops assumes that 1.0 kg of PMK Methyl Glycidate results in 0.5 L PMK oil (which equals 0.61 kg), and that 1.0 kg PMK oil results in 0.77 kg MDMA within the MDMA HCl.

128.3 Tons of pure MDMA exceeds estimates based on waste incidents and wastewater analysis in the current study by almost a factor three. However, in the current study, we have derived lower yields for the conversion of PMK methyl glycidate to PMK oil, while other yields are similar. In our calculations 1.0 kg PMK methyl glycidate would produce 0.32 L of PMK oil. The yield of the reductive amination of PMK to MDMA is similar, as 1 kg PMK oil results in 0.69 or 0.84 kg of MDMA in the MDMA-HCl end product for cold and pressure method, respectively. Correcting for the lower yields of the conversion of kg PMK methyl glycidate into PMK reduces the difference between the estimates to a factor two. Additionally, Tops' study was based on interceptions and confiscations of PMK and precursors in 2017, when the volume of interceptions were exceptionally high, compared to data of 2018–2020 (Figure S1). When the average of the interception of precursors over the period 2017–2020 would be applied to Tops' calculation the estimate of the annual production is remarkably similar to our waste based production estimate, despite of all uncertainties in both estimations.

The production volume can also be linked to consumption data. The Dutch national consumption was estimated at 2.3 tons of pure MDMA per year between 2015 and 2022 [24]. This is about 5 % of our estimated national production, leaving 95 % for export or interceptions. The EMCDDA estimates that 50–70 million MDMA tablets were sold in the European Union in 2017 [25], based on prevalence figures. This would be equal to 8.4–11.7 tons of MDMA using the average MDMA dose of 168 mg per tablet in 2017 [26]. In addition to that, 2.2 tons were intercepted in Europe in 2018 [26]. Adding up these figures results in 10.6–13.9 tons of MDMA entering the EU market annually. This is 24–32 % of the estimated national production, leaving the rest for export or interceptions outside Europe. The global demand was estimated to be 155–310 million MDMA tablets per year in the early 2000s [7]. The amount of MDMA cannot be calculated as data of MDMA dosages were lacking on a global scale at that time, but the current waste based Dutch production estimate meets the upper end of this 'historic' global demand.

Even though the waste based Dutch production estimate seems large, when compared to consumption and demand estimates, our estimate might be reasonable as the Netherlands is known to be a major global producer [7,8] and global MDMA consumption probably increased between the early 2000s and the period covered by our study. This is supported by a globally increasing number of encountered MDMA laboratories, MDMA seizures, number of countries where MDMA is seized, trends in trafficking, while MDMA doses in tablets increased and prices dropped between 2011 and 2019 [2]. Unfortunately, there is no recent global estimate of annual consumption based on prevalence figures to make a quantitative assessment, to the authors knowledge.

## 4. Concluding remarks

This study illustrates that tracing waste emissions can provide relevant information on drug production. Quantification of production is complicated as these estimates are based on assumptions and require extrapolations that are difficult to validate, and can be considered a rough estimate. However, the triangulation with corrected precursor-based production estimates [22] reveals similar figures. Furthermore, triangulation with national consumption estimates and international market estimates also reveal that the waste based Dutch production estimates are viable.

Better assessment of the local national and global market of illicit synthetic drugs requires a more structured and extensive (data)analysis of wastewater across cities and rural areas in different regions, countries and over continents [27]. Subsequently, these figures can be correlated with global prevalence figures and linked to production estimates as shown in this study. This provides a more comprehensive picture of the illicit drug market from pre-precursor to consumer and enables one to spot trends in production and correlate these with trade, demand and use on spatial and temporal scales.

## CRediT authorship contribution statement

**Thomas L. ter Laak:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pim de Voogt:** Validation, Supervision, Methodology, Investigation, Conceptualization. **Shanna Mehlbaum:** Investigation, Formal analysis, Data curation. **Erik Emke:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jorrit van den Berg:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation.

## Declaration of Competing Interest

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

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2024.112315.

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