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Methods to transform illicit drugs: A review and evaluation of drug degradation techniques

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ABSTRACT

The disposal of seized illicit drugs is highly dependent on incineration methods. Accessible alternatives for the destruction and disposal of illicit drugs may be required due to operational or risk management strategies. In this review, alternative methods of illicit drug disposal are evaluated, highlighting thermal, chemical, biological and miscellaneous degradation techniques. Chemical degradation of illicit drugs offers the most promising alternative to incineration. Oxidative processes utilise commercially available reagents and are accessible, with some methods already established as industry processes. Advanced oxidation processes have short run times (<24 h) and can completely mineralise organic compounds, overcoming the limitation of forming undesired transformation products. Other feasible methods for drug degradation include bacterial growth and gamma irradiation. It is apparent, however, that there is currently no universal alternative method for drug degradation, as diverse classes of drugs exhibit different degradation characteristics. In some instances, harmful compounds can be produced from the degradation of the illicit drugs although if the transformation products are not illicit, they can be integrated into existing chemical waste procedures using appropriate hazardous waste protocols.

1. Introduction

Illicit substances are routinely seized by law enforcement agencies worldwide. In 2023, 646 t of amphetamine-type stimulants (ATS), 2274 t of cocaine and 5760 t of cannabis herb were seized worldwide [1], most of which are subsequently destroyed or degraded. The primary method for the disposal of seized illicit drugs is incineration. This method is favoured by law enforcement as it ensures destruction of all and any illicit drugs, preventing redistribution into the community [2]. The *destruction* of illicit drugs is characterised by complete breakdown into matter such as carbon dioxide, ash and char (e.g. by incineration), while *degradation* involves the breakdown and transformation of the drugs into other compounds, referred to as transformation products (TPs). Thus, many illicit compounds can be transformed from illicit to non-controlled or restricted substances and be disposed of using conventional procedures.

However, accessible alternatives for the destruction and disposal of illicit drugs may be necessary due to changes in operational or risk management strategies. For example, alternative methods may benefit jurisdictions without access to appropriate disposal facilities, to reduce the load on incineration facilities, or as measures when incinerators are offline. Guidelines issued by the United Nations Office on Drug Control (UNODC) [3] for the disposal of chemicals and precursors used in the illicit manufacture of drugs include alternatives to incineration such as open air burning, evaporation, composting or bioremediation, remote burials, infiltration, encapsulation, rendering inert, and neutralisation.

This review evaluates the significant amount of literature that describes the degradation of illicit substances. The bulk of the literature comes from the fields of wastewater treatment, environmental remediation, and toxicology. As such, this literature does not directly describe methods for drug destruction within a forensic context, but these studies reveal potential methods that may be adapted for illicit drug disposal. This review evaluates degradation techniques wholistically to assess their potential in forensic applications.

2. Methods of drug degradation

Methods of degradation can be categorized as thermal, chemical, biological and miscellaneous. Fig. 1 summarizes the methods explored in this review.

Thermal degradation methods use heat to modify the chemical structures of compounds and can be employed in several forms with

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varying amounts of oxygen. Incineration (burning) requires oxygen to combust material. Thermal degradation is commonly employed in chemical and industrial waste industries with incineration the more prevalent technique. Any resultant ash or char is generally disposed of in landfill. Pyrolysis, however, is usually conducted in an oxygen-free or oxygen-deficient atmosphere, with thermal degradation occurring by direct or indirect addition of heat [4]. These methods are discussed in detail in Section 3: Thermal Degradation Methods.

Chemical degradation is the breakdown or transformation of compounds into simpler constituents [5] using chemical methods. It includes methods such as oxidative processes, which involve the use of oxidants (ozone or chlorine-containing compounds), photodegradation (UV or sunlight) or advanced oxidation processes (AOPs). These processes are discussed in detail in Section 4: Chemical Degradation Methods.

Biological degradation utilises microorganisms or exposure to natural processes in the environment to degrade compounds [6]. Such processes may utilise wastewater treatment methods, soil, bacteria and aquatic plants, and are discussed in Section 5: Biological Degradation Methods.

A summary of the methods that have been reported for each drug or drug class is presented in Table 1 together with the corresponding reference(s). The degradation efficiency of each technique for the reported drug has been evaluated where possible and is defined as low = 0–15 %, medium = 16–84 %, high = 85–100 %. The TPs that arise from the degradation of drugs including structures and CAS registry numbers are available in the supplementary information (Table S1). Analytical methods for each of the reported techniques are summarised in Table S2. Methamphetamine and cocaine are the focus of most of the degradation studies, with a smaller number investigating new psychoactive substances (NPS), including synthetic cannabinoids, cathinones, fentanyl derivatives, and other synthetic opioids.

3. Thermal degradation methods

3.1. Pyrolysis

Pyrolysis of drugs of abuse has been investigated for a range of illicit drug classes with studies primarily utilising smoking techniques. The reported data is useful to describe how these compounds behave under pyrolysis conditions, which may then be applied to other drug degradation processes. A summary of the illicit drugs where degradation via pyrolysis has been studied is presented in Table 2.

Pyrolysis of heroin in different smoking methods has been reported, including the impact of temperature and the addition of diluents [7,34–37]. Heroin free-base volatilised completely at 225 °C whereas heroin hydrochloride required temperatures of 225–325 °C for volatilisation to occur [34]. Pyrolysis of the free-base and hydrochloride salt was explored at temperatures ranging from 200 to 800 °C [7]. At 300 °C after 10 min, heroin hydrochloride exhibited higher degradation compared to the free-base with only 10 % recovered versus 67 %, respectively. The higher degradation of heroin hydrochloride compared to heroin free-base is a trend observed in studies where the average recovery for heroin hydrochloride was approximately 17 % compared to heroin free-base which was on average 62 % [34]. Across all methods, higher temperatures resulted in greater degradation of heroin.

Three major TPs were identified from the pyrolysis of heroin and heroin hydrochloride (**HER 2–4**), as well as other minor TPs (**HER 5–12**). Structures for heroin derived TPs (**HER**) are provided in the supporting information (Table S1). The formation of TPs was not influenced by the addition of caffeine, a common adulterant in seized heroin samples. Caffeine did not increase the volatilisation of heroin or heroin hydrochloride [7,34–37] whereas the presence of another common adulterant, ascorbic acid, did increase heroin degradation [34].

The degradation of cocaine by pyrolysis requires high temperatures. Pyrolysis at 800 °C completely degraded cocaine hydrochloride with cocaine free-base extensively degrading (16 % remaining) at this temperature [7]. At 350–400 °C, approximately 50 % of cocaine degraded, whereas at 650 °C, complete degradation of cocaine freebase was observed [8]. The higher temperatures also favoured the formation of more TPs. Another study exploring cocaine freebase degradation at similar temperatures found 35 % degraded at 500 °C, whereas at 550 °C, complete degradation occurred [9]. The impact of adulterants has been explored with paracetamol having the biggest impact on degradation. At 450 °C, cocaine was poorly degraded, up to 15 %, where as in a 1:1 mixture with paracetamol, cocaine was degraded up to 97 % [10]. Numerous TPs were identified (**COC 2–10**) [10]. At 350–750 °C, gas phase TPs including methane, carbon dioxide, hydrogen cyanide and chloromethane have been detected [11].

Pyrolysis studies of amphetamine-type stimulants (ATS) have focused on methamphetamine, dimethylamphetamine (DMA) and amphetamine. Pyrolysis of methamphetamine hydrochloride demonstrated the impact of temperature on methamphetamine degradation [38]. Between 200 and 400 °C, methamphetamine and methamphetamine hydrochloride degradation is poor with only 2 % degraded, however at 800 °C, degradation is increased to 38 % and 62 %, respectively. Atmospheric conditions also impact recovery of methamphetamine [42]. Methamphetamine hydrochloride smoked with tobacco in an inert atmosphere showed lower degradation compared to a sample smoked in air. The inert atmosphere sample resulted in greater concentrations of TPs and different TP profiles. Longer smoking intervals also increased the degradation of methamphetamine. Fifteen TPs have been identified across various studies (**ATS 1, 5–21, 55, 56**). Thermal degradation of methamphetamine between 350 °C – 750 °C resulted in the gas phase TPs methane, carbon dioxide, hydrogen cyanide and chloromethane (similar to those from cocaine listed above) [11].

Two studies analysing the pyrolysis of DMA hydrochloride have reported degradation data. DMA hydrochloride behaved methamphetamine hydrochloride under pyrolysis conditions and exhibited greater degradation at higher temperatures (99 % degradation at 500 °C, compared to 22 % at 315 °C) [39]. A second study reported similar degradation data (27 %) for DMA hydrochloride between 250 and 350 °C [40]. The TP profile of DMA was similar to that of methamphetamine (**ATS 1, 2, 5, 11–21**) [39,40].

Amphetamine sulfate was pyrolyzed at temperatures between 300 and 1000 °C and some key organic, mineral, and gaseous TPs were identified [41]. At 500 °C, 24 organic TPs were identified, consisting of

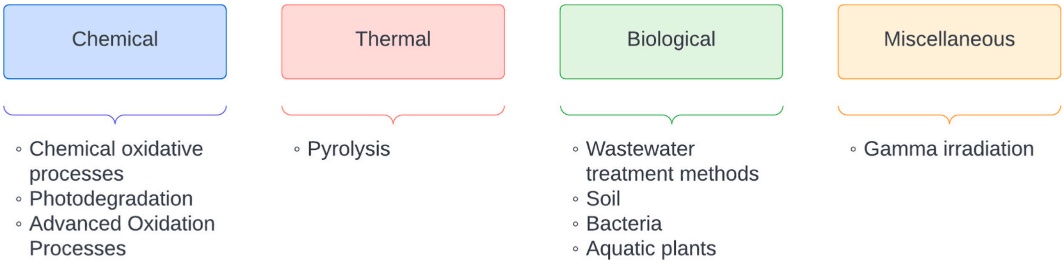

Fig. 1. Summary of techniques used for drug degradation.

Table 1
Summary of degradation processes reported for illicit drugs or drug classes.

Drug or drug class	Methods	Reference
Cocaine	Pyrolysis	[7–11]
	Chlorine-containing compounds	[12–15]
	Photodegradation	[13,16]
	Ozone	[14,17–19]
	Fenton-like	[20,21]
	Photo-Fenton	[16,22]
	Heterogeneous catalyst systems	[16]
	Biofilm	[23–26]
	Activated sludge	[27–29]
	Bacteria	[2,30]
Phencyclidine (PCP)	Pyrolysis	[31–33]
Heroin	Pyrolysis	[7,34–37]
	Ozone	[17]
	Biofilm	[24]
Amphetamine-type stimulants	Pyrolysis	[11,38–42]
	Chlorine-containing compounds	[15,43–45]
	Ozone	[15,17–19,46]
	Fe-TAML	[47]
	Fenton-like	[20,21]
	Photo-Fenton	[22,48]
	UV/persulfate	[49]
	UV/hydrogen peroxide	[50]
	Heterogeneous catalyst systems	[51–53]
	Sonochemical	[54,55]
	Wastewater	[56–58]
	Biofilm	[23,25,26,59]
	Activated sludge	[27,28,57]
	Soil	[60–62]
	Aquatic plants	[63]
	Gamma irradiation	[64]
	Long term storage	[65]
NPS	Pyrolysis	[66]
	Wastewater	[24,26,59,67]
Fentanyl	Pyrolysis	[68–70]
	Chlorine-containing compounds	[71,72]
	Hydrogen peroxide	[69,72]
	Peroxide based oxidants	[72]
	Sodium bromate	[73]
	Photodegradation	[69,74,75]
	Fenton	[76]
	Heterogeneous catalyst systems	[75]
	Biofilm	[25]
Synthetic cannabinoid receptor agonists (SCRA)	Pyrolysis	[77–86]
Synthetic cathinones	Pyrolysis	[87,88]
	Ozone	[17]
	Wastewater	[89]
	Biofilm	[26,59,67]
	Alkaline storage	[90]
Methadone	Chlorine-containing compounds	[14,91–93]
	Ozone	[14,17,92]
	Potassium permanganate	[94]
	Photodegradation	[95]
	Fenton-like	[20,21]
	Photo-Fenton	[22,48,95]
	Sunlight/chlorine-containing compounds	[96,97]
	Heterogeneous catalyst systems	[95]
	Biofilm	[24,26,67]
	Activated sludge	[27,28,98]
Ketamine	Ozone	[14,18]
	Sunlight/chlorine-containing compounds	[99]
	Sunlight/ozone	[99]
	UV/hydrogen peroxide	[50]
	Heterogeneous catalyst systems	[52]
	Wastewater	[58]
	Biofilm	[26,67]
	Activated sludge	[27,28]

mostly benzyl methyl ketone, phenylpropenes, biaryl and aryl alkyl ketones. At 1000 °C, 34 compounds were identified consisting of heavier polyaromatics. The sulfate component of amphetamine sulfate may contribute to some of the oxidative reactions occurring during pyrolysis. Of the gaseous and mineral TPs formed at 350 °C, mainly sulfate and sulfite ions were identified, whereas at 700 °C, mainly methane, hydrogen, carbon monoxide, ammonia, sulfur oxides, hydrogen cyanide, and ethylene were identified.

bk-2C-B (*β*-keto-4-bromo-2,5-dimethoxyphenethylamine) and *bk*-2C-I (*β*-keto-4-iodo-2,5-dimethoxyphenylethamine) are NPS and part of the 2C-X class of phenethylamines [100]. Pyrolysis was achieved by loading samples onto aluminium foil, placing into a crimping vial, and heating

Table 2
Summary of the degradation efficiency of drugs subjected to pyrolysis.

Drug	Degradation efficiency*			References
	Low	Medium	High	
Heroin HCl			✓	[7,34–37]
Heroin free-base		✓		
Cocaine HCl			✓	[7–11]
Cocaine free-base			✓	
Methamphetamine HCl		✓		[11,38–42]
Methamphetamine		✓		
DMA HCl			✓	
Amphetamine sulfate		Not quantified		
Bk-2C-B		Not quantified		[66]
Bk-2C-I		Not quantified		
Fentanyl		Not quantified		[68–70]
CUMYL-PEGACLONE			✓	[77–86]
JWH 018	✓			
PB 22			✓	
A-834735**			✓	
Mephedrone HCl		Not quantified		[87,88]
Methiopropamine HCl		Not quantified		
PCP		✓		[31–33]

[*] Degradation efficiency is defined as low = 0–15 %, medium = 16–84 %, high = 85–100 %.
[**] Other SCRA analysed but not quantified include UR 144, XLR 11, CUMYL-PICA, 5F-CUMYL-PICA, AMB-FUBINACA, MDMB-FUBINACA, NNEI, MN-18, AB-CHMINACA, AM-694, AB-FUBINACA, AB-PINACA, JWH-073, JWH-081, JWH-210, MAM-2201, MDMB-CHMICA, 5F-ADB, MMB-2201 and 5F-PB 22.

with a disposable lighter for 30 s [66]. Twelve TPs were identified for *bk*-2C-B (**NPS 1–12**) and nine for *bk*-2C-I (**NPS 13–21**).

Pyrolysis of fentanyl at temperatures between 250 and 900 °C revealed that fentanyl was stable up until 350 °C and decomposition at around 500 °C produced two TPs (**FEN 2** and **3**) [68]. Pyrolysis at 750 °C created more complex mixtures and formed three additional TPs (**FEN 4–6**). When fentanyl free-base was heated at 350 °C, five TPs were observed (**FEN 3, 7–10**) [69]. Pyrolysis of fentanyl and fentanyl transdermal patches (FTP) under aerobic and anaerobic conditions gave **FEN 3** as the major product with additional TPs including **FEN 11–14** [70]. The TPs specific to aerobic conditions included **FEN 15–17**, while TPs **FEN 7** and **FEN 18** were specific to anaerobic conditions. There were minimal differences in the degradation profiles of fentanyl compared to FTP profiles. Structures for fentanyl derived TPs (**FEN**) are provided in the supporting information (Table S1).

Pyrolysis data for 24 synthetic cannabinoid receptor agonists has been reported [77–86]. Table S3 contains a summary together with International Union of Pure and Applied Chemistry (IUPAC) nomenclature and structure. The reported TPs for these drugs are collected in Table 3.

Degradation of CUMYL-PEGACLONE at temperatures ranging from 250 to 350 °C revealed that increased temperature enhanced the degradation of the parent compound while simultaneously increasing the formation of TPs [83]. At 350 °C, no CUMYL-PEGACLONE was detected and only one TP was reported.

Degradation of the synthetic cannabinoids JWH 018, UR 144, XLR 11, PB 22 and A-834735 at 800 °C was investigated [82]. JWH 018 showed poor degradation at 800 °C with 10 % degraded. On the other hand, PB 22 and A-834735 underwent complete degradation at this temperature. UR 144 and XLR 11 showed varying degrees of degradation and unreacted parent compound was still present although not quantified.

The degradation of six carboxamide-type synthetic cannabinoids including CUMYL-PICA, 5F-CUMYL-PICA, AMB-FUBINACA, MDMB-FUBINACA, NNEI and MN-18 was investigated between 200 and 800 °C [84]. At 200 °C, no degradation was observed, however at 400 °C and 600 °C degradation of CUMYL-PICA, 5F-CUMYL-PICA, AMB-FUBINACA, and NNEI occurred. Higher temperatures (~800 °C) were required to degrade MN-18 and MDMB-FUBINACA. No quantification data was reported for the degradation of these SCRA's. The production of hydrogen cyanide from the pyrolysis of these compounds was examined and from the six cannabinoids analysed, AMB-FUBINACA, MDMB-FUBINACA, and MN-18 released the highest levels of cyanide compared to the other synthetic cannabinoid receptor agonists (SCRAs). The greatest quantity released was 27.4 μg/mg from MDMB-FUBINACA. For comparison, commercial tobacco cigarettes can release 10 to 400 μg/cigarette [101].

Transformation products of AB-CHMINACA, AM-694, AB-FUBINACA, AB-PINACA, JWH-073, JWH-081, JWH-210, MAM-2201, MDMB-CHMICA from pyrolysis are listed in Table 3. The SCRAs 5F-ADB, MMB-2201 and 5F-PB 22 have been studied although no TPs have been reported [85].

Pyrolysis of mephedrone and methiopropamine hydrochloride gave twelve TPs for mephedrone hydrochloride (**sCAT 1–12**) and twelve TPs for methiopropamine hydrochloride (**sCAT 13–24**) [87,88]. Unreacted parent compound was present in both, however no quantification was undertaken.

Degradation of PCP using pyrolysis is moderately to highly effective with numerous TPs identified. Cigarettes smoked in a smoking machine is a method to evaluate the impact of pyrolysis. PCP hydrochloride examined by this method degraded by up to 60 % with one TP identified (**PCP 2**) [31]. Another study reported similar degradation rates of PCP in marijuana placebo cigarettes with 60 % degraded and the other constituents consisting of TPs (**PCP 2, 4** and **5**) [32]. Temperature impacts the degradation of PCP; [33] at 400 °C, 58–74 % of PCP was recovered and two TPs were identified (**PCP 2** and **3**). Higher temperatures (600–800 °C) produced more complex mixtures that effectively

Table 3
Summary of transformation products for reported synthetic cannabinoid receptor agonists.

SCRA	TPs	Reference
CUMYL-PEGACLONE	**SCRA 1**	[83]
JWH 018	**SCRA 2–15**	[80,82,86]
UR 144	**SCRA 11, 16, 45, 46, 80**	[77–82]
XLR 11	**SCRA 11, 17, 45, 46, 55, 80**	[78,80,82]
A-834735	**SCRA 18**	[82]
QUPIC (PB 22)	**SCRA 8, 19**	[82]
CUMYL-PICA	**SCRA 8, 20–23**	[84]
AMB-FUBINACA	**SCRA 24–28**	[84]
MDMB-FUBINACA	**SCRA 24–27, 29**	[84]
5F-CUMYL-PICA	**SCRA 20, 21, 30–34**	[84]
NNEI	**SCRA 2, 5, 6, 8, 10, 11, 35, 36**	[84]
MN-18	**SCRA 2, 37–41**	[84]
JWH-250	**SCRA 42**	[86]
AM-2201	**SCRA 9–11, 13, 43–46**	[80,86]
AB-CHMINACA	**SCRA 47–54**	[80]
AM-694	**SCRA 31, 45, 55–57**	[80]
AB-FUBINACA	**SCRA 51, 52, 58, 59, 61, 62**	[80]
AB-PINACA	**SCRA 50, 51, 59, 61–64**	[80]
JWH-073	**SCRA 2, 10, 11, 14, 60, 65–70**	[80]
JWH-081	**SCRA 2, 7, 10, 11, 43, 45, 46, 60, 71**	[80]
JWH-210	**SCRA 10, 11, 14, 45, 46, 70, 72, 73**	[80]
MAM-2201	**SCRA 7, 10, 11, 45, 46, 60, 74, 75**	[80]
MDMB-CHMICA	**SCRA 76**	[85]

degraded PCP. Twelve and ten TPs were identified (at 600 °C and 800 °C, respectively) and consisted mostly of polynuclear aromatics [31–33].

3.2. *Evaluation of thermal degradation methods*

Pyrolysis techniques have been used to degrade ATS, fentanyl, cocaine, NPS, synthetic cathinones and SCRAs, making it one of the most widely studied degradation techniques. Most studies focussed on the transformation products of these drugs to assess their formation during the smoking process and thus optimisation of the degradation process was not a focus of these works. Many of the methods employed are small-scale and include smoking machines or simulators, foil/lighters and glass tubes/furnaces (highlighted in Table S2) which are not feasible methods of large-scale destruction. However, pyrolysis techniques are employed in industry for the production of carbon-based materials and fragmentation of complex organic materials [102]. Although the methods detailed in the aforementioned studies are not scalable, the chemical technique has potential as the tools and technology are already in place for large scale disposal, with the possibility to produce useful byproducts.

Pyrolysis can also occur in the injection port during chromatography (GC) where temperatures reach between 200 and 300 °C [103,104]. Numerous TPs have been identified for flephedrone (4-FMC), 2-fluromethcathinone (2-FMC), 3-fluromethcathinone (3-FMC), α-pyrrolidinopentiophenone (PVP) and methylenedioxypyrovalerone (MDVP) (**sCAT 25–40**), cocaine (**COC 3**), PB 22 (**SCRA 19**, **77–79**), *bk*-2C-B (**NPS 7**, **11** and **22**) and *bk*-2C-I (**NPS 19** and **21**) [66,104–111]. While not a feasible method of large-scale drug destruction, the degradation data provides insight into their TPs while not studied at scale or during specific pyrolysis experiments.

Additives have been shown to enhance the pyrolysis process (e.g., paracetamol enhanced the degradation of cocaine, and ascorbic acid enhanced heroin degradation) [10,34]. This is advantageous for disposal as the conditions can be optimised for the degradation of the specific drugs. Furthermore, this is one of the few techniques to explore the degradation of the freebase and salt forms of illicit drugs. Illicit drugs are commonly seized in their salt from as either pills, powders or crystals and hence existing literature describing optimal degradation conditions is advantageous.

Several of the reported TPs are themselves controlled precursors for the illicit production of drugs. For example, phenyl-2-propanone (**ATS 5**), *N*-formylmethamphetamine (**ATS 7**) and benzaldehyde (**ATS 21**) are precursors for methamphetamine production [42,112–114]. The formation of precursors marks a key challenge for the degradation of synthetic drugs as the formation of precursors negates the degradation process as they themselves require strict disposal procedures. Caution is required when using pyrolysis techniques as the release of toxic and harmful gases has been documented from the degradation of some drugs [11,41,84]. In addition, degradation products have been identified as toxic substances, for example, **FEN 15** (despropionyl fentanyl) [69,115]. Furthermore, secondary degradation pathways can be present whereby transformation products formed from the parent compound continue to undergo degradation. This presents a challenge for alternative methods of drug disposal if transformation products are not appropriately characterised [68,115].

Table 4
Redox potentials for selected oxidants (vs. NHE) [116,117].

Oxidant	Potential E^0 (V vs. NHE, at 25 °C)
Fluorine [F_2]	3.06
Hydroxyl radical [$OH^{\bullet}$]	2.80
Atomic oxygen [O]	2.42
Sulfate radical [$SO_4^{\bullet-}$]	2.5–3.1
Ozone [O_3]	2.07
Persulfate [$S_2O_8^{2-}$]	2.01
Peroxymonosulfate [HSO_5^-]	1.82
Hydrogen peroxide [H_2O_2]	1.78
Permanganate [MnO_4^-]	1.68
Chlorine dioxide [ClO_2]	1.57
Hypochlorous acid [HClO]	1.49
Chlorine [Cl_2]	1.36
Oxygen [O_2]	1.23

Note: Compounds with higher standard potentials are indicative of stronger oxidants given their higher tendency to acquire electrons.

4. Chemical degradation methods

4.1. *Chemical oxidative processes*

Oxidative degradation can be accomplished either through oxidation of the parent compound into transformation products (TPs), or by mineralisation to produce small molecules such as water, carbon dioxide, ammonium ions and nitrate ions [118]. Common oxidants include sodium hypochlorite, ozone, hydrogen peroxide, peracetic acid, and potassium permanganate with catalysts including iron-tetraamido macrocyclic ligand (Fe-TAML). The oxidation potentials of selected oxidants are shown in Table 4 and a summary of the illicit drugs for which degradation via oxidative processes has been quantified is presented in Table 5.

4.1.1. *Oxidation using chlorine-containing compounds*

Chemical oxidation using chlorine-containing compounds is used in large volumes worldwide to disinfect drinking water, swimming pools and municipal water [44]. Molecular chlorine and chlorine dioxide are used to degrade toxins in wastewater and in drinking water. Sodium hypochlorite and trichloroisocyanuric acid (TCCA) are disinfectants used in household bleach and chlorinating pool tablets [119,120].

Amphetamine-type stimulants including amphetamine, methamphetamine 3,4-methylenedioxymethamphetamine (MDMA), 3,4-methylenedioxyethamphetamine (MDEA) and 3,4-methylenedioxyamphet amine (MDA) were effectively degraded by sodium hypochlorite [44]. Hypochlorite is effective toward ATS due to its reactivity with primary and secondary amines [15]. Amphetamine and methamphetamine had the shortest degradation times compared to their ring substituted analogues, MDA, MDEA, and MDMA. No quantification data was provided across the studied ATS and no TPs were identified for amphetamine and methamphetamine, but several were identified for MDA, MDMA and MDEA. **ATS 22** was identified after treatment of MDA and MDEA, and **ATS 23** was detected after treatment of MDMA.

ATS monitored in wastewater treatment programs exhibited similar behaviours. In industrial waste and drinking water treatment processes, chlorination is generally applied twice: a prechlorination using chlorine and chlorine dioxide, and postchlorination using chlorine. After the prechlorination stage, amphetamine, methamphetamine and MDA showed high removal efficiencies, consistent with shorter degradation times seen in targeted studies [15,44]. The degradation of MDMA was slower, with one study reporting only 23 % of the initial concentration degraded after the prechlorination stage [15]. Postchlorination effectively removed MDMA in both studies [15,44].

Factors impacting the degradation of ephedrine using sodium hypochlorite have also been examined [43]. Higher pH's increased the degradation rate with 99 % of ephedrine removed in 1 min at pH 10. Bromine and iodine were explored as possible influential anions with higher concentrations of the anions enhancing degradation through the possible formation of hypobromous acid and hypoiodous acid. The degradation of pseudoephedrine has also been briefly explored using sodium hypochlorite [45]. When exposed to a 0.04 % *v*/v of sodium hypochlorite (pH 6.5), pseudoephedrine rapidly converted to methcathinone (**ATS 57**). The transformation of pseudoephedrine to methcathinone has been documented by other studies [121,122].

Degradation of cocaine in the presence of chlorine-containing

Table 5
Summary of the degradation efficiency of drugs subjected to oxidative processes.

Oxidative process	Drug	Degradation efficiency*			References
		Low	Medium	High	
Chlorine-containing oxidants	Amphetamine			✓	[15,43,44]
	Methamphetamine			✓	
	MDA			✓	
	MDMA			✓	
	Ephedrine			✓	
	Pseudoephedrine		Not quantified		[45]
	Cocaine		Variable		[12–15]
	Methadone		Variable		[14,91–93]
	Fentanyl			✓	[71,72]
Ozone	Heroin			✓	[17]
	Methadone		✓		[14,17,92]
	Cocaine		Variable		[14,17–19]
	MDMA		Variable		[15,17–19,46]
	MDA			✓	
	Amphetamine		✓		
	Methamphetamine		✓		
	Ephedrine	✓			
	Mephedrone		✓		[17]
	Ketamine		Variable		[14,18]
Other oxidative processes					
Potassium permanganate	Methadone		Not quantified		[94]
Hydrogen peroxide	Fentanyl	✓			[69,72]
SPC/TAED, peracetic acid	Fentanyl		✓		[71]
Sodium bromate/sulfuric acid/sodium sulfite	Fentanyl			✓	[73]
Fe-TAML	Methamphetamine			✓	[47]
	Ephedrine			✓	

* % Degradation efficiency is defined as low = 0–15 %, medium = 16–84 %, high = 85–100 %.

compounds has been reported with mixed findings. In aqueous sodium hypochlorite (10 mg/L) over a period of 24 h at pH 7, cocaine was degraded to 50 % of its initial concentration [12]. The main factor affecting degradation was pH, with cocaine degraded at significantly faster rates at higher pH. At pH 8.3, the half-life of cocaine was 3.7 h compared to pH 5.7 where the half-life was 39 h. Four TPs were identified from the degradation of cocaine, **COC 8, 11–13**.

Contrary to other findings, degradation of cocaine in spiked river surface water has reported to be relatively fast [13]. Using sodium hypochlorite (8 mg/L), cocaine was degraded effectively within 30 min. Eight TPs were identified with three consistent with other reports (**COC 8, 11, 13**). Three additional chlorinated and keto derivatives were identifed (**COC 14–18**). However, the position of chlorine and keto derivatives on the tropane rings were not specified.

Degradation of cocaine during water treatment using chlorine dioxide and chlorine exhibited poor degradation. During prechlorination of wastewater samples, cocaine was degraded up to 13 % [15]. Another study reported low degradation of cocaine in water treatment plants with removal at around 5 % [14].

Degradation of methadone with chlorine-containing compounds has exhibited variable results. When exposed to a 50-fold molar excess of sodium hypochorite (10 mg/L), methadone degraded up to 98 % within 2 h [91]. pH was a key factor in enhancing methadone degradation with a half-life of 2 h at pH 5.7 and a half-life of 3 min at pH 8.3. Eight TPs were identified, (**MTHD 2–9**). One major product was identified as 2-ethylidene-1,5-dimethyl-3,3-diphenylpyrrolidine (EDDP, **MTHD 4**), the major metabolite of methadone.

Degradation of methadone using chlorine and chlorine dioxide during wastewater treatment exhibited mixed results. During the prechorination stage of one study, methadone was degraded by up to 54 % [92]. Further exposure during the postchlorination stage, slightly enhanced methadone degradation, giving an overall degradation of 60

%. A second study however, reported effective degradation of methadone of up to 80 % in the prechlorination stage [14]. Treatment of methadone with monochloramine produced *N*-nitrosodimethylamine (**MTHD 10**) with greater doses of monochloramine resulting in higher yields of **MTHD 10** [93].

Chlorination of fentanyl using TCCA and calcium hypochlorite was evaluated [71]. TCCA performed better with 97 % of fentanyl degraded within the first 2 min compared to 86 % with calcium hypochlorite. A total of ten TPs were identified as a result of chlorination with TCCA, six chlorinated and one that was not identified (**FEN 3, 12, 18–24**). Polar compounds were further analysed and another six possibly identified, four of them chlorinated (**FEN 3, 25–29**). A secondy study assessed different chemical decontamination solutions for fentanyl degradation [72]. Three bleach solutions were explored, bleach at pH 5, pH 7 as well as pH 5 with surfactant, all with free available chlorine between 50 and 60 %. The most significant reduction in fentanyl concentration occurred with pH 5 bleach and pH 5 bleach with surfactant. **FEN 7** was the only TP identified from degradation using pH 5 bleach. However, norfentanyl was also identfiied in the control with no bleach, its presence was attributed to a possible impurity during synthesis.

4.1.2. *Ozonation*

Ozonation is an effective and powerful oxidative process to degrade and mineralise organic compounds. Ozone has a high oxidation potential ($E^0 = 2.07$ V), [123] and can be used in water as well as in air. It is commonly used for decontamination in wastewater treatment, food industries as well as healthcare and medical sterilisation [124]. Ozonation can proceed by direct and indirect reaction mechanisms [125]. Direct ozonation involves the reaction of ozone with the target compounds and is selective to specific functional groups including secondary and tertiary amines, activated benzene rings and olefins [15,17,18]. This is advantageous to drug disposal given many illicit drugs contain these moieties. Indirect ozonation involves the interaction of ozone with hydroxide ions or water to produce hydroxyl radicals that react with a range of organic compounds, further enhancing applicability to drug destruction [126].

Processes to degrade illicit drugs by ozonation have been described by multiple reports, however only two studies were not in the context of wastewater analysis. Variables affecting ozonation include pH and ozone dosage [17]. In pure water at pH 7, heroin, MDMA and MDA, exhibited high levels of degradation across a range of ozone concentrations. In contrast, methadone showed poor removal efficiency. Amphetamine-type stimulants including amphetamine, methamphetamine, ephedrine/pseudoephedrine and mephedrone showed little to no degradation. The effect of pH was also explored with pH ranging from 3 to 11. Higher alkalinity enhanced degradation of methadone, cocaine, amphetamine and methamphetamine. However, degradation rates were still poor with methadone degrading up to 50 % and cocaine and both ATS below 35 %. On the other hand, MDMA and MDA demonstrated decreased degradation at pH 11.

Table 6
Comparison of degradation rates of illicit drugs via ozonation in wastewater drinking plants.

Drug or drug class	Degradation	Reference
Cocaine	20 %	[17]
	30 %	[18]
	85 %	[14]
MDMA	28 %	[15]
	50 %	[18]
Amphetamine	25 %	[18]
Methamphetamine	30 %	[18]
Methadone	37 %	[14]
	44 %	[92]
Ketamine	20 %	[18]
	100 %	[14]

Gas-phase oxidation of methamphetamine has been evaluated in the context of remediation of methamphetamine contaminated surfaces [19]. Surface concentrations of methamphetamine were effectively degraded with ozone exposure by up to 97 % after 12 min. Phenyl-2-propanone (**ATS 5**) was found to be the main TP of methamphetamine (constituting 8.3 % of the degraded product), with other TPs identified including **ATS 7, 21, 24–28**. A further four TPs were found but not identified.

Drugs of abuse can be removed in wastewater treatment processes via ozonation. In the treatment processes, ozonation is typically employed after prechlorination and sand filtration but before granular activated carbon filtration [15,44,92]. The results obtained are variable across multiple bodies of work and are collected in Table 6.

Ozonation of methamphetamine and ephedrine was investigated in the context of *N*-methylamines as precursors to nitromethane formation [46]. Ozonation of ephedrine and methamphetamine both produced nitromethane as by-products in molar yields of 80 % and 8 % respectively.

4.1.3. *Other chemical oxidation processes*

Potassium permanganate has been demonstrated to oxidise methadone [94] and under neutral conditions yielded two products in a ratio of 4:1. **MTHD 5** was identified as the major product with **MTHD 11** the minor product. No quantification of degradation was undertaken. The major product identified in this study was also reported as a product of the chlorination of methadone [91].

Oxidation of fentanyl with 0.3 % H_2O_2 yielded two products, however only 10 % degradation was observed after 24 h [69]. The reaction products were identified as the diastereoisomers of fentanyl-*N*-oxide (**FEN 30**). However, based on the data, it could not be identified whether the alpha or beta isomer was the major product. Peroxide has been explored using a range of sources including potassium persulfate, hydrogen peroxide, potassium peroxymonosulfate, magnesium monoperoxyphthalate, sodium percarbonate, peracetic acid and sodium percarbonate/*N*,*N*,*N*,*N*-tetraacetylethylene diamine (SPC/TAED) [71]. Of these oxidants, SPC/TAED demonstrated the greatest amount of degradation (82 %) after 2 min, followed by peracetic acid with 91 % after 4 min. Eight TPs were identified after degradation using hydrogen peroxide, **FEN 3, 11, 12, 17, 31–33,** one which could not be identified, and three when peracetic acid was used, **FEN 3, 7** and **25**.

Recent work using percarbonate, hydrogen peroxide and peracetic acid solutions sprayed onto surfaces contaminated with fentanyl [72] reported significant degradation of fentanyl by the peroxide solutions. Peracetic acid gave >95 % degradation after 1 h, similar to the study above [71]. No TPs were identified.

Oxidation using sodium bromate has been investigated exploring factors impacting fentanyl degradation including different systems of sodium bromate, sodium sulfite and sodium hydrogen sulfite as well as pH [73]. A system of sodium bromate, sulfuric acid and sodium sulfite at pH 3.2 exhibited the best degradation of fentanyl with almost 100 % degraded after 30 min. Acidic solutions enhanced fentanyl degradation, whereas in solutions above pH 4, the degradation efficiency decreased.

Table 7
Summary of the degradation efficiency of drugs subjected to photodegradation.

Drug	Degradation efficiency*			References
	Low	Medium	High	
Methadone			✓	[95]
Cocaine			✓	[13,16]
Fentanyl			✓	[69,74,75]

* Degradation efficiency is defined as low = 0–15 %, medium = 16–84 %, high = 85–100 %.

3-Methylfentanyl and carfentanil were degraded by up to 99.9 % in 30 min, however, sufentanil was only degraded up to 74 %. In total, eight TPs were reported (**FEN 3**, **34–39**). An additional TP was reported but could not be identified. Of the seven identified products, six were brominated. Conflicting information was reported for brominated TPs **FEN 37** and **38,** thus the identification is tentative.

Recent work has adapted the use of a green chemistry catalyst, Fe-TAML for methamphetamine and ephedrine degradation [47]. Fe-TAML is a non-heme iron complex that mimics the effects of peroxidase enzymes, which catalyse the oxidation of organic and inorganic compounds by hydrogen peroxide or related compounds [127]. Initial experiments using 10 % hydrogen peroxide and 2.5 mM of Fe-TAML resulted in 90 % degradation of methamphetamine after 60 min. Degradation increased to 98 % and 97 % after 30 mins with a second dose of hydrogen peroxide and Fe-TAML/hydrogen peroxide, respectively. A total of 20 TPs were identified including unreacted methamphetamine (**ATS 1, 5, 13, 21, 24–39**). When a second dose of hydrogen peroxide was added there was a notable increase in the formation of **ATS 5** and **ATS 21**. When the second dose of Fe-TAML was added, there was a decrease in **ATS 27** which was possibly attributed to degradation of the compound by Fe-TAML.

Initial degradation of ephedrine showed up to 85 % after 60 min, a second dose of hydrogen peroxide increased degradation up to 99 % and after a second dose of Fe-TAML, degradation efficiency was 98 %. Sixteen TPs were identified from the degradation of ephedrine (**ATS 21, 29–34, 36–44**). Unreacted ephedrine was identified. **ATS 21** has previously been identified during the chlorination of ephedrine [43]. The second dose of hydrogen peroxide gave a 2-fold increase in benzaldehyde and the second dose of Fe-TAML also increased the formation of benzaldehyde.

4.2. Photodegradation

Photodegradation processes involve the degradation of a molecule based on the absorption of photons. It can be initiated by photons from different types of radiation including infrared radiation, visible light and ultraviolet light, however, can also be induced by catalysts in conjunction with these wavelengths [128]. Photodegradation has been used in industry to degrade non-biodegradable or persistent organic pollutants such as organic and industrial dyes [129]. A summary of the illicit drugs whose degradation via photodegradation has been quantified has been listed in Table 7.

Degradation via photolysis of methadone has been reported by one study. The work explored the transformation and mineralisation of methadone in aqueous solutions through photolysis and photocatalytic systems using direct sunlight [95]. Two water matrices were investigated, de-mineralised water and synthetic municipal wastewater. Methadone degraded more than 90 % after 10 h and 17 h in de-mineralised water and synthetic municipal wastewater effluent, respectively. Five transformation products were identified, four of which were also identified during the photocatalytic experiments (**MTHD 6, 12–14**). One TP was specific to photolysis, however, no structure or identification was provided.

Photolysis of cocaine has been documented in distilled water via photolysis and photocatalytic systems [16]. Slight degradation of cocaine occurred after 22 h in the dark, however, this was attributed to the hydrolysis of cocaine in water. Two transformation products were identified, **COC 11** and **COC 20** which have previously been named as the two main hydrolytic products of cocaine [130]. Under direct sunlight exposure, 90 % of cocaine was degraded after 20 h and almost complete degradation after 27 h in synthetic municipal wastewater effluent. Cocaine in distilled water exhibited poor degradation with only 22 % of cocaine degraded after 60 h. It is reported that a combination of hydrolysis and photolysis contributed to the degradation of cocaine. However, the enhanced degradation in wastewater could possibly be attributed to the additional biological degradation of cocaine in water, further discussed in biological degradation methods. Ten transformation products were identified (**COC 3**, **8**, **11**, **19**–**25**). **COC 8** and **COC 11** have previously been identified as TPs via the chlorination of cocaine [12,13].

Photolysis of cocaine in surface water has been evaluated [13]. Unlike previous work involving sunlight, this work used UV irradiation and simulated sunlight. While not explicitly analysing degradation, eight transformation products were identified including the *ortho*-, *meta*- and *para*- isomers of **COC 23** and two isomers of **COC 27** (**COC 11, 13, 23, 26, 27**).

The photolysis of fentanyl has initially been evaluated by numerous studies, first in the context of pharmaceutical drug removal under long term UV irradiation [74]. Three water matrices were evaluated over a period of 28 days: ammonium acetate buffer (pH 7), and filtered and unfiltered river water (pH 5). Of the three matrices explored, the most extensive degradation was in unfiltered river water (95 % with a half-life of 33 h). Recently, photolysis of fentanyl and identification of TPs has been explored [75]. Like previous work, fentanyl demonstrated that it is highly photostable, with a half-life in ultrapure water of close to 17 h. During photolysis, 26 transformation products were identified in ultrapure water, five of which were determined to be major products and the remaining at trace levels. The major products identified include **FEN 7**, **40**–**43**. Direct photooxidation of fentanyl was explored whereby solid fentanyl was exposed to UV light at 365 nm (300 mW/cm^2 at 15.2 cm) for 7 days, however no degradation was observed [69].

4.3. Advanced oxidation processes

Advanced oxidation processes encompass a range of systems that generate reactive oxygen species, often in situ, to degrade organic pollutants such as pharmaceuticals, drugs of abuse and synthetic dyes in wastewater and drinking water [131–134]. Hydroxyl radicals have a high oxidation potential ($E^0 = 2.80$ V), [123] can attack a broad range of substances, and completely mineralise organic compounds [132]. Other radicals involved in AOP include alkoxyl radicals (R-O$^{\bullet}$), superoxide anion radicals ($O_2^{\bullet -}$) and hydroperoxyl radicals (HOO$^{\bullet}$) [135]. AOP use a combination of oxidising agents (e.g. hydrogen peroxide or ozone), irradiation (UV or ultrasound) and catalysts (metal ions or photocatalysts) to generate hydroxyl radicals [136,137]. Common processes include chemical, photochemical, sonochemical and electrochemical, summarised in Fig. 2 [138]. These processes are characterised by the

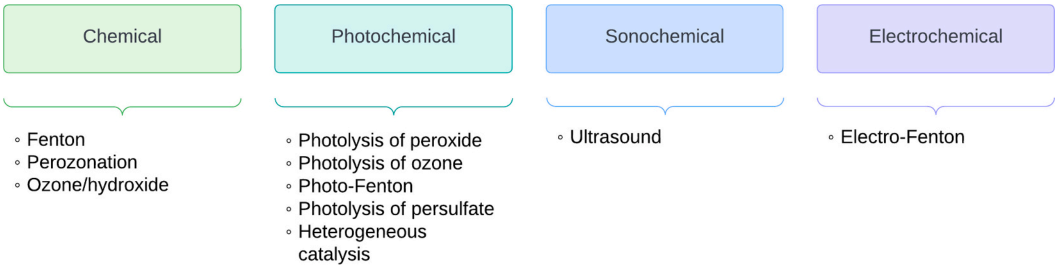

Fig. 2. Summary of common advanced oxidative processes.

Table 8
Degradation efficiencies of drugs subjected to advanced oxidation processes.

AOP	Drug	Degradation efficiency*			References
		Low	Medium	High	
Fenton and Fenton like systems	Fentanyl			✓	[76]
	Amphetamine			✓	[20,21]
	Methamphetamine			✓	
	MDMA		✓		
	Cocaine			✓	[20,21]
	Methadone			✓	[20,21]
Photo-Fenton	Cocaine		Variable		[16,22]
	Methadone			✓	[22,48,95]
	MDMA		Variable		[22,48]
Sunlight/ chlorine containing systems	Methadone			✓	[96,97]
	Ketamine			✓	[99]
Sunlight/ ozonation	Ketamine		✓		[99]
UV/persulfate	Methamphetamine			✓	[49]
UV/hydrogen peroxide	Methamphetamine			✓	[50]
	Ketamine			✓	[50]
Heterogeneous catalyst systems	Cocaine			✓	[16]
	Methadone			✓	[95]
	Methamphetamine			✓	[51–53]
	Ketamine			✓	[52]
	Fentanyl			✓	[75]
Sonochemical	Methamphetamine		✓		[54]
	Methamphetamine HCl		✓		[55]

[*] Degradation efficiency is defined as low = 0–15 %, medium = 16–84 %, high = 85–100 %.

system in which radicals are produced. A summary of the illicit drugs for which degradation via AOPs has been studied is provided in Table 8.

4.3.1. *Fenton and Fenton-like systems*

Fenton's reagent in deionised water has been evaluated for the degradation of fentanyl and its analogues [76]. Increasing iron concentrations were found to increase fentanyl degradation and degradation was found not to occur in the absence of hydrogen peroxide. Fentanyl was efficiently degraded after 5 h at the highest concentration of iron. Norfentanyl, furanylfentanyl, carfentanil and sufentanil exhibited similar results to fentanyl, with half-lives of 2–8 min. Twelve transformation products were detected from the degradation of fentanyl, with eight identified, (**FEN 3**, **7**, **44**–**49**). It should be noted multiple isomers of the TPs were identified, however, they were not defined. Hence, they were assigned separate identification from previous bodies of work which identified the specific isomers. Two of which, **FEN 3** and **FEN 7**, have been identified by previous work utilising other oxidative processes [71,73].

The degradation of illicit drugs in wastewater via Fenton and modified Fenton processes has been explored by two studies. They explored the degradation of a range of illicit drugs in wastewater influent and effluent via Fenton (Fe^{2+}/H_2O_2), Fenton-like ($Fe^0/H_2O_2/H_2SO_4$) and ferrate(VI) systems [20,21]. All Fenton systems displayed highly efficient for the degradation of amphetamine, methamphetamine, cocaine, MDMA, codeine and methadone in wastewater influent and effluent with concentrations below limits of detection. Degradation efficiencies were greater than 85 %, except for MDMA (76 %) [21].

4.3.2. *Photo-Fenton systems*

Degradation of methadone via a photo-Fenton system in both distilled water and synthetic wastewater has been reported [95]. Degradation of methadone was very efficient in both water samples with only 4 and 16 min required in distilled and synthetic wastewater, respectively. Five transformation products were identified, (**MTHD 6**, **12**–**15**). Four of which were also identified during the photolysis of methadone, (**MTHD 6**, **12**–**14**).

Cocaine has been studied in a photo-Fenton system in both distilled water and synthetic wastewater [16]. Degradation of cocaine was very effective with only 5 and 25 min required to completely degrade cocaine in distilled and synthetic wastewater, respectively. In a 58 min period in distilled water, 80 % of cocaine was mineralised compared to 70 % in synthetic municipal wastewater after 180 min. Fourteen transformation products were identified. Ten have been previously identified during photolysis (**COC 3**, **8**, **11**, **19**–**25**), and three which were specific to photocatalytic treatment (**COC 28**–**30**). It should be noted a fourth TP was identified as specific to photocatalytic treatment; however, it was identified as an isomer of **COC 25.** No distinction was made between which isomer was specific to photocatalytic treatment and which formed during photolysis.

The degradation of drugs of abuse present in surface waters has been reported using the photo-Fenton process [48]. Multiple illicit drugs were listed as target drugs of abuse, however only MDMA, ephedrine, and methadone were detected in significant quantities in surface waters collected. The study reported that the target drugs of abuse were eliminated below detection limits, however, only reported results of chemical oxygen demand and total organic carbon content before and after photo-Fenton treatment. Further reports of the use of photo-Fenton processes have explored different hydrogen peroxide and iron catalyst loadings to determine the influence of drug degradation in fluvial waters [22]. The iron catalyst chosen for this study was a mesoporous iron catalyst, Fe_2O_3/SBA-15. High removal efficiencies were reported for MDMA (>95 %), cocaine (>98 %) and methadone (98 %) with an iron catalyst loading of 0.1 g/L and 0.6 g/L. It was concluded that H_2O_2 dosage didn't affect the degradation of drugs despite different catalyst loadings.

4.3.3. *Sunlight/chlorine containing compounds*

The combined use of sunlight and chlorine containing compounds to generate hydroxyl radicals as an AOP has only been reported by three studies and only on methadone and ketamine. These studies used simulated sunlight as the irradiation source.

The first study explored the use of sodium hypochlorite as the chlorine source as well as the influence of pH and concentrations of free chlorine on the degradation of methadone [96]. The highest degradation of methadone was observed using the sunlight/free chlorine system with the degradation rate five times higher than that of sunlight alone. Three hours was required to reach a 99 % degradation efficiency in the sunlight/free chlorine system whereas five hours were needed for sunlight photolysis alone. pH was determined to be an important factor during the degradation of methadone with acidic conditions enhancing the degradation rate during the sunlight/free chlorine system. Increasing the chlorine concentration resulted in increased degradation.

Using chloramines has been shown to be less efficient than sodium hypochlorite as a source of chlorine for methadone degradation [97]. The use of sunlight/monochloramine is reported as twice as efficient as sunlight/dichloramine systems. Increased molar ratios of Cl_2/N and more acidic pH enhanced the degradation of methadone, whereas the presence of nitrate in the sunlight/chloramine system slowed the degradation of methadone. The study also reported the formation of NDMA as an oxidation product of methadone. In addition to NDMA, nine TPs were identified, (**MTHD 6**, **13**,**16**–**22**). **MTHD 13** has been reported in a previous photocatalytic study, however identified the hydroxyl group on the other benzene ring [95].

The final study reported the degradation of ketamine in a UV/chlorine system using sodium hypochlorite as the source of chlorine [99]. Under sunlight irradiation after 3 h, 87 % of ketamine was degraded. The hydroxyl radical was believed to be the main reactive species, however the formation of ozone, chlorine dioxide and chlorite later in the process contributed to the degradation of transformation products. Ozone became the dominant reactive species after the depletion of chlorine given its high reactivity toward primary and secondary amines.

4.3.4. *Sunlight/ozonation*

The sunlight/ozonation system has been briefly explored for the degradation of ketamine [99]. While the work was not centred around this system, it was explored as a reactive oxygen species contributing to the degradation of ketamine in the sunlight/chlorine containing compounds system. When ketamine was exposed to ozone in the dark, 44 % was degraded within the first 10 min and when irradiated with sunlight, 84 % degraded within 3 min. Given ketamine contains a secondary amine, an ozone reactive site, degradation without sunlight is expected.

4.3.5. *UV/persulfate*

Degradation of methamphetamine has been reported in UV/persulfate system as well as influential factors including persulfate dosage and pH [49]. Negligible degradation of methamphetamine was observed with persulfate or UV alone after 30 min, however, full degradation was observed with the combined system after 30 min. The degradation rate of methamphetamine was found to be proportional to the persulfate dosage and pH also proved an influential factor as degradation rates were faster under acidic and neutral conditions compared to basic.

4.3.6. *UV/hydrogen peroxide*

The degradation of methamphetamine and ketamine via UV/H_2O_2 has been evaluated including factors affecting degradation such as pH and hydrogen peroxide dosage [50]. Negligible degradation of methamphetamine after 60 min and ketamine after 120 min was observed using UV or H_2O_2 alone. When the combined system was employed, near complete removal of methamphetamine and ketamine was observed in 60 and 120 min respectively. Degradation rates of methamphetamine and ketamine were greater in acidic and neutral pHs due to the greater stability of H_2O_2 at pH 5 and 7.

4.3.7. *Heterogeneous catalyst systems*

Titanium dioxide (TiO_2) and zinc oxide (ZnO) have been identified as useful, low cost and environmentally friendly semiconductors, that upon irradiation with UV in water, produce hydroxyl radicals [139,140]. The use of the UV/TiO_2 and UV/ZnO systems to degrade illicit drugs has been reported by numerous studies.

The complete degradation of cocaine within 29 min using UV/TiO_2 in distilled water has been reported alongside transformation products [16]. This work also evaluated photo-Fenton systems, discussed earlier and found the photo-Fenton system was more effective at cocaine degradation. Mineralisation of cocaine occurred at a slower rate compared to compound transformation with 80 % of the organic content mineralised in distilled water after 3 h and 50 % in synthetic wastewater. Fourteen transformation products were identified, however, no distinction between products of photo-Fenton and UV/TiO_2 systems were made. Transformation products identified are listed above.

Similar work has been reported for the degradation of methadone via UV/TiO_2 in water [95]. Methadone in distilled water was completely degraded in 23 min. Like the cocaine study above, it was compared to photo-Fenton, discussed earlier and photo-Fenton was found to be more efficient. Mineralisation of methadone in distilled water reached 90 % after close to 4 h. Five transformation products were identified, one of which specific to photocatalytic treatment but no distinction between products of photo-Fenton and UV/TiO_2 systems were made. The identified transformation products are listed in Section 4.3.2.

Further investigation of UV/TiO_2 has been conducted for the degradation of methamphetamine, ketamine and morphine while also investigating another UV/photocatalytic system, UV/ZnO [52]. Two types of light sources were also investigated as part of this work including UV lamps and UVLED lamps to determine their possible influence on drug degradation. The UV/TiO_2 system was highly efficient for the degradation of both ketamine, methamphetamine and morphine with complete degradation in 20,10 and 5 min respectively. UV/ZnO were also effective at degradation however required longer run times and higher concentrations. Across all three drugs, UVLED systems were not as efficient, also requiring longer run times for degradation.

Targeted degradation of methamphetamine using the UV/TiO_2 system has been explored, further exploring possible transformation products and influential conditions including catalyst concentration, pH and contaminant concentration [53]. UV-illuminated TiO_2 (0.1 g/L and 0.4 g/L) completely degraded methamphetamine in milli-Q water within 5 min. Complex water matrices hindered degradation, with the rate of methamphetamine degradation slower. Increased degradation was found when pH was increased from 3 to 9, however, degradation decreased at pH 11. Complete mineralisation of methamphetamine was found after 3 h with a TiO_2 loading of 0.1 g/L and pH 5.

Specific degradation of fentanyl has also been explored using UV/TiO_2 and UV/ZnO systems as well as transformation products [75] (the results of direct photolysis of fentanyl by these authors have been discussed above in 4.2 Photodegradation). In the UV/TiO_2 system at the highest catalyst loading (300 mg/L), the half-life was <2 min and complete degradation was achieved in 16 min. For the UV/ZnO system, the half-life was slightly longer at 7 min however only trace amounts of fentanyl remained after 16 min. Across both systems, a total of 26 TPs were identified, seven major products for the TiO_2 system (**FEN 40**–**42**, **50**–**53**) and eight for the ZnO system (**FEN 7**, **40**–**42**, **50**–**53**). The remaining products were detected at trace levels. Fentanyl was also detected in both systems. **FEN 7** has been identified as a TP in chlorination studies and **FEN 40**–**42** were also identified during the photolysis treatment discussed earlier [71,72].

One study has evaluated the use of tungsten doped TiO_2 – SiO_2 in conjunction with simulated sunlight to degrade methamphetamine [51]. Different systems alongside sunlight were explored including TiO_2 (P25), W/TiO_2, TiO_2-SiO_2 and W/TiO_2-SiO_2. Methamphetamine degradation using TiO_2 (P25) alone exhibited poor degradation with only 28 % degraded after 60 min. Doping TiO_2 with tungsten or the addition of SiO_2 increased the degradation to 64 % and 74 %, respectively. However, a combination of all 3 systems culminating in W/TiO_2-SiO_2, performed the best almost completely degrading methamphetamine (99 %) within an hour.

4.3.8. *Sonochemical*

Sonochemical degradation involves the use of ultrasound irradiation alone or in conjunction with other oxidants to further generate hydroxyl radicals to degrade target compounds [138]. Two studies have investigated the degradation of methamphetamine and methamphetamine hydrochloride using sonocatalysis with positive results.

Degradation of methamphetamine has been reported using of Er^{3+}:$Y_3Al_5O_{12}$/WO_3-$KNbO_3$ exploring a range of factors that could impact degradation including mass ratios of WO_3 and $KNbO_3$, irradiation time, catalyst addition time and catalyst recycle times [54]. The optimal ratio of WO_3 to $KNbO_3$ was found to be 0.2:1.0 with the degradation of methamphetamine reaching 69 %. Higher mass ratios of WO_3 were found to inhibit degradation. Longer irradiation times were found to further enhance methamphetamine degradation and catalyst addition amount was also found to influence degradation. In addition, re-using the catalyst still produced moderately effective degradation of methamphetamine with the first use degrading 68 % of methamphetamine and the fourth use degrading 50 %.

A second study investigated the degradation of methamphetamine hydrochloride using the catalyst Er^{3+}:$YAlO_3$/Nb_2O_5 and similar to previous work, explored influential factors [55]. The optimal mass ratio of Er^{3+}:$YAlO_3$ to Nb_2O_5 was found to be 0.15:1 culminating in 82 % of methamphetamine hydrochloride degrading within 5 h. Increasing the ultrasonic power proved to impact degradation with higher wattage enhancing degradation, with the most effective being 700 W. The effect of temperature demonstrated that colder temperatures around 15 °C hindered degradation, and increased temperatures above 55 °C also decreased degradation, with 35 °C found to be optimal. *Re*-using Er^{3+}:$YAlO_3$/Nb_2O_5 found that the degradation efficiency was still quite high with the first use degrading 82 % of methamphetamine hydrochloride and the fifth use degrading 75 %. Finally, three TPs were identified from the degradation of methamphetamine (**ATS 1, 11, 45**).

4.4. *Evaluation of chemical degradation methods*

A number of chemical degradation methods are suitable for application to illicit drug disposal. The drugs studied to date include ATS, cocaine, methadone and fentanyl, and many of the techniques are highly effective under optimised conditions.

Many methods use commercially available oxidants including sodium hypochlorite, ozone, and peroxide-based oxidants, which are widely used as cleaning products and disinfectants as well as drinking and wastewater treatments. Chemicals to quench reactions that use these oxidants (e.g., ascorbic acid or sodium sulfite) are also commercially available. It would appear reasonable, therefore, that chemical methods could be adapted at scale.

Oxidative processes and AOPs have the advantage of short experiment run times (<24 h), which increases that rates at which drugs can be disposed. Under optimised conditions, photodegradation and AOPs exhibit high levels of degradation. Importantly, AOPs can mineralise organic compounds into carbon dioxide, water and ammonia, which eliminates the formation of undesired TPs such as drug precursors. This is a significant advantage for drug disposal as it negates the limitation of additional hazardous waste disposal. AOPs were applicable to a wide range of drugs and can be employed using a variety of conditions. Techniques including O_3/UV, UV/H_2O_2 and O_3/H_2O_2 are currently employed on industrial scales to destroy pollutants including 1,4-dioxane, NDMA and herbicides [141].

The chemical techniques discussed here are associated with some challenges. Chlorinated based oxidants, while effective at degradation, can produce chlorinated TPs. Eighteen chlorinated TPs were identified across all illicit drugs identified and six brominated TPs were identified for fentanyl using sodium bromate. The formation of halogenated TPs can be problematic as they require separate and additional treatment due to the potential for formation of chlorinated dioxin compounds. Some of the identified TPs are also precursors to synthetic illicit drugs, which could pose a challenge to large scale adoption due to legislative protocols. The photodegradation techniques and AOPs can also have high running costs associated due to the use of specialised equipment such as photoreactors which would hinder applicability to jurisdictions without access to current disposal facilities.

5. Biological degradation methods

The methods discussed in this section, together with the associated drugs and evaluations, are presented in Table 9. Biological degradation studies have significant variation between the reported degradation efficiencies, often due to geographical locations, biological, and microbial environments. Such studies have taken place in Australia, Switzerland, United States of America, China, England, Germany, Belgium, Spain, Croatia, Norway, Italy, Sweden, Canada and Slovakia. Consequently, many drugs have variable reported degradation efficiencies.

5.1. *Water treatment methods*

Wastewater treatment plants employ mechanical, chemical and biological processes to remove contaminants from drinking and sewage water. Of relevance to this work are the biological processes of sedimentation, activated sludge, and biofilms [142].

5.1.1. *Wastewater*

While currently not a formal means of drug disposal, wastewater treatment methods can degrade illicit substances. Most attention has been paid to the degradation of ATS, although ketamine and MDPV have also been investigated.

Factors that affect the degradation of ATS in wastewater include microbial activity, sedimentation, exposure to light, and aerobic or anaerobic conditions, with each of these enhancing methamphetamine degradation [56–58]. Sedimentation degraded up to 86 % of amphetamine and 78 % of methamphetamine in a 2 week period [56]. Amphetamine (**ATS 2**) was the only TP of methamphetamine degradation [56,57]. Biological aerobic conditions degraded both MDMA and MDA with the near complete degradation of MDMA in two weeks [57]. MDA (**ATS 3**) was reported as the only TP from the degradation of MDMA.

Ketamine exhibited relatively poor degradation in wastewater with only 22 % degraded under aerobic conditions with simulated daylight irradiation, with norketamine (**NPS 23**) reported as the only TP [58]. MDPV degradation in wastewater experiments focused on the identification of TPs, rather than factors that influence the biodegradation [89]. When MDPV was spiked into wastewater and stirred for 10 days, twelve TPs were observed (**sCAT 41–52**).

Wastewater (WW) and sewage water (SW) are common matrices used for stability testing and provide insight into the behaviour of illicit drugs when stored under a variety of conditions (see Table S4) [143–152].

5.1.2. *Sewage biofilms*

Biofilms are communities of microorganisms that attach to surfaces and are encased in extracellular polymeric substances (organic polymers of microbial origin) [153,154]. Biofilms are prevalent in sewers and contribute to the decomposition of organic compounds. Biofilms from two types of sewers have been examined, gravity sewers (GSs) and rising main (RM) sewers. Gravity sewers contain both aerobic and anaerobic biofilms, while rising main sewers generally contain anaerobic films only [155].

Degradation of cocaine by biofilms can be complicated by the concurrent abiotic process of hydrolysis whereby benzoylecgonine (**COC 10**) and ecgonine methyl ester (**COC 20**) form as the major products [23–25,59]. One study reported enhanced degradation from the addition of biofilm, where up to 60 % degradation was observed in a GS reactor and 45 % in a RM reactor compared to 20 % in a control (i.e. no biofilm) [23]. A second study found that aerobic conditions favoured the degradation of cocaine over anaerobic conditions, ~ 80 % vs ~60 %, respectively [24]. However, the addition of biofilm in a separate study had little impact when spiked into wastewater, with the concentration of cocaine remaining unaffected [26].

Mephedrone can be significantly degraded by biofilms, with multiple studies highlighting its instability under various conditions. Degradation of up to 40 % was observed after 24 h using biofilms in aerobic conditions [59]. Separately, biofilms in wastewater degraded up to 85 % after 24 h under aerobic conditions, whereas 67 % degradation occurred

Table 9
Summary of the degradation efficiency of drugs subjected to biological processes.

Biological process	Drug	Degradation efficiency*			References
		Low	Medium	High	
Water treatment methods					
Wastewater	Methamphetamine		✓		[56–58]
	Amphetamine			✓	
	MDMA			✓	
	MDA			✓	
	Ketamine	✓			[58]
	MDPV		Not quantified		[89]
Biofilm	Cocaine		Variable		[23–26]
	Mephedrone		✓		[24,26,59,67]
	Fentanyl		✓		[25]
	Heroin			✓	[24]
	Methylone		✓		[59,67]
	PMA		✓		[26,59]
	PMMA		Variable		[26,59]
	MDPV		✓		[26,59]
	Methamphetamine	✓			[23,26]
	Amphetamine		Variable		[25,26]
	Methadone			✓	[24,26,67]
	MDMA	✓			[23,26]
	Ketamine		✓		[26,67]
	Methiopropamine		✓		[26]
Activated sludge	Methadone		Variable		[27,28,98]
	Methamphetamine			✓	[27,28,57]
	Amphetamine			✓	
	MDMA			✓	
	MDA		✓		
	Ephedrine	✓			
	Cocaine			✓	[27–29]
	Ketamine		Variable		[27,28]
Soil	Methamphetamine sulfate	✓			[60]
	Phenyl-2-propanone			✓	[60]
	Methamphetamine			✓	[61]
	MDMA			✓	[61]

(*continued on next page*)

Table 9 (*continued*)

Biological process	Drug	Degradation efficiency*			References
		Low	Medium	High	
	Pseudoephedrine			✓	[61]
	N-Formylmethamphetamine			✓	[61]
	1-Benzyl-3-methylnaphthalene			✓	[61]
	1-(1′,4′-cyclohexadienyl)-2-methylaminopropane			✓	[62]
Bacteria	Cocaine			✓	[2,30]
Aquatic plants	Methamphetamine		✓		[63]

* Degradation efficiency is defined as low = 0–15 %, medium = 16–84 %, high = 85–100 %.

under anaerobic conditions [24]. Degradation of up to 67 % was observed in a RM sewer and only 40 % in a GS after 12 h [67]. Other reports indicated that biofilms had little impact on mephedrone degradation indicating that abiotic processes including hydrolysis were responsible for degradation [26]. Three TPs have been reported for the degradation of mephedrone (**sCAT 53** and **54**), including the two structural isomers of **sCAT 53** [59].

Table 9 contains a summary of several other illicit drug studies using biofilms including reported TPs for MDPV (**sCAT 55** and **56**), methylone (**sCAT 57**), PMMA (**ATS 46** and **47**) and PMA (**ATS 48**).

5.1.3. *Activated sludge*

Methadone was degraded by up to 33 % in sludge cultures after 13 days with three TPs identified (**MTHD 6, 16, 23**) [98]. **MTHD 6** has been identified as a TP of methadone using other degradation techniques [91,95,97]. Degradation was enhanced by up to 70 % by the addition of glucose and a further 95 % with nitrogen supplementation after 14 days. Treatment in a wastewater treatment plant during the activated sludge treatment phase degraded up to 40 % of methadone at a plant in England, [27,28] however, 10 % degradation was observed a wastewater treatment plant in Canada (Gatineau, Quebec) [27,28]. It should be noted, samples in England were taken over a 12-month period from seven WWTPs, however, samples in Canada over 4 days in August at one treatment plant.

Amphetamine-type stimulants exhibited moderate degradation in activated sludge. In a targeted study, significant degradation of MDMA, methamphetamine and amphetamine occurred within 24 h, [57] where amphetamine exhibited the fastest degradation, followed by MDMA and then methamphetamine. Single compound analysis confirmed MDA (**ATS 3**) is a TP of MDMA degradation. Monitoring of these compounds in a wastewater treatment plant that used activated sludge demonstrated that amphetamine exhibited the most significant degradation, whereas levels of methamphetamine and MDMA varied [27,28].

The behaviour of cocaine in the presence of activated sludge has been reported in wastewater treatment plant by numerous studies and consistently exhibits moderate to high levels of degradation (70–93 %) [27–29].

5.2. *Soil*

The degradation in soil of two ATS, their precursors and common impurities has been reported in a series of Australian studies [60–62]. Degradation of phenyl-2-propanone (P2P) and methamphetamine sulfate was examined in four soil types over a period of 24 days [60]. P2P exhibited rapid degradation while methamphetamine sulfate was relatively stable. Six TPs were identified from the degradation of P2P (**ATS 37–39, 49–51**). The degradation of methamphetamine, MDMA, pseudoephedrine, *N*-formylmethamphetamine and 1-benzyl-3-methylnaphthalene was explored [61] using three different soils over the course of a year. Pseudoephedrine and MDMA exhibited the greatest rates of degradation of the compounds examined. MDMA exhibited the most extensive degradation in native Australian soil with 0.2 % remaining after 4 months, whereas pseudoephedrine exhibited rapid degradation within 4 weeks in urban and agricultural soil with 0.7 % and 3 % remaining, respectively. *N*-Formylmethamphetamine exhibited moderate degradation, with near complete degradation achieved in urban and native soil after 9 months. Methamphetamine and 1-benzyl-3-methylnaphthalene were more persistent with the most degradation occurring in native soil, with 10–20 % remaining after a year. Degradation of 1-(1′,4′-cyclohexadienyl)-2-methylaminopropane [62] was faster in native Australian soil, with near complete degradation within 5 days. In agricultural soil, complete degradation occurred after 10 days.

5.3. *Bacteria*

A continuous stirred tank bioreactor (CSTBR) and a rotary biological disc reactor (RBDR) containing a mixture of bacteria have been examined for cocaine disposal [2,30]. Using cocaine as the sole carbon source to grow the bacteria, degradation of up to 99.7 % and 99.4 % was observed in the CSTBR and RBDR after 42 h. Benzoic acid (**COC 2**) and benzoylecgonine (**COC 11**) were produced in the first 24 h as TPs of the cocaine degradation, but their concentrations subsequently decreased, presumably consumed by the bacteria or undergoing further degradation.

5.4. *Aquatic plants*

Three aquatic plants, *C. caroliniana, E. naja, L sessiliflora,* and *I. pseudacorus* consumed methamphetamine over periods of 48 and 96 h. *C. caroliniana, E. naja, L sessiliflora* exhibited the greatest removal of methamphetamine ranging between 57 and 75 % [63].

5.5. *Evaluation of biological degradation methods*

The literature describing biological degradation of illicit drugs provides insights into existing industry techniques as well as natural processes that can be applied to the destruction of such drugs. Adaptations of wastewater treatment methods that can effectively degrade illicit drugs would require minimal reconfiguration and additional resources, which is ideal for a drug disposal technique. These methods can be coupled with photodegradation techniques that further enhances degradation, as shown for cocaine [16]. The use of bacteria can also be highly effective with levels of degradation comparable to that of incineration, with the advantage of low maintenance requirements and low energy consumption [30]. Aquatic plants have potential as alternatives to remove illicit drugs from aqueous environments.

Further studies on biological degradation should investigate possible TPs to assess potential hazards associated with their use. Some biological degradation methods have long run times (1–4 weeks for some wastewater treatment methods and 6 to 12 months for soil), which may be unreasonable for large scale drug disposal. The use of bacteria and aquatic plants requires large scale biomass and plants for bulk destruction, which may also be impractical. In addition, these are techniques not currently widely employed in industry, and technology and equipment are generally not in place for large scale drug destruction.

6. Miscellaneous degradation methods

6.1. Gamma irradiation

Gamma rays are a useful source of ionizing radiation that can break chemical bonds in molecules. Degradation studies of amphetamine explored using gamma irradiation coupled with persulfate anions showed that increasing the absorbed dose of gamma irradiation increased the degradation of amphetamine with complete degradation achieved with an absorbed dose of 2.8 kGy [64]. When used in conjunction with persulfate anions, the absorbed dose required to completely degrade amphetamine halved to 1.4 kGy. This was attributed to the formation of sulfate radicals ($SO_4^{\bullet -}$). Mineralisation of amphetamine was also achieved; a dose of 50 kGy mineralised up to 76 % of amphetamine and the same dose coupled with persulfate anions mineralised up to 98 %.

6.2. Evaluation of miscellaneous methods

Gamma irradiation demonstrated high degradation efficiencies and complete mineralisation for amphetamine. Furthermore, this technique is established in decontamination and sterilisation industries. This overcomes the limitation of the formation of undesired TPs and additional waste disposal. Despite these advantages, gamma irradiation is a hazardous process, with associated health risks including tissue and DNA damage [141], and can have quite high running costs and further research is required to assess other classes of illicit drugs.

The degradation of P2P and synthetic cathinones during long term or alkaline storage has also been reported. While not a likely alternative to incineration, the insight into the degradation profile is valuable to understanding the behaviour of illicit drugs and their precursors. When P2P is stored neat in a closed container for 6 months at room temperature, moderate degradation occurs with 25 % of P2P degrading [65]. Nine TPs were detected with seven identified (**ATS 21, 34, 37, 38, 52–54**). Storing samples in methanol and ethyl acetate also hindered degradation with P2P stable for up to 6 months. Degradation of 4-methylmethcathinone, 2-FMC, 3-FMC, 4-FMC, 4-methoxymethcathinone, *N*-ethylcathinone and *N,N*-dimethylcathinone (*N,N*-DMC) has been explored in alkaline conditions (pH 12) [90]. The most extensive degradation was observed for 2-FMC and 3-FMC degrading to less than 2 % after 12 h. In contrast, *N,N*-DMC exhibited minimal degradation, with 96 % remaining. Five TPs were detected and four identified for 4-methylmethcathinone (**sCAT 5, 58–60**). While both require minimal resources and intervention, degradation experiments often requires long run times (6–12 months). Furthermore, illicit drugs stored as salts can be highly stable and unlikely to undergo degradation without additional intervention.

7. Conclusions

In this review, the degradation of illicit drugs was investigated and alternative methods for the disposal of illicit drugs were evaluated. Of the main degradation techniques explored (thermal, chemical, biological and miscellaneous methods), chemical degradation methods show the most promising potential as alternatives to incineration. Chemical oxidative processes utilise commercially available oxidants to which many are already employed in industry. The straightforward nature of oxidation reactions using chlorine- and peroxide-based oxidants could be feasibly used at scale and an option for jurisdictions without access to current disposal methods or to reduce current loads on incineration.

Advanced oxidative processes are a diverse range of systems with potential to completely mineralise illicit drugs, negating the limitations associated with undesired transformation products and also with the advantage of short run times (<24 h). Other feasible techniques include bacterial growth, which can also exhibit high degrees of degradation and with low maintenance requirements and low energy consumption. Gamma irradiation is also a feasible alternative that offers complete mineralisation of the target drug.

However, key operational considerations are required for the implication of these techniques. These include their feasibility for jurisdictions that don't currently have access to proper disposal facilities and whether the incorporation of these techniques would be of net benefit. However, several of the techniques discussed here could be implemented and provide risk management strategies for disposal of drugs in the absence of incineration facilities. Some key factors to consider include:

1. There appears to be is no universal alternative method for drug degradation. Most of the reviewed degradation techniques do not operate effectively for all substances as degradation depends on the chemical and physical characteristics of the illicit drugs and how they interact under given conditions.
2. Most degradation studies have not been conducted on large scales. Bulk degradation is only one aspect of the applicability of the techniques reviewed here but more research would be required for many upscaling applications.
3. There is a greater understanding of the degradation processes of the free-base compounds compared to the corresponding salts. Many illicit drugs are distributed as the salt form of the compound either in pill, powder, or capsule form and seized as such. Many degradation studies, however, have investigated the freebase form of the illicit drugs. The freebase and salts of illicit drugs have different physical and chemical properties and so degradation data will differ.
4. New analogues of drugs are entering the market with different chemical and physical properties compared to the parent compounds and so require individual evaluation of their degradation behaviours. However, heroin, cocaine, methamphetamine and MDMA constitute the vast majority of seized illicit drugs, and the many new illicit substances represent only a small amount by weight.
5. Harmful compounds can be produced from the degradation of illicit drugs. Waste products may not contain the illicit parent drug, however the transformation products may still be toxic. If the transformation products are not illicit, they can be integrated into existing chemical waste procedures using appropriate hazardous waste protocols.

As drug seizures continue to increase, the appropriate disposal of seized drugs after analysis will be a continued effort. Accessible alternatives for drug disposal impact policing and law enforcement agencies globally as seizures continue to increase. It is imperative that further research be conducted into methods that provide accessible and viable alternatives.

CRediT authorship contribution statement

Alexandra L. Mercieca: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Morgan Alonzo:** Writing – review & editing. **Scott Chadwick:** Writing – review & editing. **Andrew M. McDonagh:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization.

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. Supplementary data

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Data availability

No data was used for the research described in the article.

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