Autopsy, thanatopraxy, cemeteries and crematoria as hotspots of toxic organic contaminants in the funeral industry continuum: A hidden health risk or myth?

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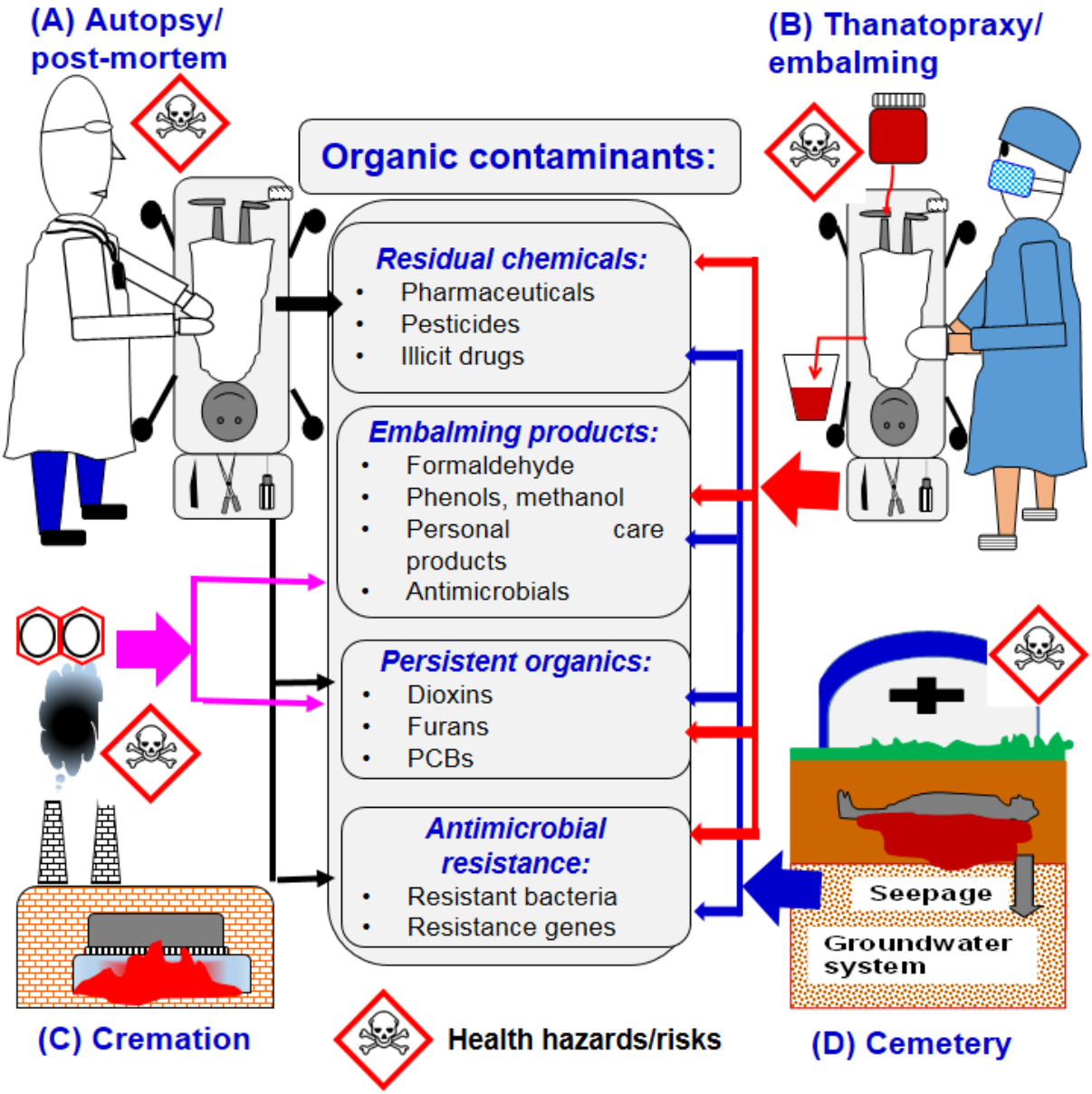
Statement of Novelty

The funeral industry is an under-studied and under-regulated potential hotspot of toxic organic contaminants (TOCs). Yet comprehensive reviews tracking TOCs in the funeral industry are missing. Embalming products, pharmaceuticals, personal care products, pesticides, persistent organics and illicit drugs are detected. Autopsy, thanatopraxy, cemeteries and crematoria are hotspots of TOCs. Health risks of TOCs, and flaws in current evidence and risk assessment protocols are discussed. Risk assessment and mitigation, including regulatory, surveillance and control systems are discussed. Knowledge gaps and emerging tools are highlighted. The findings are comprehensive and significant, hence this review is a potential '*hot*' paper on the topic.

Highlights

- The funeral industry is a hotspot source of toxic organic contaminants (TOCs).
- Yet comprehensive reviews of the occurrence and health risks of TOCs are scarce.
- Drugs, POPs, pesticides, antimicrobials, and embalming chemicals were detected.
- Human exposure, risk factors, health risks, and mitigation measures are discussed.
- Limitations of risk assessment protocols, and future directions are highlighted.

Graphical Abstract



Abstract

The occurrence and health risks of toxic organic contaminants (TOCs) in the funeral industry are relatively under-studied compared to other industries. An increasing body of literature reports TOCs including emerging contaminants in the funeral industry, but comprehensive reviews of the evidence are still lacking. Hence, evidence was analysed to address the proposition that, the funeral industry constitutes several hotspot reservoirs of a wide spectrum of TOCs posing ecological and human health risks. Embalming products, persistent organic pollutants, synthetic pesticides, pharmaceuticals, personal care products and illicit drugs are detected. Human cadavers, solid wastes, wastewaters and air-borne particulates from autopsy, thanatopraxy care facilities (mortuaries, funeral homes), cemeteries and crematoria are hotspots of TOCs. Ingestion of contaminated water, and aquatic and marine foods constitute non-occupational exposure, while occupational exposure occurs via inhalation and dermal intake. Risk factors promoting exposure to TOCs include; unhygienic burial practices, poor solid waste and wastewater disposal, and weak and poorly enforced regulations. The health risks of TOCs are quite diverse, and include; (1) genotoxicity, endocrine disruption, teratogenicity and neurodevelopmental disorders, (2) development of antimicrobial resistance; (3) info-disruption via biomimicry , and (4) disruption of ecosystem functions and trophic interactions. Barring formaldehyde and inferential evidence, the epidemiological studies linking TOCs in the funeral industry to specific health outcomes are scarce. The reasons for the lack of evidence, and limitations of current health risk assessment protocols are discussed. A comprehensive framework for hazard identification, risk assessment and mitigation (HIRAM) in the funeral industry is proposed. The HIRAM includes regulatory, surveillance and control systems such as prevention and removal of TOCs. Future directions on the ecotoxicology of mixtures, behaviour, and health risks of TOCs are highlighted. The opportunities presented by emerging tools, including isotopic labelling, genomics, big data analytics (machine learning, artificial intelligence), and *in silico* techniques in toxicokinetic modelling are highlighted.

Keywords: Embalming products; emerging contaminants; human exposure pathways; mitigation framework; pharmaceuticals; thanatopraxy

1 Introduction

The funeral industry continuum comprising of autopsy, thanatopraxy/embalming, funeral homes, and the subsequent burial of human cadavers in cemeteries, and cremation is a thriving global business. Similar to the health care system, the funeral industry is a putative hotspot reservoir of toxic organic contaminants (TOCs), posing human and ecological health risks. These TOCs include, embalming products from thanatopraxy, synthetic organic pesticides, persistent organic pollutants, and emerging contaminants originating from various sources. Despite being a seemingly obvious pollution hotspot, the occurrence and health risks of TOCs in the funeral industry are relatively under-studied compared to other industries. This is in contrast to substantial literature, including reviews, on the occurrence and health risks of TOCs including emerging contaminants in wastewater treatment systems, health care system, aquatic systems, pharmaceutical industries, and livestock production systems (Gwenzi and Chaukura, 2018; K'oreje et al., 2020; Michael et al., 2020). An earlier review discussed the several reasons accounting for this trend (Gwenzi, 2020). This include the fact that, the funeral industry is

classified under commercial service providers, which are less regulated and monitored compared to other industrial sectors such as the health care system (Davidson and Benjamin, 2006).

An increasing body of literature exists on inorganic, organic and microbial pollution from the funeral industry, particularly cemeteries, and to a less extent, embalming and cremation. Specifically, a number of studies have investigated the following: (1) inorganic contaminants such as metals and nutrients, and organic matter (i.e., COD, BOD) in surface and drainage water from cemeteries (Spongberg and Becks, 2000; Fielder et al., 2012, Fineza et al., 2014; Vaezihir and Mohammadi, 2016), (2) microbial contaminants, including bacteria and viruses, and human pathogens in thanatopraxy and cemeteries (Davidson and Benjamin, 2006; Carstens et al., 2014; Abia et al., 2018). Other studies investigated the occurrence and health risks of formaldehyde in thanatopraxy and cemeteries (Aronson et al., 2004; Zume et al., 2011; Varlet et al., 2019), while others detected persistent organic pollutants such as dioxins and furans in crematoria (Takeda et al., 2000, 2004; Wang et al., 2003). More recently, an increasing number of studies have detected several emerging contaminants, including pharmaceuticals, illicit drugs and personal care products in funeral homes and cemeteries (Paíga and Delerue-Matos, 2016; Fielder et al., 2017; McBean et al., 2018; Kleywegt et al., 2019).

Despite the increasing evidence on the occurrence of a wide spectrum of TOCs in the funeral industry, comprehensive reviews on the subject are still lacking. The few earlier reviews were limited to toxic metals, nutrients, pathogenic and indicator microorganisms (bacteria, viruses) and organic matter in cemeteries (Demiryurek et al., 2002; Oliveira et al., 2013; Żychowski, 2012; Żychowski and Bryndal, 2015. Barring cemeteries, earlier reviews excluded TOCs in other compartments in the funeral industry, specifically, autopsy, thanatopraxy, funeral homes and cremation. In addition, earlier reviews excluded several emerging contaminants recently reported in literature (e.g., Paíga and Delerue-Matos, 2016; Fielder et al., 2017; McBean et al., 2018). This is because until now, such evidence was not available to enable comprehensive reviews on the subject. Therefore, the current review traces the occurrence, behaviour, exposure pathways, risk factors, and health risks of TOCs in the funeral industry (Figure 1).

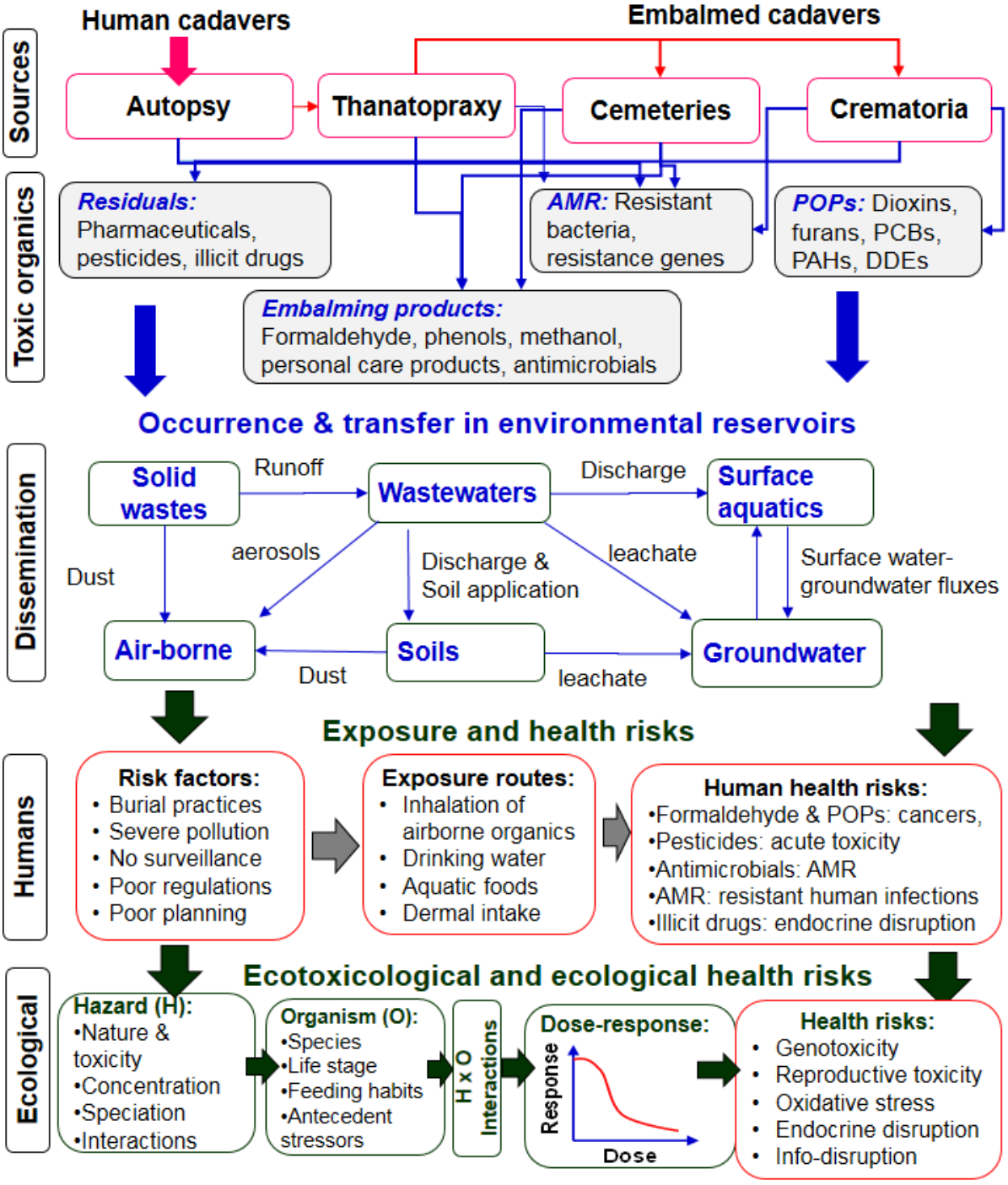


Figure 1. Summary depiction of the nature, occurrence, dissemination and health risks of organic contaminants in the funeral industry and cemeteries.

The review posits that, a wide spectrum of TOCs occur in the funeral industry, and their occurrence, coupled with the various exposure pathways and risk factors, poses significant ecological and human health risks. In summary, compared to the few earlier reviews focusing on

inorganic and microbial contamination in single compartments specifically cemeteries, the current review makes a number of contributions. First, it considers funeral industry as a continuum consisting of autopsy, thanatopraxy in funeral homes, cemeteries and crematoria. Second, it addresses a broad spectrum of TOCs, including embalming products, synthetic organic pesticides, persistent organic pollutants, and emerging contaminants, specifically pharmaceuticals, personal care products and illicit drugs. Exposure pathways and risk factors predisposing human health to TOCs in developing regions particularly Africa are discussed. The weak evidence on health risks, and limitations of existing health risk assessment protocols are highlighted. A comprehensive framework for hazard identification, risk assessment and mitigation (HIRAM), including regulatory, policy, surveillance and control systems is proposed. Finally, future research directions, including knowledge gaps and the need to harness emerging research tools are highlighted.

2 Materials and methods

Literature was retrieved from scholarly databases, including; Clarivate's Web of Science, Scopus®, ResearchGate®, Google Scholar®, ScienceDirect®) and university thesis repositories, among others. The searches were conducted using Boolean search techniques as described in earlier studies (Gwenzi et al., 2017; Gwenzi and Chaukura, 2018). Briefly, to retrieve articles with both the funeral industry and TOCs, the Boolean search technique based on the use of 'AND'/'OR' was used. The search terms used were: 'funeral industry', 'funeral service', 'funeral sector', 'funeral service provider', 'funeral homes', 'embalming', 'morgues' 'funeral parlours', 'thanatopraxy', 'mortuaries', 'autopsy', and 'necropsy'. The other terms used were; 'human cadaver', 'human corpse', 'human dead bodies', 'human remains', 'graves', 'gravesites', 'graveyards', 'burial sites', 'tombs', 'cemeteries', 'cremation' and 'crematorium(s)/crematoria'.

The search terms used for TOCs were: 'organic contaminants', 'emerging contaminants', 'contaminants of emerging concern', 'synthetic organic contaminants', and names of specific groups of TOCs, including; 'embalming fluids/chemicals/products', 'pesticides', 'persistent organic pollutants', 'pharmaceuticals', 'antimicrobials', 'antibiotics', 'anti-retrovirals', 'antifungals', 'disinfectants', 'personal care products', 'drugs', 'therapeutic drugs', 'fragrances', 'perfumes', 'anti-odorants', anticoagulants, and 'penetrating agents'. Literature on TOCs from forensic studies conducted during suicide or homicide post-mortems was also included. The reference lists of relevant articles were also manually searched for additional articles. The retrieved articles were examined, and the key findings on the occurrence and health risks of TOCs were summarized and tabulated (Tables 1 and 2). In the current study, a quantitative analysis based on bibliometric and meta-analytical approaches was not feasible because such analyses require a large dataset which was not available. Thus, given the limited dataset, the current review was limited to qualitative analysis.

3 Occurrence of TOCs in the funeral industry

3.1 The funeral industry as a continuum of TOCs

In the current review, the funeral industry is conceptualized as a continuum of various hotspot compartments of TOCs including autopsy, thanatopraxy/funeral homes, and ultimately cemeteries, and crematoria (Figure 1). On one hand, TOCs such as embalming products, antimicrobials and disinfectants are added at various points along the continuum. On the other

hand, TOCs are released from various reservoirs including human cadavers, solid wastes, body fluids, wastewaters, and air-borne particulates and aerosols. Six broad groups of TOCs were detected: (1) embalming products, (2) pharmaceuticals, (3) personal care products, (4) persistent organic contaminants, (5) synthetic organic pesticides, and (6) illicit drugs (Figure1, Table 1). Human cadavers, solid wastes, wastewaters and air-borne particulates from autopsy, thanatopraxy care facilities, cemeteries and crematoria are the hotspots of TOCs (Figure 1).

Pharmaceuticals and their metabolites occur as residuals from their widespread applications in health care systems and as over-the-counter drugs (Kleywegt et al., 2019). Embalming products, personal care products, disinfectants and antimicrobials originate from autopsy and thanatopraxy care facilities, including mortuaries and funeral homes (Varlet et al., 2019). Synthetic organic pesticides and illicit drugs originate from human cadavers following accidental and deliberate exposures in suicide and homicide cases (Pilgrim et al., 2011). Persistent organic pollutants (POPs) such as dioxins, furans and polychlorinated biphenyls (PCBs) are released during cremation (Takeda et al., 2000, 2004; Mari and Domingo, 2016). Persistent pesticides and their metabolites (e.g., Lindane, DDE) bioaccumulate in fatty tissue (ATSDR, 2019). Hence, they are also released from human bodies via body fluids (e.g., urine), and faecal matter, following long-term exposure (ATSDR, 2019; Kleywegt et al., 2019).

Besides human cadavers, the funeral industry generates solid wastes, wastewaters and airborne particulates and aerosols (Gwenzi, 2020). For example, autopsy, forensic studies and thanatopraxy involve the manipulation and dissection of human cadavers, including sampling of human tissue and body fluids (Nwanyanwu et al., 1989; Davidson and Benjamin, 2006). Aspiration from swollen organs may lead to sudden release of body fluids (Davidson and Benjamin, 2006). Excessive gurgling and frothing through the mouth and noses, and leakage of faecal matter via the anus and dissected gut system may also occur (Creely, 2004; Davidson and Benjamin, 2006).

214 **Table 1**. Summary of conventional and emerging organic contaminants reported in the autopsy, thanatopraxy, cemeteries and crematoria
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Organic contaminants	Nature, concentration and reference	Remarks
A: Embalming products:		
(1) Formaldehyde/formalin	Data from Young et al. (2002) show that: (1) 9 mg/L of formaldehyde reported in water from a cemetery in London, UK. (2) 0.1 L of formaldehyde is leached per human cadaver embalmed. 40 mg/L is expected in leachate in first year, dropping to about 5 mg/L after 10 years.	Formaldehyde originates from embalming fluids and also medium density fibreboard used to make coffins.
	87100 ng/L (median) and 561000 ng/L (maximum) of formaldehyde were reported in embalming wastewater in Ontario, Canada (Kleywegt et al., 2019)	Samples were collected during active embalming.
(2) Triclosan	18000 ng/L (median) and 505000 ng/L (maximum) detected in embalming wastewater in Ontario, Canada (Kleywegt et al., 2019)	Triclosan is used as an antimicrobial in household disinfectants
(3) Methanol, glycol, phenol and glutaraldehyde	These are common chemicals used in varying percentages in various embalming products ((NFDA, 1995)	No data is available on their concentrations in environmental media
B: Persistent organic pollutants (dioxins, furans and PCBs):		
(1) Polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)	Data in crematoria in Japan showed the following results (Takeda et al., 2000, 2014): (1) PCDDs/PCDFs concentrations of 2.2-290 ng/N m^3, giving total equivalents (TEQ) of 0.0099-6.5 ng TEQ/N m^3. (2) Estimated total PCDDs/PCDFs emission was 8.9 gTEQ/year	Concentration data were measured to 10 crematoria, while total emissions were estimated based on all crematoria in Japan. Emissions were highest in the first 20 minutes of cremation.
(2) Polychlorinated biphenyls (PCBs)	16 ng/L (mean) and 290 ng/L (maximum) total PCBs detected in embalming wastewater (Kleywegt et al., 2019)	Samples were collected during active embalming.

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224 **Table 1.** (contd.).

Organic contaminants	Nature, concentration and reference	Remarks
C: Synthetic organic pesticides:		
(1) Methyl parathion	24 ug/mL of methyl parathion detected in post-mortem blood of a 21 year old woman (Tsoukali et al., 2004).	Person died from fatal poisoning by suicide using intravenous injection of methyl-parathion
(2) Imidacloprid [1-(6-chloro-3pyridylmethyl)-N-nitroimidazolidin-2-ylideneamine]	Concentrations (ug/ml) of Imidacloprid detected in post-mortem blood of two males were (Proença et al., 2005): 33-year old: 12.5 (blood), 13.6 (kidney), 9.9 (liver), 20.6 (lung) 66-year old: 2.05 (blood), 2.5 (kidney), 1.01 (kidney), 8.8 (lung)	Imidacloprid was detected using liquid chromatography/mass spectrometry (LC/MS) in post-mortem blood samples from suicide victims in Portugal.
(3) Methomyl (S-methyl-N-[(methylcarbamoyl)oxy]thioacetimidate)	Ranges and (mean) concentration (mg/L) of methomyl, a carbamate pesticide were: Blood: 5.6-63.5 (27.4), vitreous humour: 1.4-7.0, liver 0.1-1.2 (0.6), kidney: 0.2-2.8 (1.2), brain 0.07-0.31 (0.17) (Tsatsakis and Tsakalof, 1996)	Methomyl concentrations were determined in autopsy human material from 8 cases of fatal human poisoning in Crete, Greece.
(4) Lindane	83 ng/L detected in embalming wastewater (Kleywegt et al., 2019)	Lindane is a persistent pesticide long-banned in several countries
(5) pp-DDE (1,1-dichloro-2,2-bis(p-chlorophenyl) ethylene)	11.0 ng/L (mean) and 2300 ng/L (maximum) detected in embalming wastewater (Kleywegt et al., 2019).	DDE is a metabolite of the degradation of DDT, a persistent pesticide long-banned in several countries
D: Personal care products:		
Oxybenzone	227.2 ng/L (median) and 8,160 ng/L (maximum) were detected in embalming wastewater (Kleywegt et al., 2019).	Oxybenzone is commonly used in sunscreens
DEET (N,N-Diethyl-m-toluamide)	53.6 ng/L (mean) and 3,280 ng/L (maximum) were detected in embalming wastewater (Kleywegt et al., 2019).	DEET is a common ingredient in insect repellants.
Nonyl phenol and its metabolites	Median and maximum concentrations (ng/L) of nonyl phenols in embalming wastewaters were (Kleywegt et al., 2019): Med. Max. 4-Nonylphenol 450 14000 4-Nonylphenol Monoethoxylate 230 7200 4-Nonylphenol Diethoxylate 210 5500	Nonyl phenol is used as a surfactant, while Nonylphenol monoethoxylate and -Nonylphenol diethoxylate are its metabolites

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Organic contaminants	Nature, concentration and reference	Remarks
E: Pharmaceuticals and illicit drugs:		
(1) Several therapeutic drugs	Concentration range (mean) of drugs in surface and drainage water samples (Fiedler et al., 2017): *Surface water:* / *Drainage:* Metoprolol: 2230 ng/L / 23 ng/L Carbamazepine: 43–418 (222) / 10–225 (85) Hydrochlorothiazide: Detected / Detected Diclofenac: 129–574 (314) / Not detected Atenolol: 57–301 / Not detected Naproxen: 41-81 / Not detected Ibuprofen: Not detected / Detected	Focused on cemeteries in regions with relatively high consumption of medicines in Germany. 12 pharmaceuticals tested were detected in surface water compared to just 5 in drainage. Concentrations were generally higher in surface than drainage water samples, indicating attenuation/removal in the soil.
(2) Several active pharmaceuticals	Median (med.) and maximum (max.) concentrations (ng/L) were (Kleywegt et al., 2019): Med. / Max. Caffeine: 76650 / 14,200,000 Ketoprofen: 56 / 900 Acetaminophen (paracetamol): 15,520 / 1,720,000 Hydrocortisone: 1,524 / 22,000 Lidocaine: 39.68 / 21,000 Naproxen: 389 / 310,000 Ibuprofen: 286 / 980,000 Ciprofloxacin: 43.6 / 93,000	Wastewater samples collected during active embalming in Ontario, Canada. This is probably the first study to determine emerging contaminants in embalming wastewater. The concentrations are generally higher than those reported for other environmental media in literature.
(3) Several antibiotics	Tetracyclines, Clavulanic acid, Vancomycin, Novobiocin, Butirosine and Neomycin, Streptomycin; Penicillins, Cephalosporins, Ansamysin and 12-, 14- and 16-membered Macrolides (Abia et al., 2019).	Detected on soils from cemeteries in South Africa. Biosynthesis was also observed in the study.
(4) Several drugs	The drugs amitriptyline (1811 pg/g in hair, 29.8 ug/g in liver), nortriptyline (43 pg/g in hair, 3.6 ug/g in liver) and bromazepam (740 pg/g in hair) were detected (Gaillard et al., 2011).	Autopsy was conducted 8 months after death of a one-month old girl due to homicidal poisoning.
(5) MDMA "ecstasy" (3,4-methylenedioxy-methamphetamine)	The concentrations of MDMA detected in post-mortems in Australia were (Pilgrim et al., 2011): 0.02 to 3.5 mg/L. Study based on national database of the National Coroners Information System, Australia.	Other illicit (amphetamines, codeine, cocaine, morphine) and therapeutic drugs (paracetamol, moclobemide) were detected in the order of mg/L.

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232 **Table 1.** (contd.)
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Organic contaminants	Nature, concentration and reference	Remarks
(5) Several illicit and pharmaceutical drugs	Data from 24, 876 forensic autopsies in Sweden detected over 25 drugs and their metabolites in blood (Jones and Homgren 2009). Mean concentrations (mg/L) of the top 10 most common drugs were: ethanol (1430), Acetaminophen/paracetamol (25.5), Citalopram (0.72); Diazepam (0.23), Zopiclone (0.3), Morphine (0.3), codeine (0.32), Tramadol (2.64); Alimemazine (0.54); Dextropropoxyphene (2.0)	Several other illicit drugs and therapeutic drugs were also detected in orders of mg/L. Data are based on analysis done on femoral venous blood samples for forensic purposes.
(6) Cocaine	In 49 autopsy cases covering a period of 11 years cocaine concentration range from 0.01-3.0 mg/L with a median of 0.1 mg/L (Pilgrim et al., 2013). Cocaine metabolites w also detected.	Based data from the National Coroners Information System database for all deaths in Victoria, Australia for 2000 to 2011.

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Subsequent washing, dressing and bagging of cadavers generate solid wastes and wastewaters. Data show that about approximately 13.2 litres of embalming fluid is required to embalm an average adult (Chiapelli and Chiapelli, 2008). Thus, for a country with about 2 million people embalmed each year (e.g., USA), approximately 26.5 million litres of embalming fluid is required. This generate an equivalent or even more amounts of body fluids and wastewaters that are directly released into the on-site sanitation systems, municipal wastewater systems or the environment. TOCs in solid wastes often end up in either sanitary landfills in developed counties or non-sanitary waste dumps in developing countries, where they undergo further dissemination (Figure 2). Human cadavers are ultimately buried in cemeteries or cremated. TOCs in human cadavers can be released into the environment via cadaver slurries and seepages during decomposition (Abia et al., 2018; 2019). Cremation of cadavers releases TOCs as volatiles or in air-borne particulates (Da Cruz et al., 2012). Taken together, the funeral industry is a continuum of several hotspot sources of a wide range of TOCs, including emerging contaminants. Yet despite being a hotspot of TOCs, the funeral industry is relatively under-studied relative to comparative industries such as health care systems (Horton, 2003; Davidson and Benjamin, 2006; Miranda, 2016; Kuchniski et al., 2019). The reasons accounting for this trend are discussed in detail elsewhere (Gwenzi, 2020), and they include: (1) regulatory frameworks that classify funeral industry under commercial service providers, thereby implying low health risk, (2) socio-cultural factors, (3) risk of contracting human infections, (4) Matthew or bandwagon effect, and (5) limited interest by both researchers and funding organization caused by negative perceptions and attitudes.

3.2 Nature and sources of TOCs

3.2.1 Pharmaceuticals

Pharmaceuticals have been reported in soils (Abia et al., 2019), surface water and groundwater from cemeteries (Fiedler et al., 2011; Paíga and Delerue-Matos, 2016), human cadavers (Gaillard et al., 2011), and embalming wastewaters (Kleywegt, 2019) (Table 1). Abia et al. (2019) detected over ten pharmaceuticals in cemetery soils in South Africa, including; Ansamysin, Cephalosporins, Penicillins, Streptomycin, Butirosine, Neomycin, Novobiocin, Vancomycin, Clavulanic acid, Tetracyclines and 12-, 14- and 16-membered Macrolides. In an autopsy of a one-month old girl who died due to homicidal poisoning, the following drugs were detected: (1) Amitriptyline (1811 pg/g in hair, 29.8 ug/g in liver), (2) Nortriptyline (43 pg/g in hair, 3.6 ug/g in liver), and (3) Bromazepam (740 pg/g in hair) (Gaillard et al., 2011).

In cemeteries in Germany, Fielder et al. (2017) showed that five samples contained Hydrochlorothiazide, and one each had Metoprolol (23 ng/L) and traces of Ibuprofen (Fielder et al., 2017). In the same study, eight out of the 12 pharmaceuticals tested were detected in surface water samples compared to just five in drainage water (Table 1). The concentrations were higher in surface than drainage water, as evidenced by Metropolol which had a concentration of 2230 ng/L. The lower concentrations in drainage water relative to surface water point to attenuation or degradation mechanisms in the soil. Carbamazepine was detected in the highest concentration (mean: 225 ng/L) in seven out of the total 12 drainage water samples analysed. Carbamazepine is chemically stable, highly persistent and has a low octanol/water partitioning coefficient (log K_{ow}) of about 2.25 to 2.45 (Jones et al. 2005; Fiedler et al., 2017). Hence, it undergoes limited adsorption onto solid matrix such as soils and sediments in water/wastewater treatment systems and aquatic systems (Löffler et al. 2005; Fatta-Kassinos et al., 2011; Stuart et al., 2012; Fiedler et al., 2017).

For example, concentrations of carbamazepine as high as 3600 ng/L have been reported in groundwater (Stuart et al., 2012), while 42 ng/L was detected in drinking water (Vulliet and Cren-Olive 2011). Due to its persistence and limited adsorption, carbamazepine is often applied as a tracer for anthropogenic contamination in aquatic systems (Clara et al., 2004; Ruzicka et al., 2011).

In Portugal, nonsteroidal anti-inflammatory analgesics (e.g., Salicylic Acid), antibiotics and psychiatric drugs (e.g., Carbamazepine, Fluoxetine, Nimesulide) were investigated in two groundwater samples each from a total of five cemeteries (Paíga and Delerue-Matos, 2016). Salicylic acid, Carbamazepine, Ketoprofen and Ibuprofen were detected in all ten samples. In cases where they were detected, Ibuprofen, Acetaminophen (Paracetamol), Ketoprofen and Sertraline their concentrations were below the method detection limits for the UHPLC−MS/MS triple-quadrupole mass spectrometer (Paíga and Delerue-Matos, 2016). Salicylic acid and carbamazepine were detected in all 10 samples, fluoxetine in 8 samples, while Nimesulide was detected in one sample. The mean (±RSD) concentrations (ng/L) for the four pharmaceuticals decreased in the order: (1) Salicylic Acid: 37.7 ± 4.85 – 71.0 ± 1.48, (2) Carbamazepine: 20.0 ± 0.58 – 23.8 ± 1.91, (3) Nimesulide: 9.24 ± 9.60, and (4) Fluoxetine: 1.90±1.24-1.97±4.79 (Paíga and Delerue-Matos, 2016). Salicylic Acid showed more variation than carbamazepine and fluoxetine.

In Ontario, Canada, high concentrations of pharmaceuticals were detected in embalming wastewater (Kleywegt et al., 2011; Table 1). The concentrations (median; maximum) (ng/L) were: (1) Ketoprofen (56, 900), (2) Acetaminophen (Paracetamol) (15,520; 1,720,000), (3) Hydrocortisone (1,524: 22,000), (4) Lidocaine (39.68; 21,000), (5) Naproxen (389; 310,000), (6) Ibuprofen (286; 980,000) and (7) Ciprofloxacin (43.6; 93,000). To the author's knowledge, this is the first study to investigate pharmaceuticals in embalming wastewater, and the concentrations reported are amongst the highest values reported in literature so far. Pharmaceuticals are generally not persistent in the environment, but are regarded as 'pseudo-persistent' (Ebele et al., 2017). This is because of their continual use and excretion, coupled with their low removal in water/wastewater treatment facilities (Ebele et al., 2017).

3.2.2 Embalming products

Embalming products are complex mixtures of cosmetic products, penetrating agents, anti-coagulants, cleaners, and antimicrobials such as methanol, formaldehyde, glycol, phenol and glutaraldehyde (Kleywegt et al., 2019; Varlet et al., 2019). Embalming products vary considerably in terms of brands and composition with respect to per cent formaldehyde (1-40%), propylene glycol (1-100%) phenol (2-40%), glutaraldehyde (10-30%), methanol (1-100%) and Triclosan (Kleywegt et al., 2018). Formaldehyde, glutaraldehyde and phenol have been detected in occupational settings and in the environment (Aronson et al., 2004; Zume et al., 2011; Kleywegt et al., 2017). For example, 87100 ng/L (median) and 561000 ng/L (maximum) of formaldehyde were detected in embalming wastewater in Ontario, Canada (Kleywegt et al., 2019). In Nigeria, Tume (2011) showed that 57% of groundwater samples close to graves had phenol concentrations (0.1-2.6 mg/L) which were more than 2 orders of magnitude higher than the Nigerian Standard for Drinking Water Quality of 0.001 mg/L.

Due to the toxicity of formaldehyde to both the environment and practitioners, a wide range of synthetic embalming chemicals have been developed and are currently used for thanatopraxy (Waschke et al. 2019; Varlet et al., 2019). A recent review by Varlet et al. (2019) presents over 30 organic formulations for embalming fluids, which are used as alternatives to formaldehyde. Interestingly, some antimicrobials, pharmaceuticals, personal care products and anti-coagulants

are emerging contaminants (Eljarrat et al., 2012; Gwenzi and Chaukura, 2019). Yet besides the few antimicrobials detected so far, data on penetrating agents, anticoagulants, moisturizers and fragrances and dyes used in the new embalming products are lacking (Varlet et al., 2019).

3.2.3 Personal care products

Personal care products include antimicrobials (e.g., triclosan), insect repellents (e.g., N,Ndiethyl-m-toluamide also known as DEET), sunscreen agents such as ultraviolet filters (e.g., oxybenzone) and surfactants (e.g., nonyl phenols), among others (Gros et al., 2008; Kleywegt et al., 2019). Triclosan, DEET, oxybenzone, and nonyl phenols and their metabolites have been detected in wastewater from embalming process (Kleywegt et al., 2017; Table 1). For example, 18000 ng/L (median) and 505000 ng/L (maximum) of triclosan used in both embalming products and personal care products were detected. In the same study, 53.6 ng/L (mean) and 3,280 ng/L (maximum) of DEET were detected (Kleywegt et al., 2019). Nonyl phenols, and their metabolites were also detected with the following concentrations (mean; maximum): Nonylphenol (450; 14000 ng/L), 4-Nonylphenol Monoethoxylate (230; 7200 ng/L), and 4-Nonylphenol Diethoxylate (210; 5500 ng/L). Personal care products are ubiquitous due to their widespread use in household products including; shampoos, lotions, soaps deodorants, detergent, toothpastes and disinfectants and toothpastes (Peck, 2006; Gros et al., 2008). Personal care products are complex mixture of active, non-biodegradable and pseudo-persistent emerging contaminants (Rasheed et al., 2019). Due to their lipophilicity, personal care products tend to bioaccumulate in the fatty tissue (Ebele et al., 2017). In the literature, a diverse range of personal care products is reported including parabens and solvents (Sorensen et al., 2015; Gwenzi and Chaukura, 2018). Moreover, given rapid developments in the field of synthetic chemistry, one may also expect that several personal care products are yet to be documented in literature. Thus, the few groups of personal care products highlighted here only represents a small fraction of a large group of such emerging contaminants.

3.2.4 Synthetic organic pesticides

Pesticides and their metabolites have been detected in embalming wastewaters (Klewegt et al., 2019), and autopsy and forensic studies (Tsoukali et al., 2005; Proença et al., 2005). Lindane, a persistent pesticide was detected with a concentration of 83 ng/L) in embalming wastewater (Kleywegt et al., 2019). 1,1-dichloro-2,2-bis(p-chlorophenyl) ethylene (pp-DDE) was detected in embalming wastewaters with mean and maximum concentrations of 11.0 ng/L and 2300 ng/L, respectively (Kleywegt et al., 2019). DDE is a metabolite of DDT (1,1'-(2,2,2-Trichloroethane-1,1-diyl)bis(4-chlorobenzene), a highly persistent pesticide long-banned in several countries (ATSDR, 2019; Kleywegt et al., 2019). The occurrence of DDE in Canada was highly unexpected because its use was banned nearly 50 years ago in 1972 (Kleywegt et al., 2019). DDE was attributed to high concentrations of DDT in immigrants from developing countries where DDT is still in use to some extent (Kleywegt et al., 2019. Given the persistence and bioaccumulation of DDT and its metabolites (ATSDR, 2019), a possibility also exists that some of the cadavers embalmed at the time of sampling could have been exposed to DDT before its ban in 1972.

Post-mortem and forensic studies have also reported the following pesticides: (1) Methyl parathion (Tsoukalis et al., 2004), (2) 1-(6-chloro-3pyridylmethyl)-N-nitroimidazolidin-2-ylideneamine, commonly known as Imidacloprid (Proença et al., 2005), and (3) S-methyl-N-[(methylcarbamoyl)oxy]thioacetimidate also known as Methomyl (Tsatsakis and Tsakalof, 1996,

Table 1). These three cases involved deliberate fatal poisoning (suicide) through intravenous injection or ingestion. Thus, high concentrations of pesticides in human cadavers and their body fluids, solid wastes and wastewaters may occur in cases of suicide, homicide and accidental intake (Gunnell and Eddleston, 2003; Jones and Homgren, 2009; Pilgrim et al., 2011; Freire and Koifman, 2012). In developing regions including Africa, human deaths and suicides due to fatal exposure to pesticides are prevalent in the agricultural sector (Gunnell and Eddleston, 2003). Yet limited data exist documenting the occurrence and health risks of pesticides in the funeral industry in Africa.

3.2.5 Persistent organic pollutants

Polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and polychlorinated biphenyls (PCBs) are persistent organic pollutants (POPs) formed during the combustion of chlorinated materials such as plastics in prosthetics, body bags, caskets and fuels such as wood containing chlorine (Kuchnicki, 2019). PCDDs, PCDFs and PCBs have been detected in crematoria in several countries, including; China, United Kingdom, the USA and Japan (Wang et al., 2003; Takeda et al., 2000, 2014; Dummer et al., 2003; Guttman et al., 2012; Xue et al., 2016. Table 1). A study based on ten crematoria in Japan reported PCDDs/PCDFs concentrations of 2.2-290 ng/N m^3, giving toxicity equivalents (TEQ) of 0.0099-6.5 ng TEQ/N m^3 (Takeda et al., 2000). In the same study, the estimated total PCDDs/PCDFs emission for all crematoria in Japan was 8.9 gTEQ/year. PCBs have also been detected in concentrations of 16 ng/L (mean) and 290 ng/L (maximum) in embalming wastewater (Kleywegt et al., 2019).

PCDDs, PCDFs and PCBs have long residence times in the environment, hence they undergo global transport over long distances and may have legacy health effects (Sonne et al., 2010; AMAP, 2014). PCDDs, PCDFs and PCBs are lipophilic, hence bioaccumulate in the fatty or lipid tissues of organisms, and undergo biomagnification along the trophic levels (Helgason et al., 2013; Tartu et al., 2017; Kuchniski, 2019). Due to their carcinogenicity and high toxicity, they pose significant health risks (Mari and Domingo, 2010; Kuckniski, 2019). A few reviews exist on health risks of PCDDs/PCDFs in crematoria (Maria and Domingo, 2010; Cheruiyot et al., 2016).

3.2.6 Illicit drugs

Data on illicit drugs are drawn mainly from autopsy and forensic studies (Jones and Homgren, 2009; Pilgrim et al., 2011; Table 1). One exception is a study conducted in Ontario, Canada, where high concentrations of Caffeine were detected in embalming wastewater, with median and maximum values of 76650 ng/L and 4,200,000 ng/L, respectively (Kleywegt et al., 2019). High concentrations of illicit drugs were also reported in post-mortem and forensic studies (Pilgrim et al., 2011). A study based on the national database of the National Coroners Information System in Australia showed that the concentrations of MDMA, also known as ‘Ecstacy’ in post-mortems ranged from 0.02 to 3.5 mg/L. (Pilgrim et al., 2011). In the same study, other illicit drugs detected in concentration ranges of mg/L were; Amphetamines, Codeine, Cocaine and Morphine. A study of 49 autopsy cases covering a period of 11 years in Victoria (Australia) reported Cocaine concentrations ranging from 0.01-3.0 mg/L with a median of 0.1 mg/L (Pilgrim et al., 2013). In Sweden, analysis of 24, 876 forensic autopsies detected several illicit drugs and their metabolites in femoral venous blood samples (Jones and Homgren 2009). Morphine and Codeine were detected with mean concentrations of 0.3 mg/L and codeine 0.32 mg/L, respectively.

Notably, the concentrations of illicit drugs reported here for embalming wastewater and

autopsies are several orders of magnitude higher than the ng/L ranges reported in surface waters and wastewaters (Bones et al., 2007; Zuccato et al., 2005, 2008; Rosi-Marshall et al., 2015). However, the concentrations of several other common illicit drugs remain unknown. Besides autopsy and forensic studies, and embalming, data on the occurrence of illicit drugs in other environmental compartments such as surface and groundwater from cemeteries, solid wastes and air-borne particulates in the funeral industry are also scarce.

3.3 Dissemination, behaviour and fate

Figure 2 presents a generalized summary of the dissemination, behaviour and fate of TOCs in the environment. A detailed discussion of the biogeochemical behaviour of organic contaminants, including emerging contaminants is presented in earlier reviews (Pal et al., 2010; Stuart and Lapworth, 2013; Gwenzi and Chaukura, 2019). Hydrological processes such as erosion, runoff, sub-surface flow, infiltration, recharge, and surface water-groundwater exchanges disseminate TOCs into the environment (Lunenberg et al., 2018; Gwenzi and Chaukura, 2018). TOCs, including volatiles such formaldehyde, disinfectants, perfumes and fragrances can also be disseminated via air-borne particulates, aerosols and gases (Asare-Donkor et al., 2020; Tratnyek et al., 2020). Hence, TOCs may ultimately occur in the atmosphere, terrestrial ecosystems (e.g., soils), surface aquatic systems, groundwater systems, and biota, including humans (Figure 2).

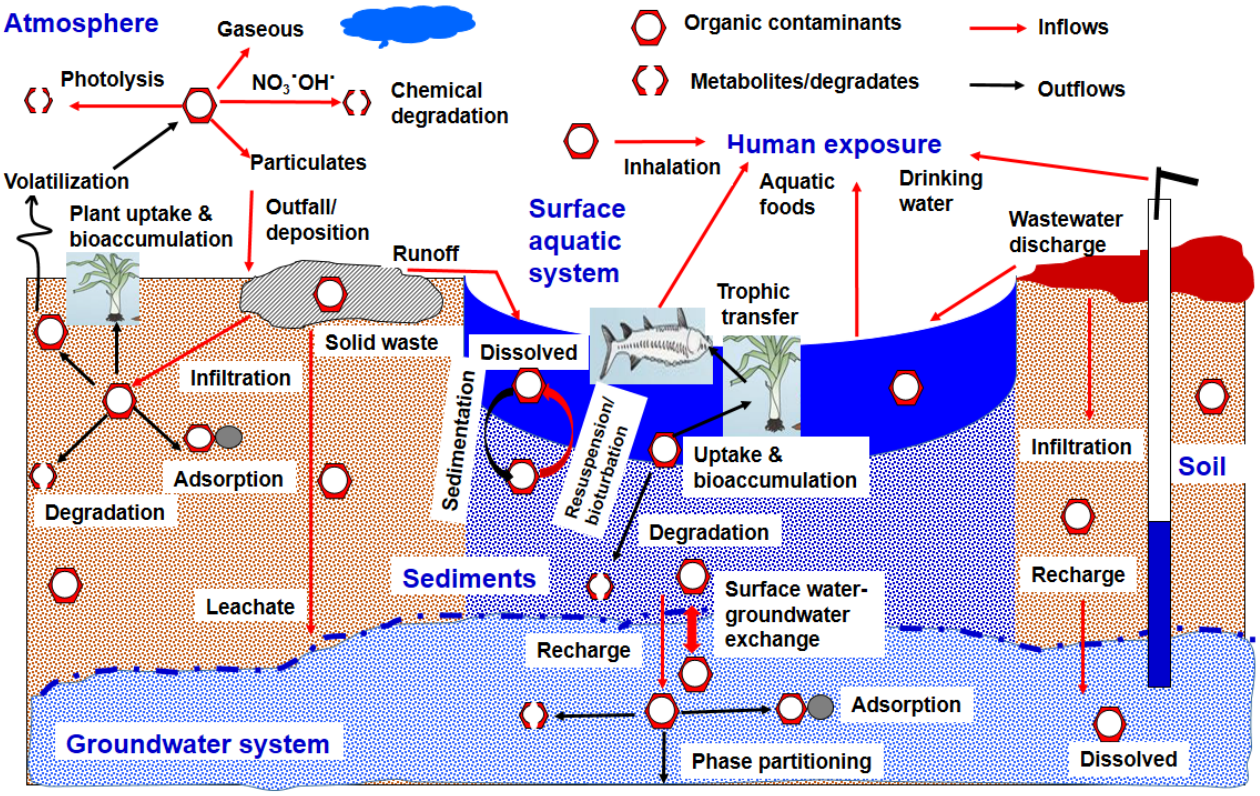

Figure 2. A generalized conceptual depiction of the circulation, behaviour and fate of organic contaminants in the various environmental compartments

TOCs undergo diverse biogeochemical behaviours, (bio)transformation and fate processes (Pal et al., 2010; Lapworth et al., 2012; Stuart and Lapworth, 2013). The behaviour and fate depend on biogeochemical conditions and the physico-chemical properties of the TOCs (Gwenzi and Chaukura, 2018, Figure 2). Physico-chemical properties include; solubility, partitioning coefficients, charge, lipophilicity and molecular diffusion coefficients (Stuart and Lapworth, 2012; Shields et al., 2014). Biogeochemical conditions include redox potential, organic carbon, pH, biochemical processes, and soil type (Shields et al., 2014). TOCs such as formaldehyde and POPs may volatilize and accumulate into the atmosphere where they in turn, undergo partitioning among gaseous, aerosols and adsorbed particulate phases (Figure 2). TOCs in the atmosphere may also undergo photochemical degradation catalysed by OH and NO_3 radicals (Shields et al., 2014).

TOCs in soils undergo phase partitioning between dissolved and adsorbed phases, re-volatilization, biochemical degradation, and uptake and bioaccumulation in biota (Fu et al., 2018; Figure 2). In surface aquatic systems, TOCs may undergo the following processes (Gwenzi and Chaukura, 2018): (1) sedimentation and re-suspension via bio-perturbation in bioactive zones, (2) uptake and bioaccumulation by aquatic biota, (3) adsorption onto sediments, and (3) degradation and re-volatilization in surface water layers (Figure 2). In groundwater systems, TOCs undergo partitioning between bulk and pore water, dissolved and particulate phases, adsorption on the solid matrix of the aquifer, and degradation (Drewes, 2003). However, further research involving the application of partitioning, transport and speciation models is required to understand the long-term behaviour and fate of TOCs especially in tropical environments.

4 Exposure and health risks of TOCs

4.1 Human exposure pathways

Human exposure to TOCs occurs via occupational and non-occupational exposure (Nimmen et al., 2006). High-risk workers include those in autopsy, embalmers, funeral directors, undertakers, grave diggers and cremators (Gwenzi, 2020). Exposure pathways include; (1) dermal intake via bruises, cuts and wounds, and (2) oral route via faecal matter and body fluids during dissection and manipulation of human cadavers (Davidson and Benjamin 2006). Air-borne particulates are reservoirs of TOCs, including personal care products (Shin et al., 2020). Hence, inhalation of air-borne particulates and aerosols may occur in autopsy, thanatopraxy, funeral homes, cemeteries and crematoria. Inhalation is likely to occur for volatile TOCs such as formaldehyde, some pesticides, aerosol antimicrobials and personal care products, and POPs (Takeda et al., 2004; Aronson et al., 2006). Non-occupational exposure occurs via ingestion of contaminated marine/aquatic foods (Llobet et al., 2008; Domingo and Bocio, 2017), and untreated drinking water (Gwenzi, 2020), and inhalation of PCDDs, PCDFs and PCBs for communities living close to crematoria (Takeda, 2000, 2004). Non-occupational exposure may also occur via inhalation of volatile TOCs and dermal contact during body viewing, washing and handling of human cadavers during home care, funerals and burials.

4.2 Risk factors: an African perspective

Earlier studies postulated that exposure and health risks of contaminants could be particularly high in Africa and other developing regions (Gwenzi and Chaukura, 2018; Gwenzi, 2020). The funeral industry is no exception, hence a similar scenario is expected due to several

risk factors. Africa has weak and poorly enforced environmental and occupational health regulations (Loewenson, 1995), and a thriving informal 'black 'market for toxic chemicals (e.g., DDT) and even pharmaceuticals (Schwarzenbach et al., 2006; Rother, 2010). A high vector and disease burden necessitates frequent and widespread use and overuse of pesticides and pharmaceuticals. The disposal of hazardous solid waste in non-engineered waste dumps, and discharge of raw or partially treatment wastewaters into aquatic systems are common (Ali et al., 2017; Angassa et al., 2020). Data on health risk assessments conducted prior to registration and approval of toxic chemicals are scarce, partly because Africa largely relies on imports of chemicals or formulations prepared in developed countries (Gwenzi and Chaukura, 2018). In this regard, evidence on health risks from developed countries is assumed to be valid for the tropical ecosystems in Africa. Rudimentary and unhygienic burial practices are common in some socio-cultural and religious settings (Santarsiero et al., 2000; Zume, 2011; Ringane et al., 2017; Turajo et al., 2019). This includes home burials, where graves are located close to shallow wells and boreholes and even wetlands (Zume, 2011; Abia et al., 2019; Turajo et al., 2019). This poses risks for groundwater contamination via cadaver slurries and leachates (Abia et al., 2019, Figure 2). Yet a significant portion of the population in Africa relies on untreated drinking water from unsafe surface water and shallow groundwater sources (Potgieter et al., 2020). In addition, low literacy levels imply that communities often lack understanding of the health risks of TOCs in the funeral industry. Therefore, understanding the health risks of TOCs in such high-risk regions is critical.

4.3 Human and ecological health effects

The health risks of TOCs depend on: (1) nature, concentration, and speciation of the contaminant, and (2) the receptor organisms, including species, developmental stage and exposure route, and (3) the co-occurrence of antecedent contaminants and health stressors. The health risks of various groups of TOCs detected are presented in Table 2 and several articles (Kümmerer, 2010; Boxall et al., 2012; Stuart et al., 2012; Vandenberg et al., 2012, William and Brooks, 2014; Liu and Wong, 2013; Aronson et al., 2014; ATSDR, 2019; Kuchniski et al., 2019). In summary, the health risks include: (1) endocrine disruption, (2) teratogenicity, (3) carcinogenicity, (4) genotoxicity, (5) developmental toxicity, (6) cell and organ toxicity, (7) disruption of information flow (info-disruption), and (8) behavioural changes (Table 2). However, the health risks are largely based on inferential evidence because data directly relating the occurrence of specific TOCs in the funeral industry to health outcomes are scarce. The only exception is formaldehyde, which has been associated with health outcomes among embalmers (Aronson et al., 2004).

530 **Table 2**. Summary of human and ecological health risks of toxic organic contaminants reported in the funeral industry
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Organic contaminants	Health risks and references	Remarks
A: Embalming products:		
(4) Formaldehyde/formalin	A highly volatile class 1 human carcinogen associated with various types of human cancers (IARC, 2006). Cancers reported in embalmers (Hauptmann et al., 2009; Aronson et al., 2014;	Human health risks high via occupational exposure (e.g., embalmers). Limited data on health effects on soil organisms
(5) Triclosan	Co-selects and promote antimicrobial resistance (Hartmann et al., 2016; Webber et al., 2017).	Data on risks suffers from methodological flaws (Goodman et al., 2018)
(6) Phenol	Acute and chronic toxicity in human and aquatic biota have been reported (Breton et al., 2003; Zhong et al., 2012).	Phenol has a short half-life e.g., 70 hr at pH 5-8.1 temperature 22-28^{o}C
B: Persistent organic pollutants (dioxins, furans and PCBs):		
(3) Polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs),	Carcinogenicity and defective neurodevelopment in infants in Europe and the USA (Arisawa et al., 2005). Disrupt endocrine and reproductive systems in arctic species (Sonne et al., 2017). Reduced testosterone and sperm viability in Arctic foxes (*Vulpes lagopus*) (Sonne et al., 2017). Decreased levels of steroids in polar bears (*Ursus maritimus*) (Gustavson et al., 2015).	Data on other human health effects inconsistent or has lack sufficient statistical power (Arisawa et al., 2005).
C: Synthetic organic pesticides:		
(1) Methyl parathion	Neurotoxic via inhibition of acetylcholine esterase in nervous systems, genotoxic and carcinogenic (Mulla et al., 2020)	Behaviour and health risks discussed in recent reviews (Mulla et al., 2020).
(2) Imidacloprid [1-(6-chloro-3pyridylmethyl)-N-nitroimidazolidin-2-ylideneamine]	Acute toxicities in humans, and oxidative stress causing reproductive disorders including oestrous cycle defects and infertility in terrestrial and aquatic organisms (Arya et al., 2019).	Human fatal toxicities reported in cases of suicide (Proença et al., 2005).
(3) Methomyl (S-methyl-N-[(methylcarbamoyl)oxy]thioacetimidate)	Oxidative stress and acute toxicity reported in humans and biota. Sub-lethal concentrations alter feeding habits, and disrupt endocrine and reproductive system in avians (Arya et al., 2019).	Human health risks such as fatal poisoning associated with suicide (Tsatsakis and Tsakalof, 1996).
(4) Lindane	Highly persistent and toxic, and listed in the Stockholm Convention (http://chm.pops.int/TheConvention/ThePOPs/ListingofPOPs/tabid/2509/Default.aspx)	Banned in most countries, but informal markets exist in developing countries.
(5) pp-DDE (1,1-dichloro-2,2-bis(p-chlorophenyl) ethylene)	Obesity and metabolic disruption via inhibition of electron transport and oxidative phosphorylation (Elmore and La Merrill, 2019). Adverse effects on human sperm and alteration of the sperm Y: X chromosome ratio reported in three European populations and Inuit population In Greenland (Tiido et al., 2006	ATSDR (2019) presents a recent review on health risks of DDT and its metabolites

532 **Table 2** (contd.)
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Organic contaminants	Health risks and references	Remarks
E: Pharmaceuticals and illicit drugs:		
(4) Pharmaceuticals	Promote the development of antimicrobial resistance (Gullberg, 2014). Wide range of health effects reported for various pharmaceuticals drugs (Li et al., 2020; Sathishkumar et al., 2020).	Reviews exist on health risk of pharmaceuticals (Li et al., 2020; Sathishkumar et al., 2020)
(5) Illicit drugs	'Pseudo-persistent due to frequent use. Concentration-dependent acute and chronic toxicities may occur in human and biota (Rosi-Marshall et al., 2015). Aquatic organisms such as bacteria, fish, invertebrates have receptors hence could be sensitive (Rosi-Marshall et al., 2015).	Human health effects including fatalities limited to deliberate intake via drug abuse (Pilgrim et al., 2011). Further research on ecological effects required in high use areas.
F: Personal care products:		
(1) Oxybenzone	Concentration-dependent toxicity and coral bleaching in laboratory studies (Adler and DeLeo, 2020). Malformation, teratogenicity and neurodegenerative effects in tadpoles (*Bufo arabicus*) exposed to 10 ppm (Seleem et al., 2018)	Epidemiological evidence linked to human health outcomes remain weak.
(2) DEET (N,N-Diethyl-m-toluamide)	Ecotoxicological data from China showed that DEET had higher toxicity in aquatic algae than animals (Gao et al., 2020).	Endocrine disruption and neurotoxicity reported in other personal care products (Shin et al., 2019).
(3) Nonyl phenol and its metabolites	Endocrine disruption via sex steroid hormone receptors and conversion of testosterone to oestrogen. They also act as info-disruptors (Kuzikova et al., 2019).	Several personal care products cause infor-disruption (Parrish et al., 2019)

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4.3.1 Pharmaceuticals

Pharmaceuticals cause a wide range of ecological health effects (Li et al., 2020; Sathishkumar et al., 2020, Table 2). The development of antimicrobial resistance is the most cited health risk of pharmaceuticals and their metabolites (Hughes and Andersson, 2012). Pharmaceuticals have low ecotoxicological thresholds, and can induce adverse health effects even at low concentrations (e.g., ng/L) (Paredes et al., 2014). This is because pharmaceuticals are designed to have therapeutic effects even at low doses (Paredes et al., 2014). Hence, even sub-lethal concentrations induce antimicrobial resistance in susceptible organisms (Hughes and Andersson, 2012; Jutkina et al., 2016). Antimicrobial resistance increases pathogenicity and promote outbreaks of antimicrobial resistant infections. For example, Aspirin, Ibuprofein and Diclofenac induce bacterial resistance to antibiotics, and sterility and feminization in aquatic animals (Agunbiade and Moodley, 2014). Some pharmaceuticals are endocrine disruptors that alter the hormonal system via blocking and biomimicry (Bolong et al., 2009). Disruption of trophic interactions and chemical information flows (info-disruption) have been reported in aquatic systems (Van Donk et al., 2016).

Studies have investigated the health risks of human exposure to pharmaceuticals via aquatic and marine foods, drinking water, and air-bone particulates. Results for the period up to 2010 concluded that human exposure to pharmaceuticals via these exposure pathways posed low to no appreciable human health risks (Schulman et al., 2002; Webb et al., 2003; Fent et al., 2006; Nimmen et al., 2006; Kummerer, 2008; Bottoni et al., 2010; Kumar et al., 2010). Subsequent studies covering the period from 2011 to 2019 confirmed the previous findings, and concluded that there is no or low risk to human health for all age groups (Houtman et al., 2014; Prosser and Sibley, 2015; Paltiel et al., 2016; Li et al., 2017; Tomasi et al., 2017; Brown et al., 2018; Fantuzzi et al., 2018; Semerjian et al., 2018; Kibuye et al., 2019; Letsinger and Kay, 2019; Praveena et al., 2019; Sharma et al., 2019). The only exceptions are a few studies suggesting health risks in children and infants consuming crops or tap water contaminated with pharmaceuticals (Leung et al., 2013; Malchi et al., 2014). These conclusions are consistent with that of the WHO (2012), who concluded that no adverse human health effects exist due to chronic exposure to pharmaceuticals in drinking water. Other authors are more cautious: Kümmerer (2010) concluded that the short-term effects of pharmaceuticals in humans are not known, while Tourand et al. (2011) concluded that no consensus exists on the topic.

However, current evidence on human health risks has several inherent limitations and assumptions (***Section 4.4***). For example, only single exposure routes to parent pharmaceuticals were considered, while multiple co-exposures and equally toxic metabolites were excluded. Interactions among pharmaceuticals, and other health stressors were not considered. Literature is also silent on the health risks associated with long-term human exposure to sub-lethal concentrations, yet pharmaceuticals are pseudo-persistent. The bulk of studies on human health risks were limited to developed countries (Tomasi et al., 2016; Brown et al., 2019), while no evidence exists in developing regions including Africa. Yet the occurrence and health risks of pharmaceuticals in the environment is global concern (Kurster and Adler, 2014).

4.3.2 Embalming products

Formaldehyde and phenols are well-known human carcinogens (IARC, 2006; Table 2). Significant associations have been established between formaldehyde exposure and high

incidences of certain cancers among embalmers (Hauptmann et al., 2009; Aronson et al., 2014). A review of retrospective studies investigating the association between formaldehyde and teratogenicity or adverse developmental and reproductive effects showed that women exposure to formaldehyde increased the risk of incidences of spontaneous abortion (Duong et al., 2011). Acute and chronic human toxicity due to phenol exposure also occur (Breton et al., 2003). A case-control study of a glutaraldehyde-based organic glue suggest that glutaraldehyde may induce intense inflammation, causing wounds to breach, thereby promoting the proliferation and spreading of bacteria (Gaberel et al., 2011).

The ecological effects of formaldehyde and phenol include acute and chronic toxicity (Breton et al., 2003; Zhong et al., 2012). Phenol and its metabolites cause endocrine disruption in terrestrial and aquatic animals (Breton et al., 2003; Zhong et al., 2012). Phenol toxicity depends on the developmental stage of the receptor organisms. The embryo-larval stage is the most sensitive in fish such as rainbow trout (*Oncorhynchus mykiss*), and amphibians such as leopard frog (*Rana pipiens*) (Breton et al., 2003). However, the health risks of other TOCs in embalming products such as penetrating agents, moisturizers and anti-coagulants remain unknown.

4.3.3 Personal care products

Compared to other personal care products in the funeral industry, Triclosan is one of the most studied with respect to human health risks, but the results are mixed (Clayton et al., 2011; Savage et al., 2011; Cullinan et al., 2012; Aronson et al., 2014). On one hand, oral exposure to Triclosan reduced the concentration of serum thyroid hormone in test animals (Aronson et al., 2014). This is because the structure of Triclosan shares some similarities with thyroid hormones. On the other hand, a controlled randomized study of 132 subjects including a placebo showed no significant differences in thyroid function and antithyroid antibodies between the control groups and those exposed to a toothpaste containing 0.3% triclosan for a year (Cullinan et al., 2012). Savage et al. (2011) investigated a case study of a 50-year old kitchen worker, who used a Triclosan-containing aerosol disinfectant. The subject had developed adverse health conditions including persistent facial eruptions, gross periorbital edema, facial erythema and pruritus, which showed irregular appearance and clearing, and often involved the chest, upper shoulders and neck (Savage et al., 2011. Results of patch tests using a baseline (control), facial and hair-dressing formulations showed a positive reaction to 2% Triclosan in the petrolatum (Savage et al., 2011). In USA, a study analysed national data obtained from the National Health and Nutrition Examination Survey for the period 2003 to 2006 (Clayton et al., 2011). The results showed that higher urinary concentrations of triclosan were significantly associated with increased incidences of allergies such as hay fever (Clayton et al., 2011). Other studies show that Triclosan co-selects and promotes antimicrobial resistance (Hartmann et al., 2016; Webber et al., 2017), but studies investigating this aspect in humans are still lacking.

Table 2 presents the ecological health risks of the detected personal care products. Oxybenzone caused concentration-dependent toxicity and coral bleaching in laboratory studies (Adler and DeLeo, 2020). Malformation, teratogenicity and neurodegenerative effects were reported in tadpoles (*Bufo arabicus*) exposed to 10 ppm (Seleem et al., 2018). Ecotoxicological data from China showed that DEET had adverse toxicity on aquatic organisms, and the toxicity effects were higher in aquatic algae than animals (Gao et al., 2020). Endocrine disruption via sex steroid hormone receptors and conversion of testosterone to oestrogen have been observed for nonyl phenol and its metabolites. Several personal care products are info-disruptors via

biomimicry of natural info-chemicals such as pheromones (Kuzikova et al., 2019). Info-disruption may alter reproductive behaviour and trophic interactions. Further research is required to understand the health risks of other personal care products commonly used in the funeral industry.

4.3.4 Synthetic organic pesticides

Post-mortem and forensic studies report the acute and chronic toxicity, and human fatalities caused by synthetic organic pesticides including organophosphates and carbamates (Tsatsakis and Tsakalof 1996; Proenca et al., 2005; Table 2). Organophosphates such as Methyl Parathion are genotoxic, carcinogenic and neurotoxic due to their ability to inhibit acetylcholine esterase in nervous systems (Mulla et al., 2020). Genotoxicity via sperm chromatin alteration and DNA damage caused by oxidative stress have been reported (Salazar-Arredondo et al., 2008). Imidacloprid and Methomyl cause acute toxicity, oxidative stress and reproductive disorders including oestrous cycle defects (Proenca et al., 2005; Arya et al., 2019). DDE causes fertility disorders, including the alteration of the sperm Y: X chromosome ratio (Tiido et al., 2006; Taylor et al., 2007; Dallaire et al., 2008; Elmore and Merrill, 2019).

The ecological health risks of pesticides is one of the most studied among TOCs (Table 2). Concentration-dependent chronic and acute toxicity of DDE, including tremors with death, reproductive disorders (e.g. reduced fertility), neurodevelopmental changes, and endocrine disruption (ATSDR, 2019) have been reported in animals (ATSDR, 2019). Imidacloprid, Methyl Parathion and Methomyl cause reproductive disorders, endocrine disruption and oxidative stress in a number of avian and animal species (Arya et al., 2019; Mulla et al., 2020, Table 2). For example, sub-lethal concentrations of Methomyl alter feeding habits, and disrupt endocrine and reproductive system in avian and aquatic species (Arya et al., 2019).

Besides post-mortem and forensic studies, the health risk of pesticides in the funeral industry have received limited research attention. The notion that homicide and suicide cases are relatively rare compared to natural deaths due to infectious diseases may explain this trend. However, data show that homicide and suicide cases are prevalent in developing countries with a thriving agricultural sector (Gunnell and Eddleston, 2003). Further research is needed to understand the occupational and non-occupational health risks of pesticides in the funeral industry.

4.3.5 Persistent organic pollutants

PCDDs, PCDFs and PCBs have been detected in human foods including meat and edible aquatic and marine foods including fish, ambient air and air-borne particulates (Libet et al., 2008; Domingo and Bocio, 2017). Hence, human exposure occurs via: (1) ingestion or dietary intake of contaminated marine and aquatic foods, and (2) inhalation of air-borne particle such as soot and dust (Libet et al., 2008; Domingo and Bocio, 2017). PCDDS, PCDFs and PCBs pose carcinogenic or cancer risks in humans (Xu et al., 2020), and adverse human health risks have been reported in terms of pregnancy outcomes (Dummer et al., 2003). Human exposure to PCDDs and PCDFs has been linked to defective neurodevelopment in infants in Europe and the USA (Arisawa et al., 2005). One study showed that PCDD/PCDF concentrations of 7.00–215 pg/g in soils from point sources such as smelters may result in cancer risks of 0.487×10^{-6} (Xu et al., 2020).

The occurrence and health risks of PCDDs, PCDFs and PCBs have been detected in terrestrial and aquatic biota including avian, aquatic and marine species (Dallaire et al., 2006, Kwon et al., 2019; Lehikoinene et al., 2019, Table 2). Studies have reported the adverse health

effects of dioxins and furans on reproductive and hormonal systems in Arctic polar bears (*Ursus maritimus*), Arctic foxes (*Alopex lagopus*, *Vulpes lagopus*) and sled dogs (*Canis lupus familiaris*) (Gustavson et al., 2015; Muijten et al., 2016; Riget et al., 2016, 2019; Sone et al., 2017). In these species, POPs reduced testosterone and sperm viability in Arctic foxes (*Vulpes lagopus*) (Sonne et al., 2017), and concentration of circulating steroids in female polar bears (*Ursus maritimus*) (Gustavson et al., 2015).

Data on the health effects on species occurring tropical ecosystems in tropical environments particularly in Africa remain limited. Further research is also required to determine the occurrence of PCDDS, PCDFs and PDBS in human media such as hair, nails and body fluids among crematorium workers and surrounding communities. Particular attention should be paid to female workers in the cremation industry and their children due to the potential risk of transfer of POPs from mothers to their unborn fetuses and infants.

4.3.6 Illicit drugs

Evidence on human health risks of illicit drugs is limited to acute and chronic toxicity, and fatalities due to drug abuse (Pilgrim et al., 2011). Illicit drugs induce behavioural and physiological changes in humans (Rosi-Marshall et al., 2015). Illicit drugs containing plant-derived alkaloids may have antimicrobial properties (Radulovic et al., 2013), hence oral intake of such drugs may alter the microbial diversity and function in the human mouth and gut. For example, significant differences in microbial diversity were observed between humans chewing *khat*, a plant containing stimulants resembling monamine amphetamine compared to non-khat chewers (control) (Al-Hebshi et al., 2010). However, it is currently unclear whether human exposure to environmentally relevant concentrations of illicit drugs via inhalation and ingestion cause adverse health effects.

The ecological health risks of illicit drugs have been reported in a number of studies, including reviews (Binelli et al., 2012; Parolini and Binelli, 2013, 2014; Rosi-Marshall et al., 2015). Aquatic organisms such as bacteria, fish and invertebrates have receptors that make them sensitive to illicit drugs (Rosi-Marshall et al., 2015). The antimicrobial properties of some illicit drugs have been reported to disrupt microbial community composition and function (Radulovic et al., 2013). Amphetamines disrupt catecholamine production and reception in mammals and algae, thereby disrupting ecological function and interactions (Rosi-Marshall et al., 2015). Exposing zebra mussel, an aquatic organism to Cocaine, and its metabolites at environmentally relevant concentrations caused adverse physiological and genotoxicity effects including DNA damage via oxidative stress (Binelli et al., 2012; Parolini and Binelli, 2013, 2014: Parolini et al., 2013). However, current evidence on ecological health risks only cover a few illicit drugs and species, while a large number of other illicit drugs and species remain under-studied. Thus, the health effects of illicit drugs require further investigation.

4.4 Health risks: A critique of the evidence and approaches

The current review posed the question whether TOCs in the funeral industry constitute a health risk or is a myth. The preceding discussion (***Section 4.3***), in conjunction with the occurrence of TOCs (Table 1) and their health risks (Table 2) partly addressed this question. However, barring formaldehyde exposure linked to health outcomes among embalmers (Aronson et al., 2006; Hauptmann et al., 2009, limited evidence exists linking TOCs in the funeral industry to health outcomes. This reflects the fact that, linking the occurrence of TOCs in environmental media to

health risks is not a trivial task. Yet the lack of evidence may be misinterpreted as lack of health risks, thereby creating a technical loophole that can be exploited by unscrupulous players in the chemical industry. The lack of direct evidence is not unique to TOCs in the funeral industry, but is generic to other contaminants and industries, including antimicrobial resistance in drinking water systems (Sanyangando and Gwenzi, 2019). Here, a few generic limitations and challenges are highlighted to illustrate the difficulties and complexity of assessing health risks of TOCs.

4.4.1 Methodological limitations

Methodological limitations, inconsistencies among results and lack of sufficient statistical power partly account for the lack of evidence. One study is illustrative in this regard: Arisawa et al. (2005) reviewed global epidemiological studies linking human intake of dioxins, furans and PCBs to diabetes mellitus, endometriosis, thyroid function and neurodevelopmental of infants. Consistent results were only observed for neurodevelopmental disorders in infants which were linked to human exposure to background concentrations of dioxins/PCBs. However, the association between human exposure to dioxins, furans and PCBs, and diabetes, endometriosis and thyroid function could not be established. This was due to: (1) lack longitudinal studies in the case of diabetes, (2) inconsistent results for thyroid function, and (3) insufficient statistical power for endometriosis. Other limitations include the use of methods that do not allow direct or quantitative estimation of health risks. The bulk of studies merely reporting occurrence of TOCs (e.g., Fielder et al., 2017; Kleywegt et al., 2019) without the corresponding data on bioaccesibility, bioavailability and intake by target organisms fall under this category. In such cases, occurrence is often misinterpreted as synonymous with adverse health effects. Some studies (e.g., case reports) often lack proper statistical experimental design and data analysis, while others may lack sufficient statistical power because of low sample size or limited replication. Hence, drawing definitive conclusions from such studies could be problematic, and may even lead to misleading interpretations. Therefore, future research should address these methodological flaws in existing literature, and quantitatively determine the health risks of TOCs.

4.4.2 The paradox of contaminant mixtures

Health risk assessment protocols largely rely on *in vitro* and *in vivo* bioassay experiments (e.g., EC, 2006; OECD, 2015; US EPA, 2020a, b). This often involves exposing target bioassay organisms to a single chemical at a given concentration via a specific exposure, followed by qualitative or quantitative estimation of risk (Linov et al., 2001). Such bioassay tests often use 'benign' media spiked with target contaminants (OECD, 2015; EC, 2006), while excluding interactions and health effects of antecedent contaminants and health stressors. In real systems, receptor organisms including humans are simultaneously exposed to a plethora of TOCs and co-occurring health stressors at various levels via multiple exposure routes. Co-exposure to mixtures of TOCs, and health stressors change the exposure scenario, resulting in complex dose-response behaviours. Such complex interactions include additive, antagonistic, neutral and synergistic health effects (Carvalho et al., 2014; Oskarsson et al., 2014; Chen et al., 2017; Parrish et al., 2019).

Chen et al. (2017) showed that, depending on specific toxicological endpoints, synergistic and antagonistic interactions between Pb and decabromodiphenyl ether occurred concurrently. A study involving 16 laboratories in Europe investigated the effects of mixtures of 14 or 19 chemicals drawn from various groups using 35 bioassay tests involving 11 organisms from various trophic

levels (Carvalho et al., 2014). The concentrations of all chemicals tested were set at the safety limits prescribed by the European Community regulations. Adverse health effects of mixtures were observed, including microalgae toxicity, fish embryo toxicity, embryo developmental toxicity and oxidative stress (Carvallo et al., 2014). In a binary mixture of two fungicides (Prochloraz, Azoxystrobin), the no-observed-effect concentration of Prochloraz reduced the median effect concentration of azoxystrobin in *Hyalella Azteca* and *Gammarus pulex*) (Fu et al., 2018).

The health risks of mixtures pose potential regulatory and research challenges. First, each single synthetic chemical is designed to have a particular effect/s at a particular dose. Therefore, although health risks of mixtures are closer to reality than single contaminants, it will be problematic to base regulatory approval decisions on data considering the health effects of a suite of contaminants. The mechanisms of how the interactions among TOCs, and with antecedent contaminants and health stressors increase toxicity remain unclear. In addition, whether or not individuals, populations, communities and ecosystems co-exposed to mixtures of TOCs and other health stressors exhibit physiological and phenotypic plasticity is poorly understood. A few studies suggest that, some organisms may exhibit phenotypic plasticity in response to health stressors such as those induced by climate change (Whiteman et al., 2018). Assuming that such ecological plasticity occurs, there is need to understand the concentration ranges over which plasticity occurs, beyond which the onset of adverse effects are expected. Further, Hayes et al. (2006) conjectured that, contaminants in mixtures may act as effectors, enhancers or even as neutrals. Therefore, it is equally important to determine the role of individual contaminants in mixtures of TOCs.

4.4.3 Trans-generational, delayed and legacy effects

Persistent and pseudo-persistent contaminants may also have trans-generational, delayed and legacy health effects, which may not be detected in typical short-term ecotoxicological studies (Tiido et al., 2006; Chen et al., 2017; Letcher et al., 2018). The developmental origins of health and disease (DOHaD) concept suggests that human exposure to contaminants may lead to inter-generational health effects (Lønnebotn et al., 2018; Miller and Lawrence, 2018). Thus, pre-conception and early childhood exposure to TOCs may later determine human health outcomes as reported for obesity, asthma and neurodevelopmental disorders (Lønnebotn et al., 2018; Miller and Lawrence, 2018). The DOHaD concept could be relevant to persistent organic pollutants (dioxins, furans, PCBs) and pesticides (e.g., DDT, DDE) (Dallaire et al., 2008; Tiido et al., 2006). Tiido et al. (2006) report trans-generational effects of DDE on fertility, including the alteration of the sperm Y: X chromosome ratio in three European populations and Inuit population (Table 2). Therefore, inter-generational, delayed and legacy health effects of TOCs warrant further research.

4.4.4 ‘Priority contaminants and the ‘equifinality’ concept

There is an increasing interest to develop and use ‘lists of priority contaminants’ for environmental surveillance and control systems (Bottoni et al., 2010; Li et al., 2020). Priority lists may create an unjustified reification, a phenomenon whereby concepts, in this case the use of ‘lists of priority contaminants’ become increasingly interpreted as scientific facts (Posthuma et .al, 2018). Besides influencing research funding decisions and choice of contaminants to monitor, reification may lead to type I and II errors (Hyman, 2010; Posthuma et al., 2018). Type I errors occur when misinterpretation of risk triggers implementation of mitigation measures, when in fact, the risk is not related to true ecological or human health impacts (Prato et al. 2014). Type II errors,

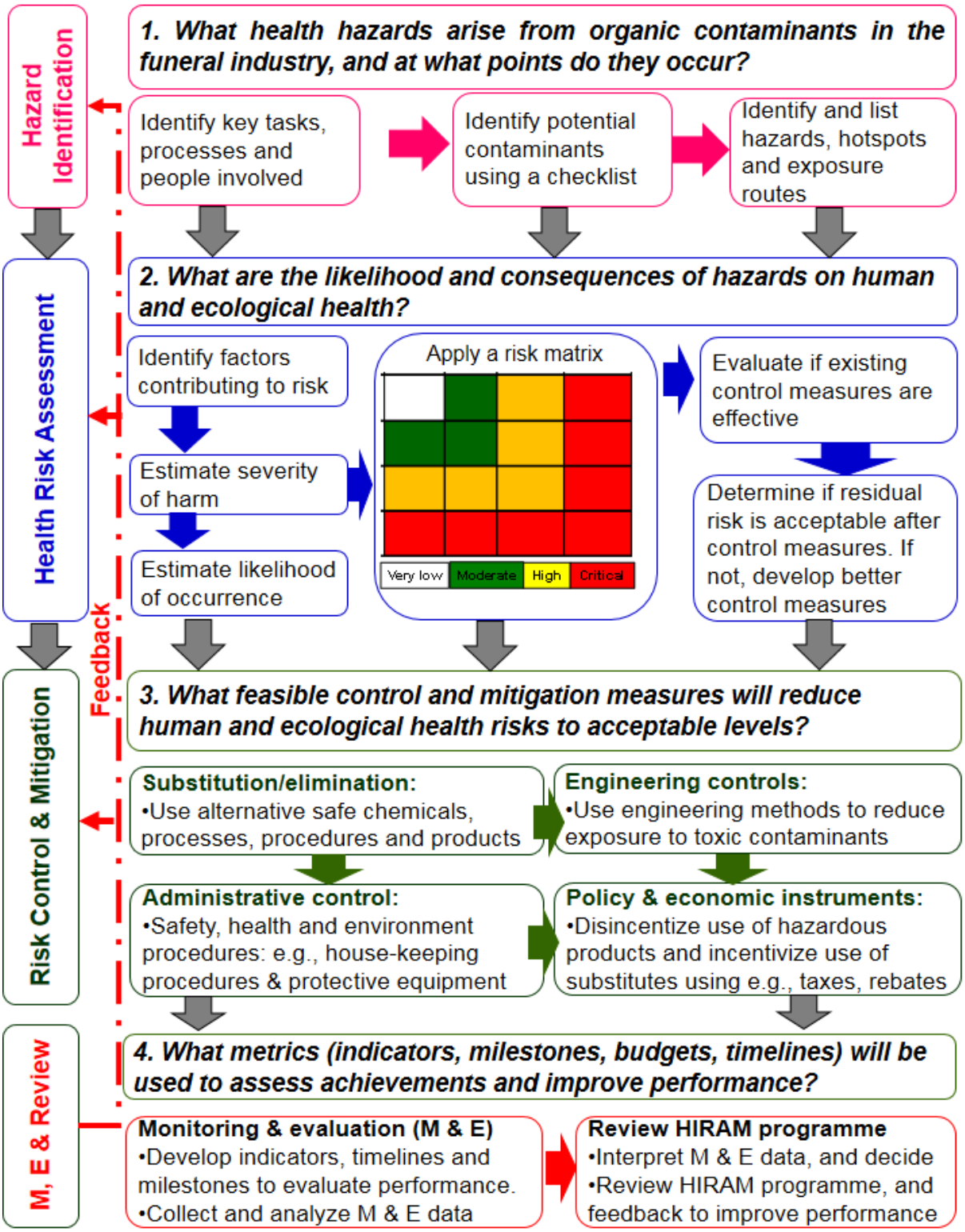
occur when the health risks of several TOCs and their interactions in mixtures, and other health stressors are unknown or neglected due imperfect knowledge caused by limitations of current scientific methods. This is particularly the case for most emerging contaminants and their mixtures, because their modes of action are still poorly understood.

Table 2 shows that several POPs, pharmaceuticals, and personal care products are carcinogens, endocrine disruptors and info-disruptors. Thus, several TOCs may result in similar health outcomes (Aronson et al., 2006; Rosi-Marshall et al., 2014). This phenomenon can be summed up as the 'equifinality' concept, a term borrowed from the science of complex systems (Aron, 2020). In the current context, the 'equifinality' concept implies that co-occurring TOCs may not necessarily result in unique health outcomes. Instead, a single health outcome may arise from several plausible TOCs. The 'equifinality' concept implies that, using conventional tools in (eco)toxicology to partition the health effects among several co-existing TOCs presents methodological challenges. Taken together, the concepts of 'equifinality' and the 'priority contaminants' imply that, for contaminants with the same health effects, some may appear in the 'priority lists' while others are excluded, hence they will be regulated differently. It is currently unclear how type I and II errors, and the 'equifinality' concept are addressed in current health risk assessment protocols.

5 Assessment and mitigation of health risks

5.1 A framework for health risk assessment and mitigation

The overall goal of risk assessment and mitigation is to ensure that the health risks are understood, communicated and mitigated to unacceptable levels. Figure 3 depicts a framework for hazard identification, risk assessment, and mitigation (HIRAM). The HIRAM comprises of four key steps: (1) hazard identification, (2) risk assessment, (3) risk mitigation and control, and (4) monitoring and evaluation (M &E), and subsequent feedback. The key questions to guide each step, and typical activities to be undertaken are also highlighted.



841
842 **Figure 3**. A conceptual framework for hazard identification, risk assessment and mitigation
843 (HRAM) in the funeral industry.

5.1.1 Hazard identification

This step characterizes the hazards posed by TOCs in key tasks and processes in the funeral industry. This include; (1) determining the nature, sources and concentrations of TOCs, (2) identifying people at risk, including embalmers, funeral directors, cleaners, assistants and service providers, and (3) identifying key exposure pathways, and intakes per unit time (e.g. day).

5.1.2 Risk assessment

This entails qualitative and quantitative estimation of the likelihood or probability of occurrence of a hazard, and the corresponding magnitude of consequences on health. Qualitative risk analysis may use a matrix with qualitative terms such as 'critical', 'high', 'moderate', 'low/negligible' to rate the likelihood of occurrence and magnitude of consequences (Figure 3). Quantitative risk assessment calculates a risk metric or quotient (US EPA, 2020a, b) using tools such as probabilistic techniques and quantitative structure-activity relationships (QSARs) (Walker et al., 2002; Cronin et al., 2003). The estimated risk is then compared to set threshold values which are considered to be acceptable. In the case of emerging contaminants, a key challenge is the lack of established ecotoxicological threshold values required to induce adverse health effects. To overcome this challenge, Gwenzi (2020) proposed a heuristic approach, whereby data from pristine or non-impacted environments are used to provide the baseline or acceptable value.

5.1.3 Risk mitigation and control

This entails the identification and evaluation of the risk mitigation and control measures based on results of risk assessment. The ultimate mitigation strategy may entail a combination of the following: (1) administrative controls or 'soft engineering', (2) substitution and/or elimination of hazardous chemicals, processes and procedures, (3) engineering controls to reduce exposure to hazards, and (4) the use of regulatory and policy instruments (***Section 5.2***).

5.1.4 Monitoring, evaluation and feedback

This involves the development of appropriate indicators, timelines and milestones for performance evaluation (Figure 3). Indicators may include fatalities and near-misses traced to occupational exposure to hazards, and even frequency of occurrence of unsafe practices. Milestones may include setting targets to reduce certain undesirable events by a specific period. Subsequent analysis and interpretation of the M & E data will be used for decision-making, including review and improvement of the HIRAM via a feedback process (Figure 3).

5.2 Mitigation and control measures

5.2.1 Administrative measures

These include measures often included in occupational safety, health and environment procedures of organizations (Figure 3). Examples include; (1) practising good house-keeping practices such as proper handling and disposal of hazardous chemicals and wastes, (2) use of personal protective equipment, and (3) routine medical examinations and use of prophylactics. The Globally Harmonized System (GHS) of Classification and Labelling of hazardous materials and material safety datasheets (MSDS) are often used for hazard/risk communication, and proper labelling and signage to indicate the existence and nature of hazards (Winder et al., 2005; US OSHA, 2013). Other options include training workshops, and awareness and educational campaigns targeting key stakeholders such as occupational workers, environmental regulators, and

environmental and public health officers. Routine occupational and environmental surveillance systems are critical for the early detection and remediation of health risks (Loewenson, 1995).

5.2.2 Substitution and elimination

This entails the substitution, replacement and even elimination of hazardous materials, processes and procedures. For example, hazardous embalming chemicals based on formaldehyde can be substituted or replaced by several newly developed and less hazardous alternatives (Varlet et al., 2019). Even the embalming process can be eliminated in cases where it is not warranted. In some societies, this may entail a shift from current unsafe funeral practices such as home burials (Zume, 2011; Turajo et al., 2019) to safer alternative practices that pose limited health risks. In such societies, this may require long-term changes in certain socio-cultural and religious beliefs.

Emerging technologies for the disposal of human cadavers such as freeze-drying and alkaline hydrolysis can also be used as alternatives for embalming and subsequent burial in cemeteries, and cremation. Da Cruz et al. (2017) presents a detailed discussion of the various funeral technologies including the relative advantages of the emerging technologies. Freeze-drying or promession entails subjecting whole human cadavers to rapid freezing using liquid nitrogen, followed by burial without embalming (Da Cruz et al., 2017). Alkaline hydrolysis involves subject a cadaver to concentrated potassium hydroxide (KOH) and steam at a temperature of 180^{o}C for a few hours, and creating a whirlpool effect to accelerate dissolution (Da Cruz et al., 2017). The end-products of alkaline hydrolysis are liquid containing dissolved tissues, and bones. The bones are turned into a powder using a cremulator or crusher and given to the bereaved family for storage, while the liquid can be used as a fertilizer (Everts et al., 2010). The potential benefits of these emerging technologies relative to conventional ones include: (1) low land requirement and costs, estimated to be about US$389 for freeze-drying compared to US$423 for cremation and US$467-622 for burial, and (2) low environmental footprints including reduced contamination by organic, inorganic and microbiological contaminants, and low energy requirement compared to cremation (Da Cruz et al., 2017). However, the costs of initial installation and operation of emerging technologies could be prohibitive especially in developing countries. Moreover, quantitative data on the environmental benefits and the long-term behaviour, fate and health risks of contaminants in the end-products of freeze-drying and alkaline hydrolysis are still limited. Hence, comparative research is needed to investigate these aspects relative to conventional funeral technologies.

5.2.3 Engineering controls

This encompasses measures aimed at reducing human exposure to risks or the removal of the hazards through the use of technology or engineering interventions. This may include automating highly hazardous procedures to reduce human exposure. Other engineering controls include application of technologies for the treatment of solid wastes, wastewaters, contaminated drinking water and air-borne particulates. The removal of organic contaminants in wastewater and contaminated drinking water sources can be achieved using several treatment processes. These include; adsorption, chlorination, advanced oxidation processes, boiling, solar disinfection (SODIS), membrane filtration and ceramic filters (Pooi and Ng, 2018, Table 3).

Table 3 presents as summary of the various treatment processes, including their advantages and limitations. The methods for removal of organic contaminants have been the subject of several papers, including reviews (Pooi and Ng, 2018, Michael et al., 2020, Table 3). These treatment processes provide critical tools for reducing contaminant loads in water and wastewater. The choice of method will depend on several factors, including water/wastewater treatment objectives,

installation and operation costs, and availability of technology and expertise. Compared to other treatment processes, the capacity of low-cost drinking water treatment methods such as boiling and solar disinfection to remove TOCs is the least studied. Hence, it remains unclear which low-cost methods are most effective in removing organic contaminants in drinking water.

942 **Table 3**. Summary of treatment processes for the removal of organic contaminants in aqueous systems.
943

Process	Summary of process and principles	Benefits and advantages	Limitations and remarks	Review
Adsorption	Removes a wide range of organic contaminant via physico-chemical sorption	Low-cost method. Several natural and synthetic adsorbents exist	Only transfers contaminants from one phase (aqueous) to solid phase and generates large quantities of sludge	Grassi et al., 2012;
Chlorination	Removes micro-organisms including antimicrobial resistant bacteria and resistance genes via. Limited capacity to remove chemical organic contaminants.	Widely used method for disinfection in both centralized and decentralized systems	May react with organic matter to generate carcinogenic disinfection by-products	Tak and Kumar, 2017
Advanced oxidation processes	Uses strong oxidants (O_3, H_2O_2) to generate reactive radicals that degrade organic contaminants. Often combined with ultraviolet irradiation (UV) and photocatalysts (e.g., TiO_2) to enhance removal efficiency.	Highly effective in degrading organic contaminants. Organic contaminants can be completely mineralized to relatively benign by-products.	Have high energy and chemical requirements, hence relatively expensive compared to other methods. May not be ideal in low-income countries due to high costs.	Michael et al., 2020; Zhou et al., 2020
Membrane filtration	Relies of size exclusion and contaminant size to remove from from aqueous systems. Processes include reverse osmosis, nano-filtration among others	Very high removal efficiencies for various contaminants. Have limited effects of organoleptic properties of water.	Prone to several fouling processes such as scaling, and relatively expensive. Limited use of the technology in developing countries due to high costs.	Pendergast and Hoek, 2011; Chang et al., 2019
Boiling	Disinfects water by using high temperatures to destroy cell components. Volatile organic contaminants may be removed via volatilization.	Low-cost disinfection methods commonly used in developing countries and humanitarian emergencies for drinking water treatment	May increase contaminant concentrations via evaporation. Limited data exist on removal of antimicrobial resistance and emerging contaminants.	Gwenzi et al., 2018
Solar disinfection (SODIS)	Relies on UV irradiation and high temperature to destroy microbial cell components and organic contaminants via photodegradation. Similar to UV violet irradiation.	Low-cost method used for drinking water treatment in developing countries. Mainly targeted for removal of pathogens.	Requires long exposure times. Limited capacity to remove organic contaminants. Limited research on removal of antimicrobial resistance and emerging contaminants.	Pooi and Ng, 2018; Pichel et al., 2019
Biosand filtration	Formation of a biofilm or *Schmutzdecke* critical for the removal of pathogens via slow filtration, and subsequent predation and/or die-off.	Low-cost method commonly used for drinking water treatment in developing countries and humanitarian emergencies.	Low capacity to remove dissolved contaminants, and may promote antimicrobial resistance via biofilms. Limited data on removal of emerging contaminants.	Pooi and Ng, 2018
Ceramic filters	Relies on size exclusion and antimicrobials (e.g., Ag nanoparticles) to remove pathogens.	Low-cost methods for treatment of drinking water in developing countries especially pathogens.	Treat small volumes, and Ag may occur in treated water. Limited data on removal of emerging contaminants.	Pooi and Ng, 2018

944

5.2.4 Regulatory and policy perspectives

Despite the occurrence of TOCs and the putative health risks, consensus exists that, globally, the funeral industry is under-regulated (Horton, 2003; Davidson and Benjamin, 2006; Miranda, 2016; Kuchniski et al., 2019). Specifically, evidence from the USA, Canada, Europe and Africa shows that the regulation and control of the funeral industry do not commensurate with the health risks (Horton, 2003; Davidson and Benjamin, 2006; Chiapelli and Chiapelli, 2008; Miranda, 2016; Kleywegt et al., 2019; Kuchniski et al., 2019; Turajo et al., 2019; Zume et al., 2019; Gwenzi, 2020). For example, compared to other hazardous wastes from the health care industry, a cursory regulatory and research attention has been paid to the disposal of human cadavers, solid waste and wastewaters from the funeral industry (Gwenzi, 2020). Thus, in several countries, thanatopraxy care facilities, cemeteries and crematoria are often excluded in routine environmental surveillance systems. This stems from the fact that, in most countries (e.g., USA, Zimbabwe), the funeral industry falls under commercial service providers, which is less regulated compared to the health care industry (Davidson and Benjamin, 2006; Gwenzi, 2020).

Regulatory inconsistencies also exist; for example, on the one hand, blood, body fluids and even solid wastes from the health care systems are classified as hazardous wastes, and are handled and disposed accordingly. Yet on the other hand, the same blood and body fluids in thanatopraxy care are directly discharged into septic systems or the municipal wastewater systems without prior treatment (Chiapelli and Chiapelli, 2008). In most countries, embalming now appears to be the norm rather than the exception. Yet evidence shows that, barring a few exceptions, embalming is not a legal requirement (e.g., USA, Chiapelli and Chiapelli, 2008; Europe, Miranda, 2016). The exceptions are long-distance transport of human cadavers and those used for medical scholarship (Chiapelli and Chiapelli, 2008; Varlet et al., 2019). Thus, the indiscriminate embalming appears to be driven by financial benefits derived from such a practice by the funeral industry, rather than being a scientific or legal justification. This further highlights the weak regulatory framework. Collectively, these scenarios point to the need to develop robust and appropriate regulatory and policy frameworks for the funeral industry.

The regulatory and policy frameworks may entail developing a dual classification system for the funeral industry: (1) the business aspects including funeral assurance can be classified under commercial service providers just like medical insurance, while, (2) the disposal of human cadavers, embalming products, wastes and wastewaters from the funeral industry should be governed by regulations similar to those of the health care industry. Therefore, the regulatory and policy frameworks should be premised on the fundamental fact that, human cadavers, embalming products, solid wastes, wastewaters and air-borne particulates from the funeral industry are 'hazardous'. This notion is similar to the one used for medical wastes from the health care industry. Yet there is need for caution to avoid classifying human cadavers as 'hazardous wastes', because this will be viewed as insensitive and inhumane in some socio-cultural settings.

Embracing the fact that human cadavers, embalming chemicals and associated wastes and wastewaters are 'hazardous' has several implications. First, the production, marketing, purchase, storage, use and final disposal embalming products will require a special permit. Such special permits may specify the need to maintain records on existing stocks, number of people embalmed, and disposal of wastes and wastewaters. In addition, such permits may also specify the following requirements: (1) mandatory accreditation and registration, including the minimum qualifications of embalmers and funeral directors, (2) best safety, health and environment procedures, including the use of appropriate labelling and insignia to communicate hazards, and (3) proper management

practices for solid wastes, wastewaters and air-borne emissions (LaGrega et al., 2001). This will ensure that, regulatory agencies regard the funeral industry among other high-risk industries (e.g., health care system) that generate hazardous wastes. In turn, funeral industry will be accorded the appropriate routine environmental, occupational and public health surveillance and control.

The notion of 'hazardous' also calls for proper planning, design, operation and monitoring of engineered systems for the disposal of human cadavers, wastes and wastewaters. In this regard, a 'new generation' of properly engineered cemeteries will be required. The design principles of such cemeteries could be adapted from that of engineered sanitary landfills (Qian et al., 2001). This include the need for; (1) runoff and drainage collection system, (2) hydraulic liners or barriers to restrict leachate migration into groundwater systems, and (3) leachate monitoring and collection system, and (4) on-site wastewater treatment system for treating contaminated leachate, drainage and runoff before discharge into the environment or sewer systems. Moreover, mandatory incineration of solid waste and on-site wastewater treatment will be required. Incinerators and crematoria should be equipped with emission control and monitoring systems.

The formulation of regulatory and policy frameworks requires a strong scientific evidence base, which is currently missing in developing regions, including Africa. Moreover, environmental and public health surveillance systems are either weak or non-existent (Loewenson, 1995). As with other health risks such as infectious diseases, local capacity and expertise to develop effective regulatory and policy frameworks, and surveillance and control systems in the funeral industry are currently lacking in developing countries. Thus, the international community, through partnerships with relevant international agencies (e.g., WHO, UNESCO, UNICEF) and developed countries could assist with the following: (1) the development of effective surveillance and control systems, and (2) facilitate and provide guidance in the formulation of regulatory and policy frameworks. This can be achieved through the following: (1) the provision of experts/specialists, (2) capacity-building initiatives, including training workshops, and (3) provision and mobilization of resources and equipment for conducting research to develop the local scientific evidence base.

6 Future research and perspectives

Future research should address key knowledge gaps in several thematic topics on TOCs in the funeral industry. The application of conventional and emerging research tools is critical in addressing these knowledge gaps (***Section 6.2***).

6.1 Future Research

(1) Occurrence and partitioning of TOCs

Limited data exist on the occurrence of TOCs in various reservoirs such as solid wastes, wastewaters and air-borne particulates in the funeral industry. Thus, further studies are needed to determine the occurrence and partitioning of TOCs and their metabolites in the various reservoirs. Such studies should estimate inventories of annual emission of TOCs in solid wastes, wastewater and air-borne particulates in various hotspot sources in the funeral industry.

(2) Behaviour and fate of TOCs

Limited data exists on the behaviour, fate and degradation kinetics of TOCs in tropical environments predominant in developing countries. Thus, comparative studies are required to understand the biogeochemical behaviour, degradation kinetics and fate of TOCs in tropical versus temperate environments. Speciation modelling may provide insights on the degradation kinetics, while chronosequence studies on cemeteries may provide cues on the long-term fate.

(3) Ecotoxicology of TOCs

Limited data exists on ecotoxicology of organic contaminants at environmentally relevant concentrations such as in solid wastes, wastewaters and air-borne particulates in funeral industry. In addition, the health risks arising from mixtures of TOCs and their interaction with other health stressors are poorly understood. Studies based on toxicokinetic, pharmacokinetic and energy budgets modelling (Dietz et al., 2015; Sonne et al., 2014, 2015) are needed to understand the uptake, bioaccumulation, (bio)transformation and fate of TOCs in biota.

(4) Ecological health risks of organic contaminants

Evidence on the ecological health effects of emerging organic contaminants remain largely inferential, while direct evidence remain weak. Thus, studies are required to better understand the ecological health risks at various level of biological organization using a combination of conventional and emerging tools (***Section. 6.2***).

(5) Removal of TOCs by low-cost water treatment processes

Literature on the removal of TOCs is limited to conventional and advanced treatment methods (Michael et al., 2020). Data on the removal of TOCs by low-cost water treatment methods such as slow biosand filtration, boiling and solar disinfection are scarce. Such low-cost methods are routinely used in humanitarian emergencies and by low-income communities. Such information is critical for the choice of methods for drinking water treatment in such settings.

(6) Quantitative human health risk assessment

Evidence on the human health risks of TOCs in the funeral industry and other environmental reservoirs is predominantly inferential. The dominant pathways contributing to human exposure and health risks in the funeral industry remain unknown. Hence, systematic case-control studies in human toxicology and epidemiology are required to directly establish the link between the occurrence of TOCs and incidences of specific human health outcomes.

6.2 Moving forward in health risk assessment

To this point, it is evident that, receptor organisms including humans are co-exposed to a milieu of contaminants and health stressors. Yet most environmental risk assessments, including those conducted for as part of the pre-registration and approval of synthetic chemicals rarely consider mixtures and the their interactions with other health stressors. Moreover, understanding the ecological and human health risks of TOCs in environmental systems is quite complex.

The limitations inherent in the current evidence and risk assessment protocols calls for caution when drawing conclusion on health risks based on single chemical bioassays. Specifically, this raises the question, '*Do current environmental guideline limits based on existing health risk assessments really protect ecological and human health, and if not, how do we move forward from here*?' This question resonates with earlier concerns raised in the USA (Hayes et al., 2016) and the European Community (Carvalho et al., 2014), questioning whether or not current environmental regulations and their guideline limits were sufficient to safeguard human and ecological health. This call for the urgent attention of the research community, regulators, funding agencies and policy makers to reflect on current evidence and risk assessment frameworks.

The development and subsequent application of the next generation tools for understanding the health risks of mixtures and their interactions with other health stressors constitute the new research frontier in (eco)toxicology and health risk assessment. Such future studies should address health risks at various level of biological organization, including molecular, organ, individual, population, community, ecosystem scales and even ecosystems goods and services. Conventional research tools for (eco)toxicology, health risk assessment and epidemiology include; (1) manipulative experiments using microcosms, mesocosms and even real ecosystems (van Donk et

al., 2016), coupled with hierarchical modelling (Chen et al., 2013), (2) protocols for ecotoxicological and health risk assessments (e.g., EC, 2006; OECD, 2015; US EPA, 2020a, b), and (3) tools in human toxicology and epidemiology of contaminants, including case-control experiments (He and Huang, 2010; Drakvik et al., 2020). However, in view of the limitations highlighted, these tools only provide a starting point, but there is need to improve and adapt them.

Recent advances in analytical techniques and data analytics provide emerging tools and unprecedented opportunities to better understand the health risks of TOCs (Table 4). These tools include; (1) advanced and highly sensitive analytical techniques including those for 2-D and 3-D imaging (Lindner et al., 2015; Mehrian et al., 2020), (2) isotopic labelling (Boecklen et al., 2011; Parnell et al., 2013), (3) molecular/genomic tools (Pulojar et al., 2012; Valli et al., 2020), (4) big data analytics such as machine learning and artificial intelligence (Vestergaard et al., 2017; Hyun et al., 2020), and (5) *in silico* or computational techniques (Vuorinen et al., 2013; Raies and Bajic, 2016; Nwaimu and Aduba, 2020). Surprisingly, despite the immense opportunities offered by emerging tools, their application has received limited attention among the research community focusing on ecotoxicology and health risks of contaminants. Table 4 presents a summary of the various emerging tools and their potential applications in understanding the behaviour, (eco)toxicology and health risks of TOCs.

It is envisaged that, future research integrating conventional and emerging tools will lead to the development more robust 'next generation' health risk assessment protocols, and surveillance and control systems. Given the multi-disciplinary nature of health risks of TOCs, such future research should bring together diverse disciplines, including; environmental scientists, toxicologists, ecologists, epidemiologists, and experts in mathematics and computer sciences.

Table 4. Potential applications of merging tools to understand the behaviour, (eco)toxicology and health risks of toxic organic contaminants (TOCs).

Emerging tools	Examples	Potential applications and remarks	References
(1) Advanced and sensitive analytical methods	(a) HPLC-ICP-MS, Laser ablation ICP-MS, (b) Computed X-ray tomography	(a) Detailed characterization of the concentrations and speciation of TOCs and their metabolites. (b) Non-invasive 2-D and 3-D imaging to understanding internal structure of complex TOC-solid matrix interactions in soils and sediments.	Lindner et al., 2015 Mehrian et al., 2020.
(2) Isotopic labelling	Use of TOCs labelled with ^{15}N and ^{13}C isotopes	Understanding the environmental behaviour, partitioning and fate of TOCs, including elimination mechanisms, uptake, bioaccumulation, biomagnification, (bio)transformation and trophic transfers.	Boecklen et al., 2011; Parnell et al., 2013
(3) Genomics/molecular techniques	(a) DNA probing, RNA sequencing, polymerase chain reaction (PCR) (b) metabolomics, proteomics, transcriptomics, metagenomics	(a) Understanding effects of TOCs on specific gene expressions via gene profiling, including those related to oxidative stress. (b) Can be coupled to network analysis to disentangle complex ecological processes, including trophic interactions, metabolic networks and ecosystem functions.	Pulojar et al., 2012 Valli et al., 2020
(4) Big data analytics	Machine learning (ML), artificial intelligence (AI), data mining (DM)	(a) Big data analytics have unique capacity for analysis, integration, synthesis and visualization of data from multiple sources (i.e., big data), including surveillance data on TOCs in environmental media, health stressors, (eco)toxicology, health risks, human toxicology and epidemiology, and their interactions (b) Machine learning, artificial intelligence and data mining tools are ideal for the prediction and extraction of spatio-temporal patterns and trends from 'big data'	Vestergaard et al., 2017; Hyun et al., 2020).
(5) *In silico* or computational techniques	Toxicokinetic modelling, network analysis, scenario modelling	(a) Rapid design and analysis of experiments to gain early insights that guide laboratory and field experimentation. (b) Complement isotopic labelling studies to understand speciation, behaviour and fate of TOCs, including bioaccumulation and (bio)transformation. (c) Ideal for scenario analysis modelling to investigate '*what if*' questions in (eco)toxicology and health risk assessments.	Vuorinen et al., 2013; Raies and Bajic, 2016)

In this research effort, international, regional and national environmental agencies (UNEP, OECD, US EPA) with experience in health risk assessment should provide the lead, in collaboration with their developing world counterparts. For now, safeguarding ecological and human health in the face of imperfect knowledge may require adopting the precautionary principle.

7 Conclusions and Outlook

The current review investigated the nature, occurrence and health risks of TOCs in the funeral industry. Data show that the funeral industry is a continuum of several hotspots of TOCs, including autopsy, thanatopraxy care facilities, cemeteries and crematoria. TOCs detected include; embalming products, persistent organic pollutants, synthetic pesticides, pharmaceuticals, personal care products and illicit drugs. Hotspot reservoirs of TOCs in the funeral industry include; human cadavers, solid wastes, wastewaters and air-borne particulates and aerosols. Surface and sub-surface hydrological processes control the transfer and dissemination of TOCs in environmental systems. Occupational exposure may occur in autopsy, thanatopraxy, cemeteries and crematoria via ingestion, inhalation of air-borne particulates and aerosols, and dermal intake via cuts and wounds. Non-occupational human exposure occurs via ingestion of contaminated drinking water, and aquatic and marine foods. Inhalation of volatile TOCs and dermal contact during body viewing, washing and handling of human cadavers during home care, funerals and burials may also occur.

Health risks of TOCs are quite diverse, and dependent on the nature of contaminants. The health risks include; (1) acute and chronic toxicity such a genotoxicity, teratogenicity, endocrine disruption and neurodevelopmental disorders, (2) antimicrobial resistance induced by pharmaceuticals and co-selecting emerging contaminants, (3) info-disruption caused by emerging contaminants via blocking and biomimickry of natural info-chemicals, and (4) disruption of ecosystem functions, including trophic interactions and biogeochemical cycling. However, barring formaldehyde, and inferential evidence, systematic quantitative studies directly linking TOCs in the funeral industry to specific health outcomes are still limited. Hence, the limitations of current evidence, and health risk assessment protocols were discussed. These limitations point to the need to develop and apply the next generation of better health risk assessment tools. To safeguard ecological and human health, a framework for hazard identification, risk assessment and mitigation (HIRAM), including prevention and control was developed. Future research directions, including key knowledge gaps, and opportunities presented by several emerging tools were highlighted.

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Conflict of interest

The author declares no conflict of interest, financially or otherwise, that could have influence his views and interpretation of the data.

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