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Review

Trace organic contaminants in biosolids: Impact of conventional wastewater and sludge processing technologies and emerging alternatives

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HIGHLIGHTS

- Hydrophobicity, charge and molecular structure influence TrOC accumulation on sludge.
- pH, temperature, solids content, SRT and chemical dosing can affect TrOC fate.
- Aerobic digestion and composting can achieve high TrOC removal from sludge.
- Sludge estrogenicity may increase following anaerobic digestion.
- Advanced oxidation and bioaugmentation may effectively remove TrOC from sludge.

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ABSTRACT

This paper critically reviews the fate of trace organic contaminants (TrOCs) in biosolids, with emphasis on identifying operation conditions that impact the accumulation of TrOCs in sludge during conventional wastewater and sludge treatment and assessing the technologies available for TrOC removal from biosolids. The fate of TrOCs during sludge thickening, stabilisation (e.g. aerobic digestion, anaerobic digestion, alkaline stabilisation, and composting), conditioning, and dewatering is elucidated. Operation pH, sludge retention time (SRT), and temperature have significant impact on the sorption and biodegradation of TrOCs in activated sludge that ends up in the sludge treatment line. Anaerobic digestion may exacerbate the estrogenicity of sludge due to bioconversion to more potent metabolites. Application of advanced oxidation or thermal pre-treatment may minimise TrOCs in biosolids by increasing the bioavailability of TrOCs, converting TrOCs into more biodegradable products, or inducing complete mineralisation of TrOCs. Treatment of sludge by bioaugmentation using various bacteria, yeast, or fungus has the potential to reduce TrOC levels in biosolids.

Contents

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1. Introduction

Excess sludge generated by biological wastewater treatment has traditionally been disposed through ocean-dumping, landfilling, or incineration. Due to increasingly stringent environmental regulations, these disposal methods are being phased out and replaced by either aerobic or anaerobic digestion. In these treatment processes, pathogens and volatile solids are removed and sludge is converted to stable "biosolids". Biosolids are rich in organic matter and nutrients, and can be utilised in various land applications (e.g. as fertilizer, soil conditioner and composting material) depending on its quality. Variables such as pathogenicity, vector attraction, odour, and heavy metals content of biosolids are regulated to protect the environment and public safety. The beneficial use of biosolids is a sustainable option because it has minimal impact on the environment (if the final product is devoid of pollutants), enables the recovery of resources, and adds economic value to what is conventionally perceived as waste [1,2]. Nonetheless, significant concern over the occurrence of trace organic contaminants (TrOCs) in biosolids, which can eventually contaminate soil and water and accumulate in plants and grazing animals, has risen in the recent years [3–5]. These TrOCs include pesticides, industrial chemicals, components of consumer products, pharmaceuticals and personal care products, hormones, and other organic pollutants that are ubiquitous in sewage and other environmental samples. Many of these TrOCs have the potential to cause chronic disorders in animals and humans [3]. TrOCs that are present in biosolids are those which are recalcitrant to wastewater and sludge treatment and have high affinity for sludge flocs. Although a few countries have already imposed controls on certain pollutants, e.g. di(2-ethylhexyl) phthalate (DEHP), linear alkylbenzene sulphonates (LASs), nonylphenol (NP) and nonylphenol ethoxylates (NPEs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dibenzo-*p*-dioxins and dibenzo-*p*-furans (PCDD/Fs), a unified directive addressing TrOCs in biosolids is not yet available [6].

The occurrence of TrOCs in biosolids are influenced by wastewater and sludge treatment operation parameters [4,7] and could be minimised by the addition of advanced treatment processes including ozonation [8], ultraviolet (UV) oxidation [9], and bioaugmentation [10] in the sludge treatment line. The fate of TrOCs during wastewater treatment is largely determined by their physicochemical properties (e.g. hydrophobicity, charge, and functional group). Thus, their occurrence in biosolids is inherent and unavoidable. Nonetheless, literature suggests that optimisable operation parameters (e.g. pH, sludge retention time (SRT), and temperature) have some degree of influence on TrOC sorption and biodegradation [7,11]. Further treatment of biosolids can remove TrOCs with high efficiency, but may require additional equipment and resources that drive up the cost of biosolids management.

The aim of this review is to analyse the occurrence and removal of TrOCs in biosolids. The first part of the review will investigate the underlying mechanisms and factors that affect the fate of TrOCs during wastewater treatment. There is a wealth of research about the fate and removal of TrOCs in the conventional activated sludge (CAS) process [12–18]. A few review articles have summarized the effect of various operation parameters on TrOC removal from the aqueous phase [7,19,20], but none has systematically collated and scrutinised the available data to identify operation conditions that are relevant for controlling the occurrence of TrOC in biosolids. The second part will discuss the fate and removal of TrOCs during sludge treatment. Most of the literature available on the fate of TrOCs in the sludge treatment line has focused on conventional aerobic and anaerobic digestion, and much less is known about the behaviour of TrOCs in other sludge treatment processes, e.g. thickening, conditioning and dewatering, and composting. The third part of the review will critically examine the mechanisms and efficiency of the emerging technologies for TrOC removal from biosolids. From these, future research priorities about the management of TrOCs in biosolids will be provided.

2. Fate of TrOCs in conventional wastewater treatment: mechanisms and relevant factors

Upon entry to WWTPs, TrOC may sorb on sludge flocs, undergo biodegradation or abiotic transformation, or remain intact in wastewater. In general, abiotic loss of TrOCs in primary or sec-