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Review

# Recovery opportunities for metals and energy from sewage sludges

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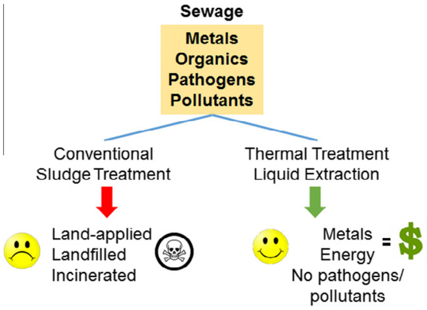
## HIGHLIGHTS

- Wastewater treatment plants can become resource recovery centers.
- Metals and nutrients can be recovered from sludges.
- Sludge pathogens are inactivated and organic pollutants are destroyed.
- Thermo-chemical technologies and liquid solvents evaluated for sludge application.
- Hydrothermal liquefaction reduces sludge mass by 50% and produces bio-oil.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Limitations on current wastewater treatment plant (WWTP) biological processes and solids disposal options present opportunities to implement novel technologies that convert WWTPs into resource recovery facilities. This review considered replacing or augmenting extensive dewatering, anaerobic digestion, and off-site disposal with new thermo-chemical and liquid extraction processes. These technologies may better recover energy and metals while inactivating pathogens and destroying organic pollutants. Because limited direct comparisons between different sludge types exist in the literature for hydrothermal liquefaction, this study augments the findings with experimental data. These experiments demonstrated 50% reduction in sludge mass, with 30% of liquefaction products converted to bio-oil and most metals sequestered within a small mass of solid bio-char residue. Finally, each technology's contribution to the three sustainability pillars is investigated. Although limiting hazardous materials reintroduction to the *environment* may increase *economic* cost of sludge treatment, it is balanced by cleaner environment and valuable resource benefits for *society*.

## Contents

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## 1. Introduction – Sewage sludge issues

Increasingly restrictive regulations for wastewater treatment prior to discharge coupled with the rising costs for sludge disposal pose two interrelated problems: (1) sludges loaded with contaminants may no longer be disposed in traditional ways, and (2) sludge treatment technologies, which have slowly evolved over the past 50 years to adapt to the changing regulations, have increased infrastructure and cost of treatment exponentially. Rather than continuing slow evolution of tweaking of sludge treatment, the authors believe there are existing technologies that provide a new approach to sludge treatment.

The history of sewage sludge treatment and disposal can be viewed as a game of playing catch-up with the regulations. In 1988, Congress passed the Ocean Dumping Ban Act, essentially mandating that all sewage sludge disposal be land-based. The Clean Water Act was amended in 1993 with Code of Federal Regulations Title 40 Part 503 to regulate the use and disposal of treated sewage sludges (U.S. EPA, 1994). Land application of Class B sludges (i.e., treated sludges that still contain pathogens) on agricultural fields was encouraged under the idea that organics in the sludges would promote soil stabilization, enrich soils, and enhance crop growth. However, land application, by which 55% of sludge is disposed, continues to face setbacks ranging from public tolerance for odor to public health and environmental concerns stemming from presence of non-regulated metals and contaminants of emerging concern (CECs). Alternatives to land application include landfill disposal (30% of sludge) and incineration (15% of sludge) (Peccia and Westerhoff, 2015). Incineration poses human toxicity concerns associated with releasing heavy metals and particulates into the air (Hong et al., 2009). Thus, for treated sludges with high metal or CEC content, landfilling is increasingly the only remaining disposal method. These sludges are subject to municipal and hazardous waste landfill regulations set forth by the Resource Conservation and Recovery Act (RCRA). (40 CFR 261, 2011) Landfilling faces several drawbacks – specifically, space is limited due to the growing strain of urbanization, leading to increased cost of hauling to distant locations. Additionally, there is public distaste towards landfill odor, and environmental concerns regarding the release of greenhouse gases and the potential for groundwater contamination from the leachate. (Giusti, 2009).

Wastewater treatment technology has adapted to increasing regulations and concerns regarding the effects of disposal on aquatic life and water reuse applications. Activated sludge technology to reduce biological oxygen demand was first implemented in the mid-20th century. In the 1960s, chemical phosphorous precipitation was added, followed by biological treatment trains with nitrification, denitrification, and enhanced biological phosphorous removal (EBPR). These modifications produced higher quality effluents and increased viability for reuse; however, the biological processes also produce large volumes of low density (98% water) biological solids, chemicals, and inert particles associated with the lipid-rich bio-cellular materials. This ultimately results in a longer solids retention time (SRT) for sludge stabilization during anaerobic digestion, up to 30 days. These very long SRTs result in large reactor volumes with high capital costs and consequently only become economically viable for larger utilities (i.e., WWTPs that serve populations on the order of >100,000) (Peccia and Westerhoff, 2015).

Sewage solids treatments rely on sludge stabilization (e.g., alkaline lime stabilization, anaerobic digestion, aerobic digestion, and composting) to remove pathogens, pollutants, and odor. Anaerobic digestion has been used since the early 1900s and is one of the most popular sludge stabilization technologies. In the absence of oxygen, organic compounds and cells break down to produce biogas (65–70 vol% of methane, $CH_4$, 30–35 vol% $CO_2$). A 56–65.5% reduction in volatile suspended solids (VSS) occurs after a SRT between 15 and 30 days (depending on the operating temperature of the reactor). Aerobic digestion (i.e., in the presence of oxygen) can also stabilize sludges, but it does not allow for energy recovery, and the resulting sludge has poor dewaterability. Stabilized sludges are only 5–10 wt% dry solids and must be mechanically dewatered to 25–35 wt% dry solids using centrifuges and belt presses prior to disposal in order to reduce volume and mass for transportation (Appels et al., 2008; Metcalf and Eddy, 2013).

While biosolids may amend soil and provide plants with beneficial nutrients, they are only applied on <1% of the total agricultural land in the United States (U.S. EPA, 2015). In Germany, only 2.6% of organic fertilizer is composed of sewage sludge (Kruger et al., 2014). Soils are approaching their cumulative heavy metal loading rates (Table 1), and the hauling distance required for land application is increasing. The authors argue that land application is merely a preferred sludge disposal alternative when compared to landfill or incineration, and there would be minimal agricultural loss if the total volume of solids produced was reduced and/or a separate, more beneficial use was found for them.

It is worthwhile to consider shifting the perspective of WWTPs from being waste treatment and disposal facilities to resource recovery facilities. Human-generated wastes consist of most everything used to nourish health and livelihood – metals, nutrients, organics, and more. Rather than disposing these items and investing time, money, and labor to produce and mine additional