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We Should Expect More out of Our Sewage Sludge

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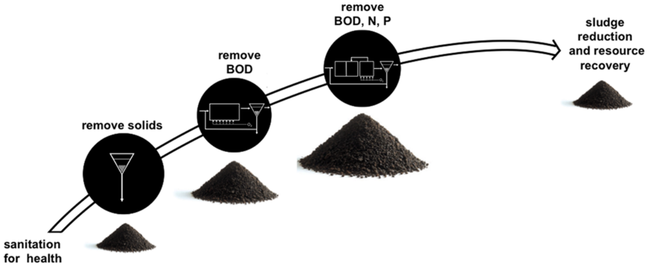

Bending the arc of sewage sludge history

Sewage sludge and biosolids production and management are a central component of water and sanitation engineering. The culmination of previous incremental technologies and regulations aimed at solving a current treatment problem, rather than developing the practice for the higher goals of sustainability have resulted in sludge becoming an economic and social liability. Sludge management practice must shift from treatment of a liability toward recovery of the embedded energy and chemical assets, while continuing to protect the environment and human health. This shift will require new research, treatment technologies and infrastructure and must be guided by the application of green engineering principles to ensure economic, social, and environmental sustainability.

INTRODUCTION

Domestic wastewater treatment uses both physical removal and the biological transformation of particles, pathogens, organic compounds and nutrients to dramatically improve the quality of effluent water. The solids removed during a primary sedimentation step and the settled microorganisms produced during biological transformation processes after secondary clarification are collectively called “sewage sludge”, which is the major byproduct of wastewater treatment. Subsequent sewage sludge processing and stabilization consists of moisture reductions by thickening, drying, or dewatering, and then stabilizing organic material by composting, digesting, or heat treatment. “Biosolids” is the industry wide term used for stabilized sewage sludge that has a beneficial use. Sludge disposal and biosolids reuse is regulated under the Title 40 Code of Federal Regulations, Part 503.[5] Sewage sludges and biosolids contain 2−30% dry solids, and must be hauled off-site for disposal in landfills, incineration facilities or reuse via land application.

The most common fate of sewage sludge in the U.S. is to land apply as class B biosolids, which benefits soils by adding nutrients, increasing organic matter content and improving water holding capacity. However, land application is under increasing public and regulatory pressure at many municipalities. Greater than 8 million dry tons of biosolids are generated in the U.S. annually (Table 1), and as wastewater treatment has intensified to remove nutrients and more homes and commercial buildings are connected to trunk sewers, this amount continues to increase. In many locations, urbanization has encroached upon wastewater treatment plants (WWTP) built in the 1960s and 1970s and as a consequence, biosolids must be hauled greater distances, often across state lines, for land application or disposal, necessitating energy intensive dewatering processes and transport costs. Land application is often accompanied by strong odors, and biosolids contain heavy metals, hazardous organic chemicals, microbial pathogens, and antibiotic resistant bacteria (see Box 1). In 37 of 50 U.S. states, local ordinances either ban land application or impose restrictions that are greater than the federal regulations.[7] These stricter regulations, which range from more stringent limitations on pathogens and pollutants to changes in management such as reduced set-back limits from dwellings and water sources, commonly occur in areas of high population density. In attempts to curb costs, improve public perception, and meet more stringent state and local regulations, many municipalities are building capital intensive, incremental processes to further

Table 1. Sewage Sludge by the Numbers, Based on U.S. Production of 7.2[7] Million Dry Tons per Year

production	
[a]sludge yield/BOD (aerobic)	~0.5 kg dry sludge/kg COD
[b]sludge yield/BOD (anaerobic)	~0.05 kg dry sludge/kg COD
U.S. sludge per capita production (aerobic)	~23 kg/person/year
disposal/reuse[c]	
landfill	30% of all sludge produced
land application	55% of all sludge produced. Of land applied sludge, 60% is class B, 40% is class A.
incineration	15% of all sludge produced
cost[d]	
land application (dewatering, storage, stabilization, hauling, land application)	\$300−800 per dry ton
landfill (tipping fees and hauling)	\$100−650 per dry ton
incineration (hauling, incineration costs)	\$300−500 per dry ton

[a]Estimates do not include primary sludge, which is typically 50% of total sludge production in an activated sludge facility. [b]Based on ~10 times secondary sludge reduction for anaerobic systems.[12] [c]From ref 7. [d]Cost represent a range reported by interviews with treatment plant operators and governmental biosolids program managers.[13]

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Box 1. Hazardous Chemical and Pathogen Content

Words that start with the letters "slu" do not usually connote something with a positive public image. Sewage sludge is no exception. Sludge is a record of what society excretes. This includes any pathogen that is contained in human feces, urine, and vomitus. A recent study found more than 27 different forms of human viruses in the sewage sludges of five large U.S. cities, ranging from Adenovirus to Corona virus to HIV.[1] Antibiotic resistant bacteria and antibiotic resistance genes are common in wastewater and biosolids.[2,3] Stabilization is meant to reduce this pathogen load, usually by 1−2 orders of magnitude for class B treatments. Microbial risk analyses, which have typically shown limited risk to residents for *Salmonella* spp. and Enterovirus[4] have recently suggested significantly increased risk of infection due to emerging viruses such as Norovirus.[6] Metals and organic chemicals that resist biological mineralization can sorb to solid particles and also accumulate in sludge. These include polybrominated flame retardants, pharmaceuticals like Prozac and Tagamet, human hormones such as estrogen, antibiotics, narcotics including cocaine, and the metabolites of these compounds.[8,9] Class B land application can include spreading tons of sludge per acre of land, producing a strong odor and attracting disease vectors. The chemical and microbial content and sludge odor are important drivers to the public resistance to land application.[10] Land application disputes are a large source of litigation and hundreds of human health complaints from residents living near land application sites have been logged.[11] More so than regulations, costs, or environmental concerns, those that manage biosolids land application programs cite concerns from neighbors, environmental groups, and others as the top pressures on their programs.[7]

reduce biosolids odors and pathogen content. Consequently, municipalities are reaching tipping points where major infrastructure decisions are being made, creating opportunities to allow for leap-frogging—rather than incremental—technologies that can transform WWTPs from waste disposal facilities into resource recovery facilities.

Despite decades of efforts to view them in terms of resource recovery, WWTPs have been viewed as "waste treatment" facilities, receiving water carrying a wide range of pathogens, chemicals and metals and discharging treated water plus sewage sludges. Many policies and practices have been used to solve problems as they occur, rather than following the broader goals of environmental, economic, and human society. Ensuring the sustainability of current, biological wastewater treatment requires a rethinking of the production, disposal and resource exploitation of sewage sludge. The goal of this feature article is to chart a future approach for improving the social, economic an environmental sustainability of domestic sewage sludge. This article focuses specifically on sludge management, but recognizes the importance of integrating sludge resource recovery with current efforts for improving the sustainability of entire wastewater facilities.[14]

Good Intentions, Wrong Approach. How did sludge reuse and disposal policy get to the point where municipalities pay for the majority of a wastewater treatment plant's energy, hazardous chemicals, and pathogen content to become embedded in biosolids, which are then dispersed into the environment? This current regime is a product of solving problems and implementing regulations as disposal issues emerged, rather than striving for an over arching goal of economic, social, and environmental sustainability. Legislation banning the ocean dumping of sludges passed in 1988, and required all sludge disposal to be land-based. In 1993 the U.S. Environmental Protection Agency provided guidance for the use or disposal of sewage sludge in their Part 503 rules and encouraged the practice of land applying a Class B biosolids product. Class B biosolids required a less intensive stabilization of sewage sludge versus Class A biosolids, but resulted in limited social acceptance due to odors and human health concern of pathogens and chemical content. Practice is now trending toward producing a Class A product, which may have more economic value, but does not alleviate concerns of chemical content and embedded energy. Along the way, many utilities have lost track of sludge handling costs. This historical arc of sewage sludge disposal is depicted graphically in Figure 1.

Many current trends in wastewater treatment may exacerbate sludge disposal and reuse difficulties. In a reoccurring theme, environmental benefits and developments in wastewater treatment such as nutrient removal are gained at the expense of sludge production. By adding biological nitrification and denitrification and enhanced biological phosphorus removal (EBPR) processes to treatment trains, new growth substrates are added while solids and hydraulic retention times are lengthened. Both treatment trains result in increasing the growth of biomass and overall sludge production. Increased phosphorus (P) removal to meet more stringent total maximum daily loading for receiving streams dictates the use of chemical precipitation (e.g., ferric addition) in many locations. This process nearly doubles the quantity of secondary sludge. Both EBPR and chemical precipitation put P in a less mobile form in biosolids and limit efficiencies of struvite ($MgNH_4PO_3$-$6(H_2O)$) precipitation or other physical-chemical processes for recovery of P. The growing use of anaerobic digesters to codigest biomass and food wastes may potentially reduce the emission of CH_4 that would be released if food waste was composted, and is a very positive trend in harnessing municipal treatment infrastructure to improve the environment and produce valuable products. Again, however, such a practice both increases a plant's annual tonnage of solids and makes digested food a sludge-regulated waste. New, promising technologies that use heat drying and peletization of sludge and biosolids effectively reduce pathogens and odors to form a Class A product, but embed even more energy and costs into an environmentally dispersed product that still contains metals and persistent organic pollutants.

Sludge as an Asset. Solutions must balance the development of sludges as resources against the paramount necessity to protect human health and the environment. Sewage sludge can be exploited for assets greater than its current use as a soil amendment, in part because this only solves part of the problem (i.e., metals and persistent organic pollutants remain in the sludges). Nutrients, high value metals, embedded energy potential, and the avoidance of sludge handling costs are important examples of recoverable assets.

Nutrients. Research has intensified on methods to separate phosphorus from wastewater as a valuable fertilizer.[15] The nitrogen and phosphorus content of biosolids, which is largely attributed to the importation and consumption of proteinaceous foods by people, are currently viewed as a significant asset. On a dry weight basis sewage sludges contain 3−4% (median values)[16] nitrogen, present mostly as organic N. In a modern facility that off-gases N_2 as a consequence of

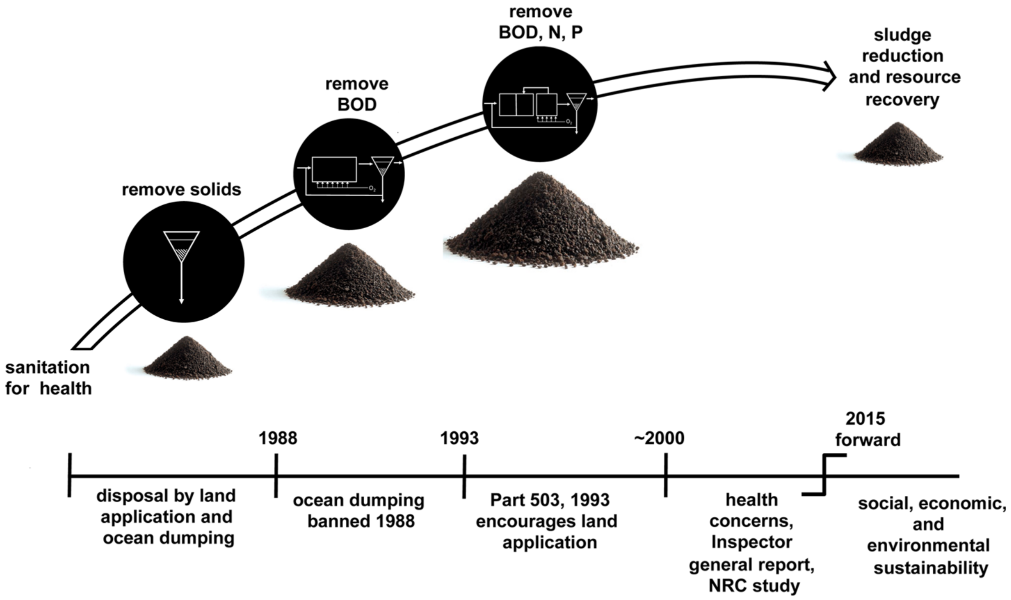

Figure 1. The Arc of Sewage Sludge History. As wastewater treatment improved, sludge production increased. Coinciding with this increase, regulations moved the practice from open disposal on land and oceans, to bans on ocean dumping, and beneficial land-based reuse. Public concern and local and state ordinances banning or severely limiting land application are now common. Rather than addressing the next issue incrementally, a change in the arc of history must include the reduction of sludge and the exploitation of sludge chemical and energy content—converting sludge from a cost to an asset.

denitrification, only limited amounts of nitrogen in wastewater ends up in sludge. A case study in the Phoenix, AZ metro area found that of the total net nitrogen flux into the plant, less than 10% remained in the biosolids applied to agricultural fields. The majority of N left the plant during denitrification processes.[17]

Because phosphorus is not converted to gaseous products during wastewater treatment, most of the P accumulates in biomass in facilities that perform EBPR or chemical precipitation. Like nitrogen, P in sewage sludges includes mostly organic P. Assuming 7.2 million dry tons of sewage sludge produced each year, 55% is land applied[7] and a N and P content of 3.4 and 2.3% respectively, then potential annual net flux of N and P are on the order of 135 000 t N/yr and 91 000 tons P/yr. In comparison, the net annual N and P fertilizer consumption is on the order of 11 650 000 tons N/yr and 1 710 000 tons P/yr.[18] Sewage sludge represents ∼1% of the annual N fertilizers applied in the U.S. and ∼5% of the applied P. While not insignificant, the real value of N and P removal at WWTPs may be in keeping these nutrients out of waterways, where they cause eutrophication, rather than relying upon them as important source of nutrients for agriculture.

Energy. Primary and secondary sewage sludges represent a significant amount of embedded energy, on the order of 15 and 20 MJ/kg of dry sludge. Production of 23 kg of sludge per person per year containing 20 MJ/kg of embedded energy equates to 127 kW-hr or roughly 1.1% of the annual electricity usage of a person in their home. More specific to the net energy consumption of wastewater treatment processes, wastewater treatment plants account for approximately 3% of the electricity consumption in the U.S.[19] By reducing the embedded energy in secondary sludge, and practicing energy recovery from primary and secondary sludge, it has been estimated that WWTP could be energy producers.[12] A significant portion of a conventional activated sludge/anaerobic digester treatment plant's energy consumption is dedicated to sludge production. Aeration to remove BOD, NH_4^+ and produce secondary sludge consumes approximately 50% of a plant's total energy utilization.[12] Additional sludge handling processes including dewatering and transport increase the fraction of energy devoted to sludge production.

In the ∼45% of sludges that are disposed of in landfills and incinerators, there are energy recovery opportunities from stimulating landfill biogas production or utilization of the high-grade waste heat from incineration. Other than stabilization by anaerobic digestion and biogas recovery, which is currently practiced in ∼11% of the larger-capacity U.S. WWTPs,[12] there is no energy recovery associated with land applying biosolids.

Metals. Recent reports on the occurrence of 58 regulated and nonregulated elements explored opportunities for removal and recovery from U.S. sewage sludges. Rare-earth elements and minor metals (Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) detected in sludges showed little enrichment, suggesting dust or soils as likely dominant sources. In contrast, most platinum group elements (i.e., Ru, Rh, Pd, Pt) showed high enrichments factors, indicating anthropogenic sources. For a community of 1 million people, elements in sewage sludges were valued at US $13 million annually ($480/dry ton), with 13 elements (Ag, Cu, Au, P, Fe, Pd, Mn, Zn, Ir, Al, Cd, Ti, Ga and Cr) having the highest relative economic potential to recover. In this example, the annual value of P in sludges would be on the order of $55,000/yr—indicating the potential significance of other elements. Approximately 20% of the value was accounted ($2.6 million per year) for by gold and silver (one sludge incinerator reported 2 kg (∼$85,000) of gold in one ton of ash[20]). Several of these enriched elements are energy-critical-elements (Ga, Pd, Ag, Ir) or critical elements.[21] Additionally, most the metals considered toxic to ecosystem organisms and regulated in biosolids that are land applied have significant potential economic value. Thus, recovering metals could be an economic and environmental win-win scenario. Values of chemical constituents in sewage sludge are listed in Table 2.

Table 2. Value of Chemicals in Sewage Sludge

nutrients	
[a]nitrogen (as NH_4^+)	$ 24 per ton
[b]phosphorus	$ 7 per ton
metals	
Ag, Cu, Au, P, Fe, Pd, Mn, Zn, Ir, Al, Cd, Ti, Ga and Cr	$480 per ton
Au, Ag	$103 per ton
energy	
[c]energy content as coal	$50 per ton

[a]Using U.S. Department of Agriculture cost of $700/ton anhydrous NH_4^+, and total NH_4^+ and organic N content in biosolids of 3.4% dry mass.[18] [b]February 2015 commodity cost of rock phosphate (35% P) is $115 per ton. Assume P sludge content is 2.3% dry mass.[18] [c]Assuming 18 MJ/g energy content for dry sludge and 24 MG/kg energy content for coal.

Converting Infrastructure to Extract Value from Sludge. Sludge is the receptor of wastewater's contaminants. It may not ever be feasible to treat the product to a level that contains no pathogens, no toxins, no hazardous chemicals, and no odors, and can be spread back into the environment with no public objections. Based on the above analysis, the more economical, socially acceptable, and environmentally sustainable approach may be to exploit sewage sludges for metals, nutrients, and energy. These *assets* are currently in the range of $550 in assets per ton, versus the $300−800 estimated *costs* of sludge handling, stabilization, dewatering, and land application. The industry seems far from economic sustainability. The costs of disposal and reuse are not well documented, with many utilities uncertain what fraction of capital and operational and maintenance costs are dedicated to sludge management. Moreover, many WWTPs must adjust to ever changing requirements and financial expenditures controlled by a set of ever changing local regulatory, permitting, agricultural, and public demands. Although land application is considered beneficial reuse, treatment plants do not recover costs from the end user of Class B biosolids. More efficient recovery of energy and chemical assets from sludge, however, will require new research and an overhaul of infrastructure. Many WWTPs built in 1970s are aging, expanding or needing major retrofit, thus presenting opportunities for sustainably reinventing sludge treatment and produce recovery processes.

As important as the technology, the broad concepts of sustainability must be applied to individual and overall processes to ensure that these redesigns do result in environmental, economic, and social sustainability. This includes life cycle analyses that determine and compare net energy consumption, green house gas, land, and water footprints. Economic analysis, including environmental benefits associated with removing wastewater contaminants from land and receiving streams must be included along with an analysis of public health metrics, and environmental toxicity, and emissions.

Some Candidate Technologies. *Sludge Reduction.* Producing less biomass in the first place would reduce the costs associated with treatment, management, and disposal of sewage sludges, and also reduce costs of chemical recovery by concentrating chemical assets. For example, reducing the amount of aeration during activated sludge processes through greater reliance on anaerobic process appears to offer significant energy savings opportunities. Anaerobic BOD removal produces about $^1/_{10}$th of the secondary sludge that activated sludge does[12] and a near 50% reduction in total primary and secondary sludge. The development of membrane bioreactors for anaerobic treatment circumvents many of the prior difficulties associated with longer residence times and treatment of low strength wastewater. One important trade-off is to note that relying solely on anaerobic BOD removal strategies will not significantly reduce N and P, thus requiring additional technologies to reduce N and P in wastewater effluent (e.g., Annamox for N removal, recovery of P upstream or downstream activated sludge processes) in cases where agricultural reuse cannot be performed. Other strategies for secondary sludge reduction are based on metabolic uncoupling, lysis, predation, and maintenance metabolism.[22] More broadly, the concepts of sludge reduction and sludge disposal and reuse are dependent upon upstream wastewater processes, demonstrating that efforts toward sludge sustainability must be integrated with resource recovery throughout the entire wastewater treatment facility.[14]

Energy Recovery. One approach capable of achieving several treatment and recovery goals for biosolids would be combustion-based technologies associated with incineration, gasification or liquifaction. Combustion can destroy pathogens and mineralize persistent organic chemical contaminants, while producing energy and concentrating valuable metals and inorganic chemicals. The process, however, is energy intensive for sewage sludges due to their inherent moisture content. Driers using incinerator waste heat and coincineration of sewage sludges with yard-waste and/or other refuse is practiced to circumvent this moisture barrier. If a goal is to recover metals and phosphorus, coincineration may not be the best approach as this may "dilute" the high-value element content of the ash. Modern, low emissions sludge incinerators are operated in some large U.S. municipalities and in Europe. Such incinerators are capital intensive, but are able to utilize the high temperature waste heat to produce electricity at a net energy gain and offset the total energy costs of the wastewater treatment facility.

Driven by biofuel research and the desire to extract energy and nutrients from plant and agricultural waste, several modern examples of pyrolysis or gasification are now emerging at pilot- and larger-scale. Recent attention has been given to supercritical fluids and hydrothermal liquefaction (HTL). HTL converts proteins and carbohydrates into oil, increasing potential energy recovery compared against just lipid extraction. HTL mimics, in a very accelerated manner, the natural production of crude oil from vegetative and other organic matter, which has occurred over millions of year under high temperature and pressure. Key benefits of HTL technology have been inclusion of heat recovery systems and the ability to use wet solids without a moisture penalty. Products include biocrude, bio char, and gaseous and liquid waste streams. Prior research in algae, has demonstrated that more than 80% of the N and P can be recovered into the liquid product stream.[23] Recent studies have applied HTL to sewage sludges, and that show less biocrude content, but liberation of metals (Cu, Zn, Pb, Cd, Cr, Ni) into the liquid product stream.[24] Lipid extracts or biocrude represent liquid fuel stocks that could be sold, or could be utilized-onsite to produce electricity. For all these technologies, more research is needed on incinerator ash and waste streams to optimize element recovery from specific feedstocks, and to estimate the emissions of modern equipment in comparison to other major air pollutant and greenhouse emission sources inside and outside of treatment plants. Longer-term prospects center on the amount of net energy produced, ability to recover metals and nutrients, comparisons of per ton emissions with that of homes, other industries, and other sludge reuse schemes, and cultivating a more positive public perception.

Lipids comprise 8% w/w of sewage sludge at a municipal wastewater treatment plant and recent report from Korea found it economically viable to recover lipids from sludge to produce biodiesel.[25] The two approaches that exist generally involve either organic chemical solvent extraction from dried microbial biomass or, more recently, various novel phase separations using wet biomass through supercritical CO_2 extraction, thereby offering significant energy benefits compared to drying the biomass.[26]

Phosphorus and Metals Recovery. Several physical-chemical processes for phosphorus removal already exist (e.g., struvite precipitation and pelletization), and can be integrated with existing sludge stabilization processes such as anaerobic digestion.[27] In unpublished work, we have found that adding ozone (<0.2 mgO$_3$ per mg org-P) to liberate cell-bound P, increased ortho-P and would presumably increase struvite recovery potential. Oxidation of organic N & P will produce inorganic forms, and technologies to selectively extract and/or concentrate these forms such as hybrid ion exchange resins may have the potential to produce "mobile nutrients" which could be transported to agricultural applications further away from waste water treatment plants (WWTPs).

Many elements are present in sewage sludges as colloids and particles, rather than dissolved ions. In some cases, physical separation using membranes may be feasible to recover these colloids and particles. However, it may be advantageous to lyse or oxidize sewage sludges to liberate colloids and potentially other metal forms from organic biomass. Oxidation may have the added benefits of both inactivating pathogens and transforming refractory organic contaminants of emerging concern. While ozone or other common oxidants used in water sanitation already could be used, other technologies also exist. Wet chemical oxidation involves addition of oxygen, and then under pressure (0.3−1.5 MPa) and elevated temperatures (100−130 °C), hydroxyl radicals and other oxidants are produced that can decompose organic matter and organic contaminants.[28]

Currently, few techniques have been demonstrated to recover elements of economic or regulatory concern beyond N or P. Inspiration for these technologies could emerge from other fields including mining practices or on-site recovery at plating or semielectronic manufacturing facilities. Gold ore grades range from 0.3 to 80 g per metric ton (g/t), and from 0.2 to 7 g/t in biosolids.[29] In hard rock mining practices strong acids and oxidants are used to selectively modulate redox conditions in pulverized rock to liberate metals, and then complex these metals with surfactants and/or chelating agents. One major concern is that processes for recovering metals have historically not been environmentally benign. Proposed "green" solutions using thiourea method involves pH adjustment and creating a highly oxidizing environment to separate and complex gold from soils.[30] Other strategies and technologies to recover metals from biosolids include pyrolysis, electrolysis, biobleaching or other means of lysing cellular matter to release ionic forms of metals, which can be separated using chemical precipitation, membranes or other means.[31] It is likely, but remains unvalidated, that any number of the element recovery processes—most of which involve some modulation of redox—should also create oxidizing conditions suitable for pathogen inactivation and destruction of organic contaminants of concern.

Building a Framework. Finally, socio-techno-economic research is needed to develop technology roadmaps that sustainably achieve multiple treatment objectives (recover elements, recover usable forms of fuel, inactivate pathogens, oxidize CECs). We encourage the water sanitation community to move beyond technologies in the current toolboxes, and take a systems-level approach. The age of incremental advancement (e.g., the transition from *removing* P from wastewater to *recovering* P; now let us be sure to treat for CECs) should be de-emphasized if the community desires longer-term solutions that are capable of achieving multiple treatment objectives. Regulatory acceptance should not be viewed as an initial roadblock to consideration of new technologies, because a new approach at resource recovery facilities (rather than waste treatment facilities) achieves and often exceeds the aims of the regulatory community. The public perception of investing in facilities that recover wastes and thereby help offset looming infrastructure investment should be beneficial. Finally, the examples given above represent only a small number of the potential solutions. Many other technologies exist or are emerging and some of these may not be sustainable. Inclusion of two tools could significantly accelerate both the pace of change and innovation potential. First, life cycle, economic, and toxicity analyses should be used as a guide for evaluating and ranking integrated *systems* of technologies. Second, new inspirational design modes of thinking could be brought to bear. Among these are the principles of *biomimicry* which aim to look at how the natural environment at the process, organismal or ecosystem scale deals with managing fluxes of elements and energy when they are present in concentrated forms. Wastewater treatment facilities themselves have been highly inspired by mimicking environmental transformation processes, now we should extend this to understand how the environment uses low-temperature liquid-based processes to separate and store elements or store energy.

Conclusions: We Should Expect More. Sludge management is a central component of water quality engineering. Regardless of the approach to treating wastewater, primary and secondary sludge will be produced. A future that is concerned with economics, water usage, energy conservation, beneficial reuse, recycling and environmental health will demand more of sewage sludge. We do not advocate the continuation of land application, as it has limited social and economic sustainability. Sludge management must convert from the traditional regulatory-driven treatment-based approach, to a resource recovery-based enterprise. Environmental scientists and engineers must lead by first exploring the basic science and technological options that are needed to reinvent biosolids treatment. New approaches that fully utilize sludge as an asset will require a step change, rather than a modification of current practice, and will demand new research, engineering, and infrastructure to recover energy, metals, and nutrients, while still meeting environmental protection goals. Ultimately processes must be systematically developed in conjunction with a life-cycle, economic, and human health based assessments as a framework for ensuring sustainability.

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Notes

The authors declare no competing financial interest.

Biography

Jordan Peccia is an associated professor of Chemical and Environmental Engineering at Yale University. His research interests lie at the intersection of engineering and microbiology and include human exposure to and risk of infective agents produced during the land application of biosolids.

Paul Westerhoff is a Professor in the School of Sustainable Engineering and the Build Environment and Vice Provost for Academic Research Programming at Arizona State University. He is interested in the physical and chemical characterization of water and wastewater treatment systems, including the fate of nanomaterials in biosolids.

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