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Energy positive wastewater treatment and sludge management

Veera Gnaneswar Gude

Increasing population and high living standards around the world demand for resources to maintain clean and safe environment. Wastewater needs to be processed to remove biological, chemical and physical contaminants before it can be discharged into receiving water bodies such as rivers, creeks, lakes and oceans. Current wastewater treatment processes, especially, aerated systems are energy intensive. However, wastewater is considered a rich energy source. This energy, if properly extracted, can exceed the treatment energy requirements by up to 10-fold [1]. Wastewater treatment inevitably produces large quantities of biomass (sludge) which is one of the main forms of energy feedstock [2]. A general treatment scheme includes primary (physical and chemical processes such as inorganic solids separation by sedimentation, aeration and pH adjustment) treatment followed by secondary treatment (chemical and biological treatment involving organic substrate degradation by microorganisms coupled with biochemical reactions) with successive filtration, disinfection and aeration steps. This treatment scheme is often referred to as secondary or biological treatment which is the standard for all wastewater treatment plants around the world. While wastewater treatment can be energy intensive, several options are available for making this process energy-yielding rather than an energy-consuming one.

Wastewater contains approximately 60% (dry basis) of organic compounds which are mostly biodegradable, nutrient compounds such as nitrogen and phosphorous elements, toxic inorganic and organic pollutants which include heavy metals such as Cd, Cr, Cu, Ni, Pb, Zn, and Hg and polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dioxins, pesticides, linear-alkyl-sulfonates, nonylphenols, polybrominated fire retardants, etc., pathogens and other microbiological pollutants, inorganic compounds such as siliates, aluminates, and calcium and magnesium containing compounds [2, 3]. The organic portion contains 50–55% carbon, 25–30% oxygen, 10–15% nitrogen, 6–10% hydrogen, 1–3% phosphorus and 0.5–1.5% sulfur. Nontoxic organic and nutrient compounds can be utilized to grow the microbial biomass to produce sludge which can be processed for energy recovery. Energy recovery from wastewater can be achieved in three viable configurations as shown in Figure 1. Strategy 1 includes anaerobic digestion of sludge collected from primary and secondary treatment units to meet the treatment energy expenses. However, this alone may not be adequate to generate all the energy required for wastewater treatment due to technological and scientific barriers that prevail in these systems. Instead integration of other organic wastes for co-digestion can be considered. Strategy 2 involves wastewater treatment with mixotrophic systems (i.e., bacteria and algae) to enhance carbon utilization, nutrient removal and biomass production. Strategy 3 is to use secondary effluents from the wastewater treatment plants to cultivate algae for biofuel production through thermo-chemical processes whether on-site or off-site.

Energy and sludge management issues in wastewater treatment plants can be collectively addressed by implementing the above mentioned three strategies. Several technologies are available for sludge management which include anaerobic digestion, thermochemical processes such as super- and sub-critical water (hydrothermal) processes, pyrolysis, incineration, and gasification [2, 3]. Anaerobic digestion produces biogas which can be further converted into other valuable energy forms (heat, natural gas and electricity). Thermochemical processes produce biocrude or biofuels and other value-added bioproducts while incineration can be practiced to generate electricity and ash to be used for other specific

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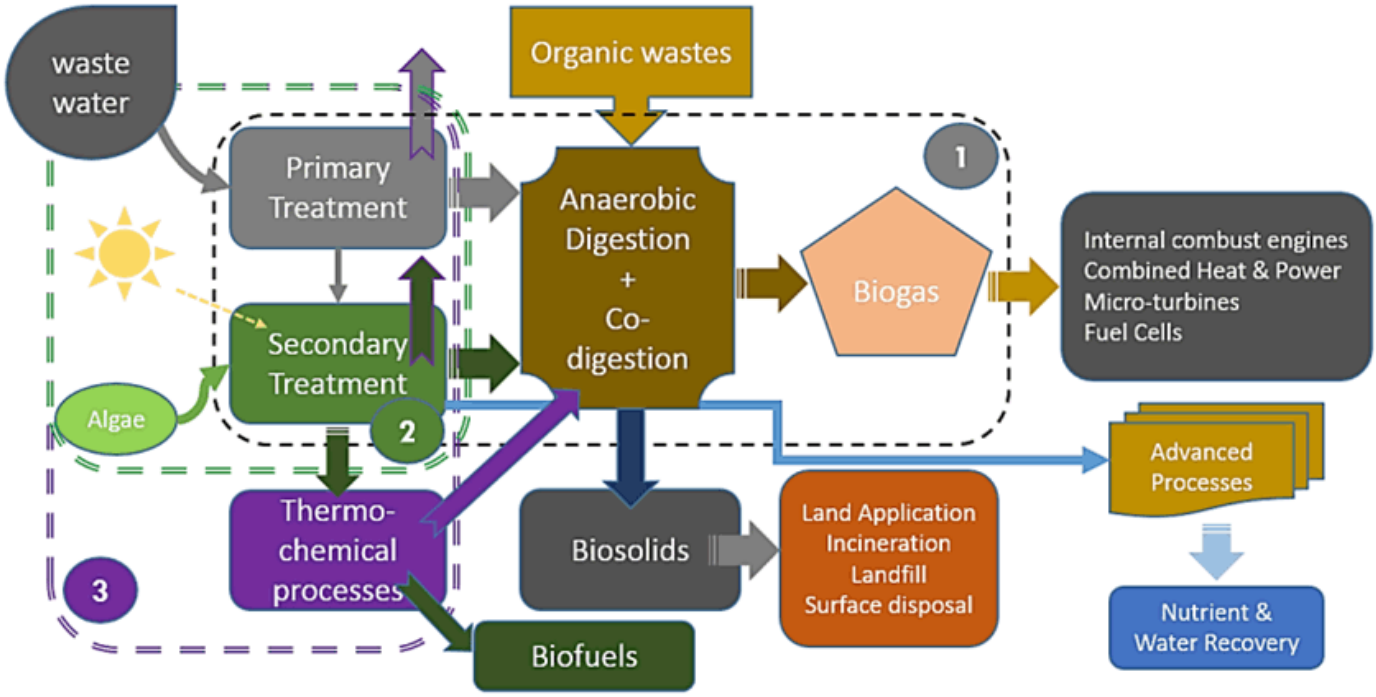

Figure 1. Possible pathways for energy-positive sludge treatment in wastewater treatment plants: 1. Enhanced primary sludge collection and co-digestion of organic wastes for biogas generation, 2. Hetero-photoautotrophic (algae-bacteria) based sludge system for co-digestion, and 3. Separate algae cultivation system or algae-bacteria system for thermochemical biofuel production.

construction applications. Among these anaerobic digestion (AD) is mostly favored due to economics and its viability [4]. Other options are available for specific cases where costs are not the primary criteria but other environmental and site-specific factors dominate the situation. Anaerobic digestion is a biochemical process which involves degradation of organic matter by bacteria under anaerobic conditions [4]. Methanogens (methane producing bacteria) present in anaerobic digesters convert organic matter into carbon dioxide (CO_2), methane gas (CH_4), and organic acids. Anaerobic digesters require less energy inputs and can tolerate solids with high water content. With anaerobic technologies as a central energy recovery unit, strategies 1 and 2 are discussed in detail.

To become energy-neutral or energy-positive, wastewater treatment facilities need to identify suitable processing schemes for energy recovery, especially from the sludge produced from the primary and secondary treatment units including AD [1]. Anaerobic digestion of wastewater sludge alone does not have the potential to generate a net positive energy ratio. Current wastewater treatment plants relying on this technology are able to achieve energy recovery up to 50% which is already on the high end and is achievable for large scale systems only with treatment capacities exceeding 10 MGD (~37,850 m^3/d) [1]. Anaerobic digestion can become energy positive when other organic wastes such as food waste, brewery and dairy wastes are included in the feed. This process is called co-digestion.

Strategy 1. Primary sludge has an energy content in the range of 15–15.9 MJ/kg and secondary sludge has a value between 12.4 and 17.3 MJ/kg [5, 6]. Therefore, use of primary treatment and secondary treatment followed by sludge co-digested with organic wastes (such as FOG – fats, oils and grease) from other industrial units may enhance the energy recovery making it even energy positive. Where co-digestion is not possible, process amendments can be pursued to increase primary sludge recovery for biogas generation.

Standalone organic waste processing facilities require a pre-treatment scheme, digesters, and biogas processing units such as a combined heat and pump (CHP) unit with an internal combustion engine which might prove to be capital intensive. These capital costs can be offset by transporting the organic wastes to the municipal wastewater treatment plants where these resources are generally available. The capital and operating costs and capital recovery options are attractive for this scheme. Since food wastes produce higher volumes of biogas, which wastewater treatment plants can sell to other end users to generate revenues. In addition, WWTPs can charge a tipping fee for processing the organic wastes. On the other hand, the organic waste is transported and treated offsite increasing aesthetic value of the industrial facility resulting in a win-win situation [7]. Other bioproducts that could be produced from AD are acetic acid, aliphatic hydrocarbons, ammonia, hydrogen, metals, methanol, phosphorous soil conditioner and thermoplastics for beneficial use in agricultural, domestic and industrial sectors. Some of the technological

developments are under experimental or pilot scale stages while others are emerging in applications or have reached commercialization status [8].

Strategy 2. In biological treatment, some of the carbon sources are converted and released in the form of carbon dioxide emissions resulting in both the loss of potential energy that could be recovered and increased environmental emissions. Algae-bacteria mixed consortium can be used to increase the carbon uptake and nutrient removal which also enhances algae and biomass production. Incorporation of sunlight and carbon dioxide sequestration by algae generates excess sludge for biogas generation. This process can be operated as mixotrophic culture meaning that the algal species does not need to be pure culture but heterotrophic and photoautotrophic algal species can be used as medium. Energy demands for this process can be reduced significantly due to in-situ production of oxygen by algae which would be available for microbial respiration and organic oxidation processes. Heterotrophic algae grow faster and help reduce the oxygen demands during non-sunlight hours. This process scheme has potential to result in energy-positive endeavour.

Co-digestion with algal sludge appears to be promising alternative. Systems integrating algal biomass tend to consume less energy for aeration, yet produce higher sludge quantities suitable for co-digestion with the microbial biomass. For example, algae based wastewater treatment can be justified by the potential to offset the high costs of wastewater treatment [9]. The U.S. has wastewater infrastructure investment requirements of $13 billion to $21 billion annually with an additional $21.4 billion to $25.2 billion required for annual operation and maintenance. In addition to revenues from the biodiesel produced by wastewater grown algae, anaerobic digestion of the leftover biomass can produce biomethane for electricity generation. Using the same biomass production calculations as above, and assuming a methane yield of 0.3 l g^{-1} for biomass after oil extraction, a methane heating value of 55,500 kJ kg^{-1}, and an electricity generation efficiency of 30%, 70.6 GWh day^{-1} of cost offsetting electricity can be produced from algae grown in U.S. wastewater treatment plants [9]. A recent analysis showed that algae integrated wastewater systems have the potential to reach energy-neutral or energy-positive status. Algae based technologies can be designed as high rate algal ponds (HRAP), photobioreactor (PBR), stirred tank reactor, waste stabilization pond (WSP), and algal turf scrubber (ATS). These systems can produce energy rich algal biomass that can be used as feedstock for high value energy products. A comparison between the anaerobic and phototrophic (algae based) technologies indicates the average bioenergy feedstock production by phototrophic technologies ranged from 1200–4700 kJ per capita per day or 3400–13,000 kJ/m^3 (exceeding anaerobic technologies and, at times, the energetic content of the influent organic carbon),with usable energy production dependent upon downstream conversion to fuels [10]. Table 1 gives the energy production potential (kJ) per g of nutrients removed from wastewater via different energy-conversion processes such as hydrothermal liquefaction (HTL), anaerobic digestion, transesterification (conversion of oils to biodiesel) and combustion. The details on this analysis are presented in detail in Shoener et al. [10].

Whether a wastewater treatment plant can reach energy-neutral or energy-positive status and cost-competitiveness depends on the process schemes used for energy conservation, efficiency, recovery and reuse. Several technologies are available to generate useful forms of energy from the biogas generated by AD. This means the energy balance depends significantly on the conversion technologies such as combined heat and power from the digester gas using internal combustion engines, or electricity from microturbines, gas turbines and fuel cells [11]. The capacities and costs for these technologies are shown in Table 2. Gas turbines or internal combustion units are the cost-effective technologies at present [11].

Strategy 3. As given in Table 1, algae biomass can be cultivated in secondary effluents rich in nutrient and dissolved carbon dioxide concentrations for biofuel production. Similar to biomass generated in algae-microorganism systems, algae biomass can be used for biofuel production by subjecting them thermochemical processes and the residues to anaerobic digestion, thus increasing energy recovery potential. Hydrothermal (thermochemical) process is promising since it produces higher biocrude volumes capturing most of the carbon content in the biomass. Studies integrating biofuel and biogas production have not been reported widely.

Sludge minimization can be indirectly pursued through bioelectrochemical systems such as microbial fuel cells or microbial electrolysis cells which sludge growth is minimized by 50–70% compared to conventional activated sludge processes [1]. These processes produce clean electricity or valuable bioproducts directly from the organic wastes. The output from current systems are low and economics do not favour their large scale application. Research needs to be aggressively pursued in this area to develop sustainable energy-positive bioelectrochemical systems.

Biosolids Management

The population receiving wastewater sanitation has increased steadily in the United States over the past decades (Figure 2). Wastewater treatment plants produce large quantities of sludge which need to be properly treated prior to disposal or other end reuse applications as biosolids. The sludge minimizing steps such as anaerobic digestion achieve drastic volumetric reductions resulting in nutrient rich biosolids which are suitable for many beneficial uses. The sludge generated from AD and its treatment and disposal continues to be the area of most concern for the wastewater treatment plants due to its economic, energetic, environmental burdens, and

legislative factors. Sludge management costs can account up to 65% of the total operating costs. About eight million tons of biosolids are generated from the wastewater treatment which serves 75% of the US population (225 millions in 2014) with sanitation needs. Biosolids can be used for various beneficial uses [12]. Figure 2 shows the

Table 1: Energy recovery potential from algae based wastewater systems [10]

Technology	Nutrient	HTL	Anaerobic digestion	Transesterification	Combustion
HRAP	N	75–160	32–160	34–100	90–130
	P	320–1500	730–1600	330–980	880–1300
PBR	N	270–590	120–580	120–370	330–500
	P	230–500	100–490	100–310	280–420
Stirred tank	P	900–1900	400–1900	400–1200	1100–1600
ATS	N	110–240	47–230	49–150	130–200
	P	580–1300	250–1200	260–790	700–1100

Table 2: Comparison of biogas-energy recovery technologies from anaerobic digesters

Technology	Size range	Electric Conversion Efficiency	CO2 Emissions Lbs/MWh	NOx Emissions Lbs/MWh	Installation cost
Microturbines	30–400 kW	23%–28%	1780–1440	0.08–0.25	2500–4300/kW
Gas Turbines	1–5.5 MW	21%–28%	1920–1440	0.17–0.20 $1200–3300/kW	
Internal Combustion Engines	1 kW–5 MW	28%–39%	1440–1030	0.06	1500–2900/kW
Fuel Cells	250 kW modules	25%–55%	1660–730	0.03	5000–6500/kW

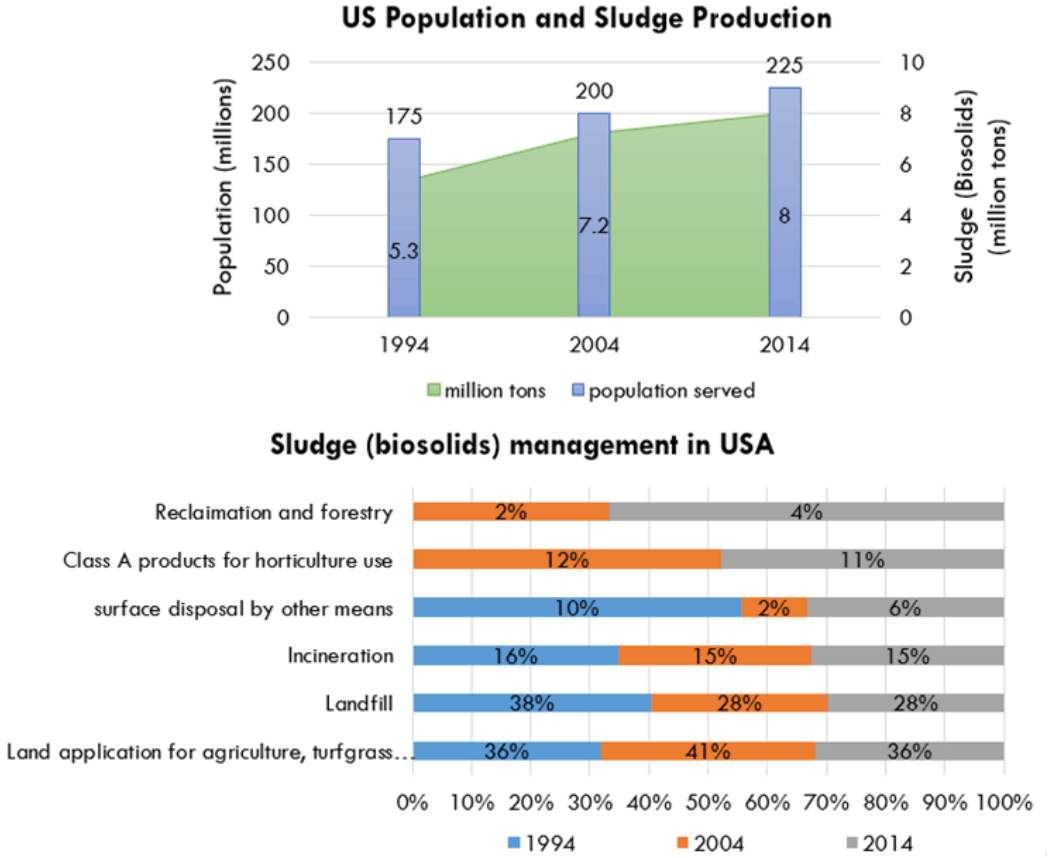

Figure 2: Sludge (biosolids) production and the management trends between 1994 and 2014 in the USA.

trends in biosolids uses and disposal practices over the past decades. It can be noticed that interest in Class A products (pathogen free and safe) for irrigation uses has increased over the past years while the sludge quantities directed to landfills declined. Reclamation and forestry applications also increased. The ideal situation would be to use all the sludge in land application, several issues that prevent utilization of biosolids for agricultural applications which include accumulation of high concentrations of metals, sulfur, chlorine, and especially nitrogen, together with other elements, such as heavy metals (zinc (Zn), copper (Cu), nickel (Ni), cadmium (Cd), lead (Pb), mercury (Hg) and chromium (Cr)), and pharmaceutical and other emerging contaminants present in wastewater [2, 3]. Bioavailability and eco-toxicity of these trace compounds should be properly quantified [13–16]. It is preferable to develop suitable processing schemes to selectively remove the metals and the emerging contaminants [8]. Removing the former might result in a revenue-generating endeavor depending on the available concentrations and the demand for the recovered products. This reduces the biosolids that end up in landfills or are used in incineration plants to generate energy.

Concluding remarks

Wastewater sanitation continues to be the most fundamental need for sustainable environment and human development. The inevitable energy consumption and excess sludge production issues should be dealt with together to result in an energy-positive endeavour to eliminate associated environmental emissions. Co-digestion of other organic wastes should be pursued where feasible. Integrated approaches to wastewater treatment with algal cultivation systems are viable alternatives for sustainable energy recovery from wastewater. Biofuel production schemes based on thermochemical process and incineration should be carefully evaluated for their net emissions in all forms, i.e., air, liquid and solid phases and a basic insight into the nitrogen, sulfur, chlorine transformations and heavy metals mobility is crucial for safe utilization of sludge as an energy source.

Reinforcement of environmental laws and regulations in many developed and developing countries create an urge for the municipalities to produce safe, valuable and nutrient rich biosolids suitable for various beneficial end uses. This process can be sustainable only if it is environmentally-friendly, economically affordable, and technically feasible, and socially acceptable. Land application seems to be the most acceptable, convenient, and environmentally-friendly approach provided it is safe and the quality of biosolids meets the required standards. Landfills are not an option for long-term sustainable management of biosolids and this option should be a last resort for waste management. Proper treatment techniques should be developed to generate biosolids suitable for more land applications such as irrigation.

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The corresponding author is the guarantor of submission.

Conflict of Interest

Authors declare no conflict of interest.

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