Renewable and Sustainable Energy Reviews 25 (2013) 708–728

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Sludge: A waste or renewable source for energy and resources recovery?

Vinay Kumar Tyagi, Shang-Lien Lo*

*Graduate Institute of Environmental Engineering, National Taiwan University, Taiwan, Republic of China*

ARTICLE INFO

*Article history:*
Received 1 December 2012
Received in revised form
25 March 2013
Accepted 8 May 2013

*Keywords:*
Sludge
Energy and resource recovery
Renewable
Sustainable

ABSTRACT

Utilization of waste sludge as a renewable resource for energy recovery is the appropriate solution of how to manage the continuously increasing waste sludge generation effectively in order to meet stringent environmental quality standards, and at the same time, how to sustain the supply of reliable and affordable energy for our future generations and ourselves. The valuable characteristics of sludge, including high energy and nutrient content, with the stringent criteria of sludge disposal, driving the environmental engineers and scientist to change their standpoint to considering sludge as a viable resource of energy instead of a waste. It may be an important move towards the development of a sustainable energy solution to fulfill present and future energy requirements and thus reduce the dependency on non-renewable resource. Thus, this review discusses about the type of resources that can be recovered from waste sludge and, conventional and emerging methods used to convert the sludge into valuable resources. Moreover, the major factors involved in the process, stage of application, advantages and possible drawbacks of the methods are also discussed.


**Contents**



*Abbreviations:* AD, anaerobic digestion; ALWA, artificial lightweight aggregate; AOP, advanced oxidation process; BNR, biological nutrient removal; Bt, *Bacillus thuringiensis*; C/N, carbon to nitrogen ratio; CHP, combined heat and power; DO, dissolved oxygen; DS, dry solids; FFA, free fatty acids; HPH, high pressure homogenizer; HRT, hydraulic retention time; kWh, kilowatt per hour; LHV, low heating value; MFC, microbial fuel cells; mgd, million gallon/day; MPa, megapascal; MT, metric ton; MW, megawatt; MW, microwave; MWh, megawatt per hour; NACWA O&M, National Association of Clean Water Agencies Operation and Maintenance; OLR, organic loading rate; p.e., population equivalent; PAH, polycyclic aromatic hydrocarbons; PAO, polyphosphate accumulating organisms; PCB, polychlorinated biphenyls; PCB, printed circuit board; PHA, polyhydroxyalkanoates; PHB, poly-β-hydroxybutyric acid; SCOD, soluble chemical oxygen demand; SCWO, supercritical water oxidation; SRT, sludge retention time; SS, suspended solids; STORS, sludge to oil reaction system; TCOD, total chemical oxygen demand; TKN, total kjeldahl nitrogen; TOC, total organic carbon; TP, total phosphorus; TS, total solids; UASB, up-flow anaerobic sludge blanket; USEPA, United States Environmental Protection Agency; VFA, volatile fatty acids; VS, volatile solids; VSS, volatile suspended solids; w/v, weight by volume; w/w, weight by weight; WAO, wet air oxidation; WAS, waste activated sludge; WWTP, wastewater treatment plant

* Correspondence to: Graduate Institute of Environmental Engineering, National Taiwan University, No.71, Chou-Shan Road, Taipei 106, Taiwan. Tel.: +886 2 2362 5373; fax: +886 2 2392 8821.
*E-mail addresses:* vinayiitrp@gmail.com (V.K. Tyagi), sllo@ntu.edu.tw (S.-L. Lo).

1364-0321/$ - see front matter 
http://dx.doi.org/10.1016/j.rser.2013.05.029

## 1. Introduction

The growing global urbanization of society coupled with increasingly stringent sludge reuse/disposal regulations and increasing public pressure, is forcing both public and private sludge generators to re-evaluate their sludge management strategies [1]. Conventionally, the waste sludge is disposed via incineration, landfilling or ocean disposal as well as reused as soil conditioner in agriculture. With the recent banning of ocean disposal and new stringent European landfilling criteria, much more sludge is now beneficially reused, both in agriculture and via a variety of thermal technologies [2]. The selection of a sludge management strategy is of interest to a wide variety of groups including facility owners, engineering consultants, contract operators, equipment suppliers, politicians, regulators, environmental groups and the general public. Selection of a sludge management strategy based on the actual needs of the community rather than on some artificial set of criteria is probably the single most important component in achieving long-term sustainability [3]. It is anticipated that upcoming sludge management efforts will accentuate upon the recovery and reuse of value added crops from sludge [4]. This interest in renewable energy has been driven by a combination of shrinking reserve of fossil fuels due to rising demand for primary energy, fuel price spikes, climate change concerns, public awareness, and advancements in renewable energy technologies [5,6].

The two components in sludge that are technically and economically feasible to recycle are nutrients (primarily nitrogen and phosphorus) and energy (carbon) [3]. There are several options available for energy recovery from waste sludge. The utmost significant routes are anaerobic digestion of sludge with biogas recovery, co-digestion, incineration and co-incineration with energy recovery, pyrolysis, gasification, supercritical (wet) oxidation, use in the production of construction materials, production of bio-fuels (hydrogen, syngas, bio-oil), electricity generation by using specific microbes, and beneficial recovery of heavy metals, nutrient (nitrogen and phosphorus), protein and enzymes. Thus the present efforts are aimed to provide an overview, and discuss the ways to achieve more sustainable sludge management strategy by recovering the energy rich products.

## 2. Sludge characterization

Sewage sludge is a complex heterogeneous mixture of micro-organisms, undigested organics such as paper, plant residues, oils, or fecal material, inorganic materials and moisture [7]. The undigested organic materials contain a highly complex mixture of molecules coming from proteins and peptides, lipids, polysaccharides, plant macromolecules with phenolic structures (e.g. lignins or tannins) or aliphatic structures (e.g. cutins or suberins), along with organic micro-pollutants such as polycyclic aromatic hydrocarbons (PAH) or dibenzofurans [8]. Table 1 depicts the characteristics of primary and secondary activated sludge.

Primary sewage sludge is generated through mechanical (screening, grit removal, sedimentation) wastewater treatment

**Table 1**
Characteristics of primary sludge and activated sludge [10].

| Parameter | Primary sludge | Activated sludge | Composition |
|---|---|---|---|
| Total dry solids (total solids, TS) % | 5–9 | 0.8–1.2 | • Non-toxic organic carbon compounds (appx. 60% on dry basis), Kjeldhal-N, phosphorus containing components. |
| Volatile solids, VS (%TS) | 60–80 | 59–68 | |
| Nitrogen (%TS) | 1.5–4 | 2.4–5.0 | • Toxic pollutants: heavy metals (Zn, Pb, Cu, Cr, Ni, Cd, Hg, As: Concentration vary from 1000 mg/L to less than 1 mg/L), polychlorinated biphenyls (PCB), PAH, Dioxins, Pesticides, Endocrine disrupters, Nonyl-phenols. |
| Phosphorus (%TS) | 0.8–2.8 | 0.5–0.7 | |
| Potash ($K_2O$ %TS) | 0–1 | 0.5–0.7 | |
| Cellulose (%TS) | 8–15 | 7–9.7 | |
| Iron (Fe g/kg) | 2–4 | – | • Pathogens and other microbiological pollutants. |
| Silica ($SiO_2$%TS) | 15–20 | – | • Inorganic Compounds: Silicates, aluminates, calcium and magnesium containing compounds. |
| pH | 5.0–8.0 | 6.5–8.0 | |
| Grease and fats (%TS) | 7–35 | 5–12 | • Water, varying from a few percent to more than 95%. |
| Protein (%TS) | 20–30 | 32–41 | |
| Alkalinity (mg/L as $CaCO_3$) | 500–1500 | 580–1100 | |
| Organic acids (mg/L as acetate) | 200–2000 | 1100–1700 | |
| Energy content (kJ/kg TS) | 23,000–2900 | 19,000–23,000 | |