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Zhongzhe Liu
Marquette University, zhongzhe.liu@marquette.edu

Brooke Mayer
Marquette University, Brooke.Mayer@marquette.edu

Kaushik Venkiteshwaran
Marquette University, kaushik.venkiteshwaran@marquette.edu

Saba Seyedi
Marquette University

Arun S.K. Raju
University of California - Riverside

See next page for additional authors

Authors

Zhongzhe Liu, Brooke Mayer, Kaushik Venkiteshwaran, Saba Seyedi, Arun S.K. Raju, Daniel Zitomer, and Patrick J. McNamara

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Zhongzhe Liu
Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI
Department of Physics and Engineering, California State University-Bakersfield, Bakersfield, CA
Brooke K. Mayer
Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI
Kaushik Venkiteshwaran
Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI
Saba Seyedi
Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI

Arun S.K. Raju

Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT), Department of Chemical and Environmental Engineering, University of California, Riverside, CA

Daniel Zitomer

Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI

Patrick J. McNamara

Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI

Abstract

Wastewater resource recovery facilities produce wastewater solids that offer potential for energy recovery. This opinion article provides a perspective on state-of-the-art technologies to recover energy from sludge (unstabilized wastewater residual solids) and biosolids (stabilized wastewater solids meeting criteria for application on land). The production of biodiesel fuel is an emerging technology for energy recovery from sludge, whereas advancements in pretreatment technologies have improved energy recovery from anaerobic digestion of sludge. Incineration is an established technology to recover energy from sludge or biosolids. Gasification, and to a greater extent, pyrolysis are emerging technologies well-suited for energy recovery from biosolids. While gasification produces high-energy gases, pyrolysis has the benefit of producing biochar in addition to pyrolysis gas. Research on the use of pyrolysis liquids, however, must proceed to advance pyrolysis implementation efforts. Future research on improvements to dewatering and drying of sewage sludge and biosolids will help advance all technologies reviewed.

Keywords

Pyrolysis, Gasification, Anaerobic digestion, Biodiesel, Sludge, Biochar

Introduction

Increasing population adds additional strain on Water Resource Recovery Facilities (WRRFs), municipal infrastructure previously referred to as wastewater treatment plants [1]. WRRFs were conventionally designed to meet pollutant discharge limits and simply remove pollutants. WRRFs are now considered opportunities to recover nutrients, generate value-added products, and produce energy, all while, treating water for various reuse options. WRRF-derived biosolids, i.e. the stabilized organic material resulting from treatment of domestic sewage and meeting federal guidelines for application on land, are a nutrient-rich product with value as a soil amendment. Concern over the presence of contaminants can limit demand for land applied biosolids and cause WRRF managers to search for alternative options for beneficial use of WRRF biosolids. Energy extraction from biosolids should be a primary incentive, as will be outlined in this article.

In this opinion article, we evaluate beneficial use options beyond biosolids land application, focusing on technologies to recover energy from wastewater solids. We distinguish two types of wastewater solids: sludge, defined as solids not yet digested or otherwise stabilized, and biosolids, as defined above. We evaluate biodiesel production and anaerobic digestion (AD) to recover energy from sludge. We evaluate incineration, gasification, and pyrolysis to recover energy from biosolids. We look at the current state-of-the-art, including commentary on which waste-to-resource treatment technologies are well developed and which require more research to meet their potential.

Biodiesel production

In biodiesel production, lipids are extracted from the feedstock, converted to fatty acid methyl esters via transesterification, and purified. Wastewater sludge, i.e. unstabilized wastewater residual solids not yet suitable for application to land, is a promising raw material for biodiesel production because it contains 5–20% w/w lipids [2,3]. However, to transition from current bench-scale tests to full-scale implementation, challenges related to production (e.g., feedstock, dewatering) and biodiesel quality must be addressed [4].

For biodiesel production, wastewater can either be used to culture oleaginous microorganisms to accumulate lipids or wastewater sludge can be used to directly extract lipids (e.g., sludge drying followed by physical grinding of the solids and solvent extraction of lipids), both of which are potentially net negative greenhouse gas processes [5]. Chen et al. (2018) [2] found that direct extraction of lipids from dry sludge was more cost effective compared with the sludge-cultivated microbes and soybean-derived biodiesel. In an alternative wastewater-derived approach, Anderson et al. (2018) conducted pilot-scale tests of a floatable wastewater scum-to-biodiesel transesterification system that produced biodiesel in compliance with all ASTM D6751 Standards at a cost of $0.36/L [6]. The scum-to-biodiesel technology was estimated to provide higher revenue and greater environmental benefits in comparison to AD and incineration of scum [7].

As dewatering and drying can account for 50% of total biodiesel production costs[8], innovations focused on wet sludge extraction are important. Kech et al. (2018) [8] tested a range of solvents in wet sludge and found that cyclohexane/isopropyl alcohol/water was best on the basis of lipid yield (34.5% wt dry matter) and avoidance of chlorinated solvents. Lipid extraction from wet biomass has been reported to be as efficient as extraction from dry biomass [2]. Choi et al. (2019) [4] tested wet *in situ* transesterification using xylene as a high boiling point co-solvent and observed good biodiesel yield (11%) at a production cost of $5.76/L (9% less than using the conventional drying method) [4]. After purification, the biodiesel complied with major biodiesel standards in EN 14214 [4].

In addition to biodiesel production, transesterification of waste activated sludge (WAS) can reduce sludge production and improve anaerobic digester performance. In spite of the relatively high energy input, using transesterification before AD could improve net energy gain by three-fold [9]. Transesterification-treated WAS was more readily biodegradable compared with thermal NaOH treatment, suggesting that recycling of the lysis product into the aeration basin could promote cryptic growth while reducing sludge production (maximum of 48% reduction observed) [10]. Alternately, postextraction, the sludge may undergo evaporation for solvent recovery, followed by typical routes of final disposal (e.g., landfill or land application) [5].

Anaerobic digestion

AD technology is seen as an essential part of modern WRRFs for recovering energy from WAS in the form of methane gas [11]. The recovered methane can cover part of the energy requirements and reduce costs for WRRFs. AD includes biological steps of hydrolysis, acidogenesis (fermentation), acetogenesis, and methanogenesis, each involving different groups of microorganisms [12]. Generally hydrolysis is the rate limiting step for WAS digestion [11]. WAS components such as extracellular polymeric substances and cell walls are especially difficult to hydrolyze [13]. To improve energy recovery via AD, most recent studies have focused on developing WAS pretreatment/disintegration methods to increase the rate of biological methane production. Several methods have been studied, including mechanical (grinding, ultrasonic, microwave, and high-pressure homogenization) [14, 15, 16], thermal [13], chemical (acidic, alkali, and chemical oxidation) [17,18], and biological (hydrolytic enzymes or microorganisms) [19] pretreatment options; several patented mechanical and thermal processes have been commercially implemented. Most pretreatment methods demonstrated an increase in methane production from 10% to over 100% [11]. Common limitations for thermal and mechanical processes are their high capital costs, energy demand and operation, and maintenance requirements [11]. Chemical processes have lower energy demand than thermal but high chemical costs. Additionally, chemical pretreatment can cause corrosion and form undesirable compounds during the pretreatment process [11]. Biological pretreatment technologies (hydrolytic enzymes or microorganisms) are promising as they have a lower energy demand. However, biological processes are still in a relatively nascent stage, and further investigation is needed [11].

Incineration/combustion

Biosolids (or even sludge) incineration (combustion) thermally oxidizes organic solids with oxygen for energy recovery. Incineration is a commercially available technology, and energy conversion using different incinerators such as multiple hearth and fluidized bed has been fully studied. Because incineration is already mature, recent research has focused on the environmental impact of this process, including emissions and the utilization of byproducts.

Conventional heavy metal emissions from biosolids incineration are still of great interest. Takaoka et al. (2017) confirmed that wet scrubbers effectively removed Hg emissions from sludge in two incinerators and a melting furnace [20]. Bairq et al. (2018) found that chlorinating agents ($MgCl_2$ and KCl) increased heavy metal removal efficiency from incineration ash, especially Cu, Zn, and Pb [21]. Chlorine also weakened the affinity between Cu and minerals in the sludge such as Al_2O_3, CaO, and Fe_2O_3 [22].

The major incineration byproduct, incinerated biosolids ash, has several uses. Lin et al. (2018) showed that ash can be used as a land reclamation material [23]. Joseph et al. (2019) found that ash with high P solubility significantly increased soil available P [24]. Ash can also be used as an additive in construction materials such as geopolymer [25]. Furthermore, ash can improve AD; however, the heating value of the ash-added digestate is reduced, affecting the energy recovery potential during biosolids incineration. Therefore, an energy balance is required to assess the overall efficiency [26].

Gasification

Gasification is the thermochemical conversion of carbonaceous feedstocks to a high energy gas product, synthesis gas (syngas), in the presence of a gasifying agent (air, oxygen, steam, or hydrogen). Gasification uses high temperatures (700–1400 °C) and a range of pressures (atmospheric to 35 bar) in an oxygen-deficient environment to achieve near complete conversion of the feed carbon [27,28]. Gasification is a pathway for energy recovery from biosolids or sludge, particularly to produce high-value fuels and chemicals including syngas, hydrogen, renewable methane, and synthetic liquid fuels. However, biosolids or sludge pose significant challenges as a feedstock because of high water content, high ash content, tar formation tendency, contaminants such as sulfur and nitrogen, and resource scarcity [27,29, 30, 31, 32]. Considerable energy must be expended in drying the biosolids or sludge because most gasification technologies require a feed moisture content of less than 35% (often 20% or less) [29,33,34]. Tar formation in the gasifier is a major challenge resulting in fouling and downstream catalyst deactivation [29,33]. Biosolids or sludge have a high ash content (20–40% dry basis), which results in clinkering and poor gas diffusion [31,34]. Biosolids and sludge, by nature, are a distributed resource, and commercial viability of energy recovery is a major issue, even in highly populated areas [35]. One way to address the resource scarcity and high water content is to co-gasify biosolids or sludge with other renewable feedstocks such as municipal solid waste, conventional biomass, etc. [31,32].

Although commercial success has not been achieved for wastewater solids gasification, a number of "wet" gasification technologies designed to accept high moisture content feedstocks are under development [28]. Examples include the Japanese EBARA fluidized bed technology (co-gasification), the VERENA group and University of Twente pilot projects (supercritical gasification), and KOPF gasification technology (solar drying followed by a fluidized bed) [36,37]. Projects are often developed for combined heat and power because of the gas cleanup and scale requirements of fuel production. Much of the current research is focused on gasification of dried biosolids with high solid content (70–95%) in bench-scale rotary kiln gasifiers, fixed bed, downdraft, and fluidized bed gasifiers [29,31, 32, 33, 34, 35].

Overall, gasification is a possible option for energy recovery from biosolids, but commercial potential is severely limited except in the cases of co-mingled feedstocks and integrated bio-refineries. Even for these cases, considerable research, development, and demonstration is still required. Options such as the fixed bed or downdraft gasifiers may become attractive when waste volume reduction and heat or power generation are the goals.

Pyrolysis

Pyrolysis is the decomposition of organic materials to solid, liquid, and gas at high temperatures with limited or no oxygen. Biochar, the solid product, is charcoal that can sequester carbon, increase plant growth [38], and have other beneficial uses [39]. The pyrolysis gas (py-gas) is composed of hydrogen, carbon monoxide, and other constituents and is a fuel, releasing approximately 1500 kJ/kg gas [40]. Two pyrolysis liquids are produced: a light nonaqueous phase liquid called pyrolysis oil (py-oil) that can be conditioned and used as a liquid fuel and an aqueous pyrolysis liquid (APL) that currently has no known use. Pyrolysis is likely to follow stabilization technologies such as AD, and therefore, research has been conducted on biosolids. In addition to energy generation, benefits of biosolids pyrolysis include reduced volume, minimized pathogen, and emerging contaminant concentrations, and total estrogenicity reduction while producing a value-added soil amendment product, biochar [41, 42, 43].

More research and development are required before achieving reliable, net energy positive biosolids pyrolysis at full scale. While the pyrolysis product py-oil could be a liquid fuel on the basis of energy content, the py-oil requires energy to remove water, organic acids, and other constituents that render it corrosive and difficult to combust using standard equipment. To preclude the need for py-oil conditioning, researchers have investigated methods to reduce or eliminate py-oil yield while increasing the yield of relatively clean-burning py-gas. In autocatalytic pyrolysis, previously produced biochar (-containing metals, e.g., Ca^{+2}, Mg^{+2}) is added to produce more py-gas from py-oil [44]. Other potential methods to decrease energy use or increase energy generation include microwave-assisted pyrolysis [45,46] and AD of the currently unusable APL to generate methane for energy [47].

APL is currently a waste with no apparent use [47,48]. In theory, the APL produced from the pyrolysis of anaerobically digested biosolids could be fed back to the digester as it contains numerous organic compounds including acetic acid that can serve as a substrate for AD [47,49]. However, toxic organics in APL hinder AD. Seyedi et al. (2018) reported the APL contains aromatics including phenols, xylene, ethylbenzene, cresol, and acetophenone as well as acetic acid and nitrogen-containing organics [50]. APL can contain high NH_3–N which also exerts toxicity during AD. Stripping NH_3–N reduced toxicity of APL at low organic loading rates, but inhibition still occurred at high loading rates, indicating that NH_3–N is not the sole reason for AD inhibition [47]. AD of APL derived from corn stalk pyrolysis under 400 °C was carried out using unacclimated methanogenic culture, and methane production was inhibited [51]. The toxicity of APL generally increases as pyrolysis temperature increases [52]. AD of APL could be a promising approach to recover energy; however, more research is required on pretreatment to remove toxic compounds and on biomass acclimation.

Additional considerations

Wastewater solids moisture content substantially affects energy requirements of the above technologies, and thus dewatering and drying processes are key steps to recover energy from sludge and biosolids. The entire wet biosolids treatment process, including steps for gasification or pyrolysis, might not be net energy positive under existing conditions. More research is required to derive accurate energy balances under variable scenarios. For pyrolysis, the balance typically includes energy production from the py-gas and py-oil as well as energy usage for dewatering, drying, and pyrolysis. Biochar is typically used as a soil conditioner rather than as a fuel because it is a beneficial soil amendment. Pyrolysis of previously thickened and dried biosolids has been reported to be net energy positive if the thickening/drying energy demand is not considered [53,54] Some suggest that pyrolysis of dewatered biosolids with a total solids concentration above 25–50% can result in net positive energy, whereas lower total solids concentrations require more energy for drying [53,55]. Additionally, biochar could be used as a fuel with py-oil and py-gas to attain net positive energy [40]. Currently, the moisture content of the raw biosolids dictates to a large extent the economic feasibility of implementing a process such as pyrolysis, gasification, or incineration. Water in sludge also negatively affects transesterification reactions, making sludge drying a prerequisite in most cases [4,8].

Therefore, processes that reduce drying energy demands increase the overall energy value of wastewater solids. Recent advances include the use of renewable energy for drying wastewater solids, e.g., geothermal energy is viable for areas with access to geothermal fluids [56]. An integrated drying system combining biogas from AD with solar energy had an estimated payback period of 3.4 years [57]. As the wastewater industry develops more efficient sludge drying systems, energy recovery processes such as transesterification, gasification, and pyrolysis will become more viable.

Factors not described in detail will also affect energy recovery technology viability. Biochar, e.g., might be sold at a very high price as supply is low during the early adopters phase. As more utilities employ pyrolysis, the price of biochar will drop and will affect the final cost-benefit analysis. Other aspects such as biochar toxicity or ash toxicity from specific feed wastes need to be considered before use, as do any air permit issues. Operation and maintenance (O&M) costs are well established for mature technologies such as AD or incineration and would be high for new technologies such as pyrolysis. The advantages of generating value-added products versus added capital and O&M costs must be weighed for each individual utility. Research will continue to advance these technologies as we look for opportunities to recover energy from wastewater solids.

Conflict of interest statement

Nothing declared.

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