Thermal Effects

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ABSTRACT: This review focuses on the research literatures published in 2015 relating to topics of thermal effects in water pollution control. This review is divided into the following sections: biological nitrogen and phosphorus removal, wastewater treatment for organic conversion, industrial wastewater treatment, anaerobic digestion of sewage sludge and solid waste, sludge biochar preparation and application, pyrolysis of sewage sludge, reduction heavy metal in sewage sludge and soil, and other issues of wastewater and sludge treatment.

KEYWORDS: thermal effects, biological nitrogen and phosphorus removal, wastewater treatment for organic conversion, industrial wastewater treatment, anaerobic digestion of sewage sludge and solid waste, sludge biochar preparation and application, pyrolysis of sewage sludge, reduction heavy metal in sewage sludge and soil.

doi: 10.2175/106143016X14696400495730

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Biological Nitrogen and Phosphorus Removal

The short-term effect of temperature on the maximum biomass specific activity of anaerobic ammonium oxidizing (anammox) bacteria was reported by Lotti et al. (2015). The results indicated that for the anammox conversion, the temperature dependency could not be accurately modeled by one single Arrhenius coefficient as typically applied for other biological processes. The temperature effect increased at lower temperatures. Adapted anammox sludge had a higher specific rate at lower temperature. Anammox sludge cultivated in an aerated partial nitritation/anammox process and/or in biofilm seemed to be less influenced be a decrease in temperature than anammox sludge grown under non-arated conditions and/or in suspension.

Lackner et al. (2015) compared partial nitritation-anammox in two laboratory-scale reactors, a sequencing batch reactor (SBR) and a moving bed biofilm reactor (MBBR). Experiments were carried out with realistic seasonal temperature variations over a 1-year period. The results revealed that both systems had to face the decrease of ammonium conversion rates and nitrite accumulation at a temperature lower than 12 °C. The SBR did not recover from the loss in anammox activity even when the temperature increased again. The MBBR only showed a short nitrite peak and recovered its initial ammonium turnover when the temperature rose back to >15 °C.

The influence of temperature on the anammox process for high salinity wastewater was investigated by Xing et al. (2015). Four upflow anaerobic sludge blanket reactors were operated in parallel at ambient temperatures from 25 to 9 °C and thermostatic room temperatures of 35 ± 2 °C. The results demonstrated that low ambient temperature and high sodium levels impaired the nitrogen removal performance of anammox granular sludge. The anaerobic ammonium-oxidizing bacteria gradually adapted to a salt concentration of 15 g/L at low ambient temperature, and a nitrogen removal rate of 1.34 ± 0.12 kg N/m^3·d was achieved, compared with 1.90 ± 0.01 kg N/m^3·d at a salt concentration of 15 g/L and a temperature of 35 ± 2 °C.

Partial nitritation for a low-strength wastewater (70 mg NH_4^+–N) at low temperature was stably achieved in an aerobic granular reactor in continuous mode (Isanta et al., 2015). The temperature progressively decreased from 30 to 12.5 °C, and a suitable effluent nitrite to ammonium concentrations ratio to a subsequent anammox reactor was maintained stable during 300 days at 12.5 °C. The average applied nitrogen loading rate at 12.5 °C was 0.7 ± 0.3 g N/L·d, with an effluent nitrate concentration of only 2.5 ± 0.7 mg NO_3^-–N/L. The biomass fraction of nitrite-oxidizing bacteria in the granular sludge decreased from 19% to only 1% in 6 months of reactor operation at 12.5 °C. *Nitrobacter* spp. were found as the dominant NOB population, whereas *Nitrospira* spp. were not detected.

Activity and growth of anammox biomass on municipal wastewater was researched by Michele et al. (2015). The reactors were operated at a total nitrogen (TN) concentrations in the range of 5-20 mg/L. Anammox activities reached 465 mg/L·d at 29 °C with minimum doubling time of 18 d. The Lower temperature of 12.5 °C resulted in a significant decrease in activity to 46 mg/L·d and the doubling time was 79 d.

A novel system integrating Johannesburg (JHB) and sulfur autotrophic denitrification (SAD) process was proposed by Li et al. (2015), to enhance nitrogen removal in treating low COD/TN ratio (COD 129 mg/L, TN 29 mg/L on average) municipal wastewater at low temperature (12.2 ± 0.5 °C). The results showed that under a HRT of 11.3 h, the average effluent COD, TN, and NH_4^+-N of JHB process were 32, 13.8, and 1.6 mg/L, respectively. It was found that 87.0 % JHB effluent nitrogen was removed by SAD process under the most efficient nominal hydraulic retention time (HRT) of 0.32 h. The SAD process effluent of COD, TN, and NH_4^+–N were 21, 1.8, and 1.0 mg/L, respectively. Most importantly, the JHB-SAD system could achieve complete nitrogen removal theoretically as long as the NH_4^+–N was sufficiently oxidized.

With inoculum sludge from a conventional activated sludge wastewater treatment plant, the formation of aerobic granular sludge (AGS) for simultaneous organic and nutrient removal in three SBRs at different high temperatures (30, 40 and 50 ± 1 °C) was studied by Halim et al. (2015). The complete cycle time of SBRs was 3 h. The results revealed that granules developed at 50 °C have the highest average diameter of 3.36 mm, and the removal efficiency of COD, ammonia and phosphate was 98.17%, 94.45% and 72.46%, respectively. The study also demonstrated that the AGS formed at high temperatures was suitable for hot climate conditions.

Liu et al. (2015) studied the accumulation of denitrifying polyphosphate-accumulating organisms (DNPAOs) using an improved SBR system in which anaerobic-aerobic-anoxic and anaerobic-anoxic were adopted at a low temperature of 15 °C. The results indicated that it was feasible to accumulate DNPAOs with concurrent nitrogen and phosphorus removals in the improved SBR system. Moreover, a DNPAOs strain was isolated and was identified as *Acinetobacter* sp. J6. The strain J6 had the highest N and P removal rates under an original pH of 8.0, a total phosphorus (TP) concentration of 4.16 mg/L and a temperature of 15 °C.

Dong et al. (2015) produced immobilized pellets entrapping activated sludge in waterborne polyurethane, and applied to treat ammonium (NH_4^+–N) synthetic wastewater in SBRs at low temperatures. The oxygen uptake rate of immobilized pellets reached 240.83±15.59 mg O_2/(L·h), and the oxygen was primarily consumed by the bacteria on the pellet surfaces (0–600 μm). The dosing of the pellets (30 ml/L) into an SBR significantly improved the nitrification efficiency at low temperatures of 7–11 °C, achieving an average NH_4^+–N removal of 84.09%, which is higher than the removal of 67.46% observed for the control group.

Modeling of multimode anaerobic/anoxic/aerobic (AAO) wastewater treatment process at low temperature of 12.5 °C was studied by Zhou et al. (2015). Influences of sludge retention time (SRT) on effluent quality, functional biomass and operating cost were evaluated for each mode, and the AAO showed a better performance at SRT of 5–25 d under the same operating cost for its higher pollutant removal efficiency and concentration of phosphorus-accumulating organisms. Furthermore, the optimal condition was obtained using mixed liquor recirculation of 100%, returned activated sludge of 50%, and SRT of 16 d.

Sayi-Ucar et al. (2015) conducted a long-term study on the impact of high temperature on enhanced biological phosphorus and nitrogen removal in membrane bioreactor. The MBR system was operated at relatively high temperatures (24–41 °C). The TP removal gradually increased from 50% up to 95% while the temperature descended from 41 to 24 °C. At high temperatures, anaerobic volatile fatty acid (VFA) uptake occurred with low phosphorus release implying the competition of glycogen accumulating organisms (GAOs) with polyphosphate accumulating organisms (PAOs). The gross membrane flux was 43 LMH corresponding to the specific permeability of 413 LMH/bar at 39 °C in the MBR tank. The specific permeability increased by the factor of 43% at 39 °C compared to that of 25 °C during long-term operation.

Ma et al. (2015) assessed a long-term investigation of a novel electrochemical membrane bioreactor (EMBR) for low-strength municipal wastewater treatment under low temperature. At lower temperatures (<10–15 °C), power production in the EMBR was negligible and therefore the integration did not improve the reactor performance. With the rebound of water temperature over 15–20 °C, efficient redox reactions were achieved in the EMBR, which subsequently resulted in sludge reduction (27.3% lower than the control MBR) and membrane fouling alleviation. The total nitrogen removal efficiency of the EMBR averaged 78.2% at high temperatures, despite the decrease of organic loading rate of the feed for heterotrophic denitrification. Energy balance analysis indicated that the total energy consumption of the EMBR decreased by 20% compared to that of the control MBR (0.386 kWh/m^3 wastewater).

Huang et al. (2015) applied a deep-sea psychrotolerant bacteria to improve the performance of wastewater treatment by aerobic dynamic membrane bioreactors (ADMBR) at low temperature. Compared to the control reactor, the bioaugmented reactor showed a shorter start-up period, and better wastewater treatment performance at ≤15 °C for a sudden decrease, and ≤7 °C for a gradual decrease in temperature. Severe membrane fouling was not observed with bioaugmentation and the nonwoven fabric module was convenient to clean with tap water. Fluorescence in situ hybridization (FISH) analysis displayed the dominance of two inoculated strains at the low temperature of 5 °C.

The effect of temperature on microalgal ammonium uptake was investigated by Ruiz-Martínez et al. (2015). Experiments were carried out with a mixed culture of microalgae, composed mainly of *Scenedesmus* sp. within the usual temperature working range in Mediterranean climate (15–34 °C). Ammonium removal rates increased with temperature up to 26 °C and stabilized thereafter. Ratkowsky and Cardinal temperatures models demonstrated that the optimum (31.3 °C), minimum (8.8 °C) and maximum (46.1 °C) temperatures for ammonium removal by *Scenedesmus* sp. were obtained as model parameters.

Cho et al. (2015) evaluated the factors influencing diversity and growth of indigenous algal consortium cultivated on untreated municipal wastewater in a high rate algal pond (HRAP) for a period of 1 year. Diversity analyses revealed the presence of *Chlorophyta*, *Cyanophyta* and *Bacillariophyta*. Dominant microalgal genera by biovolume in various seasons were *Scenedesmus* sp., *Microcystis* sp., and *Chlorella* sp. *Scenedesmus* sp., persisted throughout the year but none of three strains co-dominated with the other. The most significant factors affecting genus dominance were temperature, inflow *cyanophyta* and organic carbon concentration. *Cyanophyta* concentration affected microalgal biomass and diversity, whereas temperature impacted biomass.

Wastewater Treatment for Organic Conversion

Saha et al. (2015) hypothesized that methanol could induce the growth of low-temperature resilient, methanol utilizing, hydrogenotrophs in upflow anaerobic sludge blanket (UASB) reactor. The results showed that 0.04% (v/v) methanol increased methane up to 15 times and its effect was more pronounced at lower temperatures. Both *Methanobacteriales* and *Methanosetaceae* grew abundantly at low temperature, which indicated that methanol induced the growth of both the hydrogenotrophic and acetoclastic groups through direct and indirect routes, respectively.

Wirth et al. (2015) examined the anaerobic digestion of process liquor from hydrothermal carbonization (HTC) of sewage sludge. The process was performed at 37 °C (mesophilic) and 55 °C (thermophilic) on two identical continuously-fed anaerobic filters (26 L each) for 20 weeks. Significant differences in methane production were not observed as both reactors yielded up to 0.18 L_{CH4}/g_{COD}. Increased temperature had no effect on the steady-state COD removal efficiency with both reactors stabilized at 68–75%. Methanogenesis was identified as the speed-limiting step in anaerobic digestion of HTC liquor.

The operational feasibility of an anaerobic membrane bioreactor (AnMBR), consisting of an UASB reactor coupled to an ultrafiltration membrane unit was assessed by Ozgun et al. (2015), to treat municipal wastewater at two operational temperatures (25 and 15 °C). The results showed that membrane fouling at 15 °C was more severe than that at 25 °C. Higher COD and soluble microbial products (SMP) concentrations, lower mean particle diameter, and higher turbidity in the UASB effluent at lower temperature aggravated membrane fouling compared to the 25 °C operation. It is concluded that an AnMBR, consisting of a UASB coupled membrane unit, is not found technically feasible for the treatment of municipal wastewater at 15 °C, considering the rapid deterioration of the filtration performance.

Smith et al. (2015) examined the effect of psychrophilic temperature on the AnMBR treatment of domestic wastewater. The evaluated temperatures were 15, 12, 9, 6, and 3 °C. The COD removal higher than 95% was achieved when the temperatures was as low as 6 °C, but fell to 86% at 3 °C. As the temperature decreased, the soluble COD in the bioreactor increased, suggesting a reduction in suspended biomass activity. Sequencing of 16S rRNA suggested that the biofilm's metabolic diversity increased as the temperature decreased in response to a greater flux of complex organics into the biofilm due to temperature-based suspended biomass inhibition. The research demonstrated that AnMBR treatment of domestic wastewater at very low temperatures is feasible.

Differential methanogenic protein expression associated with low-temperature anaerobic digestion (AD) was described by Gunnigle et al. (2015). Comparative investigation of key microbial groups underpinning laboratory-scale AD bioreactors operated at 37, 15 and 7 °C was carried out. The results showed that *δ-Proteobacteria* were prevalent at 37°C, and their abundance decreased dramatically at lower temperatures with inverse trends observed for *Bacteroidetes* and *Firmicutes*. *Methanobacteriales* and *Methanosaeta* were predominant at all temperatures investigated, while *Methanomicrobiales* abundance increased at 15 °C compared with that at 37 and 7 °C. The temperature changes resulted in the differential expression of proteins involved in methanogenesis in all bioreactors.

Arora et al. (2015) carried out a whole year experiment to make clear the effect of seasonal temperature on pathogen removal efficacy of vermifilter for wastewater treatment. The higher BOD and COD removal was observed during spring and autumn period with a mean temperature of 25–27 °C, and this temperature range was optimum for earthworm sp. *Eisenia fetida* for its activity, growth and reproduction. However, during summer with a maximum temperature of 38–40 °C, the indicator bacteria removal was maximum by 99.9%, *Salmonella* reduction by 96.9% and *Escherichia coli* by 99.3%. The pathogen removal efficacy of vermifiltration increased with the increase in temperature, which implied that temperature had a significant contribution to the pathogen removal efficiency of vermifiltration.

Impact of temperature and photoperiod on anaerobic biodegradability of microalgae grown in urban wastewater was investigated by González-Fernández et al. (2015). Experiments were carried out under three different scenarios (I: 23 °C/14 h illumination, II: 15 °C/14 h and III: 15 °C/11 h). With respect to biomass cultivation, temperature affected biomass productivity but not final biomass concentration. Carbohydrates accumulation prevailed under Scenario I while low temperature (Scenario II) and short photoperiod (Scenario III) increased lipid and protein content. Comparison between the theoretically calculated and experimentally obtained methane yield values showed that biomass collected at Scenario III only reached 36.1% of the theoretical methane yield achievable compared to 46.5% attained with the biomass collected at Scenario I.

Industrial Wastewater Treatment

The effect of temperature on trichloroethylene (TCE) removal in an up-flow anaerobic sludge blanket reactor was studied by Zhang et al. (2015) within a temperature range from 20 to 40 °C. There was a rise in COD removal efficiency from 20 to 35 °C and a decline when temperature further increased to 40 °C. The TCE removal efficiency increased with temperature varying from 20 to 35 °C, and dropped dramatically to 78.38 % at 40 °C, presumably because the genus of *Dehalobacter*, a kind of bacteria with the ability to dechlorinate TCE to the corresponding chlorinated products, was not detected at 40 °C

Yang et al. (2015) carried out a study to examine the effect of novel ceramic media from sludge and coal cinder and straw on the combined up-flow anaerobic bio-filter (UAF) and up-flow biological aerated filter (UBAF) system to treat the synthetic wastewater containing tetracycline (TET) at low temperature of 16 °C. Due to the novel ceramics fillers, the start periods of the UAF and UBAF were shortening to 42 and 10 d. Moreover, compared to conventional reactor, the new system had advantages of high processing efficiency, high organic load, strong shock and tetracycline resistance. When original influent COD, NH_4^+-N and TET were 4000, 200 and 45 mg/L, the total COD, NH_4^+-N and TET reductions could reach to 97%, 99% and 89%. Furthermore, the low temperature did not influence the system.

High-temperature Fenton oxidation was applied by Díaz de Tuesta et al. (2015), to treat sulfonation plant wastewater. The results demonstrated that the high-temperature Fenton oxidation provided a better performance than other advanced oxidation processes. The optimal conditions of Fenton oxidation were the temperature of 94 °C, 70% of the stoichiometric H_2O_2 dose relative to initial COD, 1 h reaction time and the pH of the wastewater as received (1.7) to achieve the discharge limits into the exiting activated sludge plant of the petrochemical complex where the sulfonation plant is located.

A bench-scale test was conducted with a novel multi-stage loop membrane bioreactor (MsLMBR) to treat chemical synthesis-based pharmaceutical wastewater containing 7-ACA (Chen et al., 2015). Results showed that for MsLMBR1 at 15 °C, MsLMBR2 at 25 °C and MsLMBR3 at 35 °C, the average total COD (TCOD) of the effluent were all less than 80 mg/L. For MsLMBR2 and MsLMBR3, the microorganisms had better microbial activities and drug-resistances, and the biological removal was given priority to TCOD removal. But for MsLMBR1, there was no significant difference between biological removal and physical removal at the early stage. The 7-ACA pharmaceutical wastewater was effectively treated in a MsLMBR system, which also performed well at low temperature.

Effects of hydraulic retention time, temperature, and organic load on two horizontal subsurface flow constructed wetland (CW) units (one planted and one unplanted) treating secondary cheese whey were discussed by Sultana et al. (2015). Tested temperature was from 2.4 to 32.9 °C. CWs successfully treated secondary cheese whey and provided COD effluent concentrations below EU legislation, when hydraulic residence time was above 2 d and COD influent concentration ranged from 1200 to 3500 mg/L. The temperature significantly affected COD removal only in unplanted unit.

Other Issues in Wastewater Treatment

Influence of temperature on N_2O and NO emissions during wastewater denitrification was investigated. Experiments were carried out at pH 7 in a batch reactor with acetate as the carbon source. Results showed that NO and N_2O emissions increased when the temperature decreased. NO emissions appeared only at 10 and 5 °C, with respectively 8% and 18% of the total denitrified nitrogen. N_2O emissions increased from 13% to 40% then 82% of the total denitrified nitrogen at 20, 10 and 5 °C, respectively (Adouani et al., 2015).

The challenge of keeping downstream temperatures below established maxima in the face of climate-induced variations in stream discharge and temperature was analyzed (Huisenga and Travis, 2015). Changes in receiving waters, especially stream temperature or discharge, may have a significant effect on permit levels for a wastewater treatment facility. Therefore, understanding the effects of climate variation on stream discharge and temperature is important in assessing potential changes to future wastewater effluent permits.

Wastewater heat recovery applications are becoming widespread in energy saving applications. Culha et al. (2015) reviewed a sustainable and low emissions operation in air conditioning and heating processes achieved by harvesting the otherwise wasted energy in wastewater through specially designed heat exchangers, lying at the core of heat pumps. In their study, wastewater heat exchangers in wastewater source heat pump applications was presented, and wastewater heat exchangers were classified in detail based on multiple features, including utilization and construction methodology. The potential of wastewater, types of wastewater source heat pumps, and their applications are briefly discussed.

Anaerobic Digestion of Sewage Sludge and Solid Waste

Abelleira-Pereira et al. (2015) studied the advanced thermal hydrolysis (ATH) of sludge for improvement of mesophilic anaerobic digestion pretreatments. ATH is a novel anaerobic digestion pretreatment based on a thermal hydrolysis (TH) process plus hydrogen peroxide (H_2O_2) addition that takes advantage of a peroxidation/direct steam injection synergistic effect. Results showed that both TH and ATH patently improved methane production in subsequent mesophilic biochemical methane potential (BMP) tests in comparison with control BMP tests (raw secondary sewage sludge). A promising result was obtained since ATH, operated at temperature (115 °C), pretreatment time (5 min) and pressure (1 bar) considerably below those typically used in TH (170 °C, 30 min, 8 bar), managed to enhance the methane production in subsequent mesophilic BMP tests.

Riau et al. (2015) applied ultrasonic method to pretreat waste activated sludge by upgrading temperature-phased anaerobic digestion (TPAD). The research found no significant differences in the overall performance of the TPAD process, but different behaviours were observed between the thermophilic and mesophilic stages. Total methane production was enhanced by more than 50% and the volatile solid removal increased by 13% in comparison to the TPAD control process.

Yin et al. (2015) developed a detailed kinetic model for hydrothermal decomposition (HTD) of sewage sludge based on an explicit reaction scheme considering exact intermediates including protein, saccharide, NH_4^+–N and acetic acid. The parameters were estimated by a series of kinetic data at a temperature range of 180–300 °C. The protein and saccharide are the primary intermediates in the initial stage of HTD resulting from the fast reduction of biomass. The oxidation processes of macromolecular products to acetic acid are highly dependent on reaction temperature and dramatically restrained when temperature is below 220 °C.

Hao and Wang (2015) studied the microbial responses to different fermentation temperatures during the volatile fatty acids productions by mesophilic and thermophilic sludge fermentation. The results showed that thermophilic fermentation led to 10-fold more accumulation of VFAs compared to mesophilic fermentation. α-glucosidase and protease had much higher activities in thermophilic reactor, especially protease. Illumina sequencing manifested that raising fermentation temperature increased the abundances of *Clostridiaceae*, *Microthrixaceae* and *Thermotogaceae*, which could facilitate either hydrolysis or acidification. Real-time PCR analysis demonstrated that under thermophilic condition the relative abundance of homoacetogens increased in batch tests and reached higher level at stable fermentation, whereas under mesophilic condition it only increased slightly in batch tests.

Microbial diversity in an innovative mesophilic/thermophilic temperature-phased anaerobic digestion of sludge was investigated by Gagliano et al. (2015). The increase of digestion temperature drastically affected the microbial composition and selected specialized biomass. Hydrogenotrophic *Methanobacteriales* and the protein fermentative bacterium *Coprothermobacter* spp. were identified in the thermophilic anaerobic biomass. Species richness was lower under thermophilic conditions compared with that estimated in mesophilic samples, and it was flanked by similar trend of the evenness indicating that thermophilic communities may be therefore more susceptible to sudden changes and less prompt to adapting to operative variations.

Ariunbaatar et al. (2015) studied the enhancement of mesophilic anaerobic digestion of food waste by substrate thermal (heating the food waste in a separate chamber) and thermophilic (heating the full reactor content containing both food waste and inoculum) pretreatments at 50, 60, 70 and 80 °C. Pretreatments at a lower temperature (50 °C) and a shorter time (<12 h) had a positive effect on the anaerobic digestion process. The highest enhancement of the biomethane production with an increase by 44–46% was achieved with a thermophilic pretreatment at 50 °C for 6–12 h or a thermal pretreatment at 80 °C for 1.5 h. Thermophilic pretreatments at higher temperatures (>55 °C) and longer operating times (>12 h) yielded higher soluble COD (SCOD), but had a negative effect on the methanogenic activity.

Thermochemical pretreatments have been applied on the organic fraction of municipal solid waste (OFMSW) coming from a full-scale mechanical-biological treatment (MBT) plant, in order to pre-hydrolyze the waste and improve the organic matter solubilisation (Álvarez-Gallego et al., 2015). The process variables analyzed were temperature, pressure and NaOH dosage. The best conditions for organic matter solubilisation were 160 °C, 3 g NaOH/L, 6.5 bar and 30 min, with yields in terms of dissolved organic carbon (DOC), SCOD, total VFA (TVFA) and acidogenic substrate as carbon (ASC) of 176%, 123%, 119% and 178% respectively.

Fernández-Rodríguez et al. (2015) carried out a temperature-phased anaerobic digestion (TPAD) without microbiological separation (thermophilic 55 °C–mesophilic 35 °C) to the biomethanation of organic fraction of municipal solid waste (OFMSW). The higher organic matter removal (VS removal 82–85%) and the maximum specific growth rates of microorganisms (0.31–0.43 d^{-1}) were obtained for thermophilic phase operation at 5 and 4 d, respectively. It could be concluded that the optimum time for the thermophilic first-phase in TPAD would be between 5 and 4 d.

Yan et al. (2015) investigated the effects of initial substrate concentration (ISC), C/N ratio, and temperature on the biogasification of solid-state AD (SS-AD) from composting rice straw. Rice straw compounds, such as lignin, cellulose, and hemicellulose, were significantly degraded after composting. A significant interactive effect of temperature, ISC and C/N ratio was found on the biogasification of SS-AD of composting RS, and a maximum biogas production was achieved at 35.6 °C, with a 20% ISC and a C/N ratio of 29.6:1. High-throughput sequencing analysis indicated that microbial communities in the SS-AD mainly consist of *Methanobacteria*, *Bacteroidia*, *Clostridia*, *Betaproteobacteria*, and *Gammaproteobacteria*.

Pyrolysis of Sewage Sludge

The polycyclic aromatic hydrocarbons (PAHs) toxicity and sorption behaviour of biochars prepared from pyrolysis of paper mill effluent treatment plant sludge in temperature range 200–700 °C was studied by Devi and Saroha (2015). The sorption behaviour was found to depend on the degree of carbonization, where the fractions of carbonized and uncarbonized organic content in the biochars act as an adsorption media and partition media, respectively. The risk assessment for the 16 priority EPA PAHs present in the biochar matrix was performed and it was found that the concentrations of the PAHs in the biochar were within the permissible limits prescribed by US EPA (except BC400 and BC500 for high molecular weight PAHs).

Yuan et al. (2015) examined the influence of pyrolysis temperature on the physical and chemical properties of biochar made from sewage sludge. Biochar yield decreased and its pore structure developed with the increase of temperature from 300 to 700 °C. Biochar produced at 300 °C was acidic whereas at higher temperatures it was alkaline. Fewer dissolved salts were contained in the biochars produced at higher temperatures. The rich nutrients, other than nitrogen, were intensified with the temperature rise. The leaching toxicity of Pb, Zn, Ni, Cd, As, Cu and Cr in the biochars was lower than that in the sewage sludge although the pyrolysis process enriched the heavy metals in the biochars.

Sewage sludge chars produced at four different pyrolysis temperatures (550, 650, 750 and 800 °C) were investigated to check their CO and SO_2 emissions in a hot flue gas flow, and the recycle sewage sludge char was used as flue gas De-NOx catalyst within low temperature ranges (Chen et al., 2015). The chars produced at 750 and 800 °C were highly temperature- and oxidant-resistant and their CO emissions were considerably inhibited in the temperature range of 100 to 400 °C with oxygen level of 5–10%, at the same time, De-NOx efficiencies were increased by 25% to 50%. The char obtained at 750 °C had the best ability to remove NOx both as an absorbent and as a catalyst.

Lu et al. (2015) investigated the characteristic of heavy metals (Pb, Zn, Cu, Cd, Cr, Ni and As) in biochar derived from sewage sludge at different pyrolysis temperatures (300, 400, 500, 600 and 700 °C). The results showed that a great percentage of the heavy metals remained in biochar, the concentrations of heavy metals in biochar (except Cd at a temperature of 700 °C) were higher than that in sludge, and the enrichment of the heavy metals in biochar enhanced with the pyrolysis temperature. However, the potential risk of biochar on soil and groundwater contamination was lower than sewage sludge.

Sewage sludge (SS) was pyrolyzed in a fixed bed reactor from 400 to 600 °C using composite alumina (CA) as catalyst (Sun et al., 2015). The product yields and component distribution of non-condensable gas were more sensitive to the change of temperature, and the maximum liquid yield of 48.44 wt.% and maximum useable energy of liquid of 3871 kJ/kg sludge were observed at 500 °C with 1/5 CA/SS (mass ratio). The gas chromatography-mass spectrometry results showed that the increase of temperature enhanced devolatilization of organic matter and promoted cyclization and aromatization of aliphatics. The effects of CA on decomposition of fatty acids and formation of aromatics were similar to that of temperature. This means that the reaction temperature could be lowered by introducing CA, which has a positive effect on reducing energy consumption.

Ridout et al. (2015) discussed the influence of reactor temperature and pellet size on the pyrolysis efficiency of paper waste sludge (PWS). Maximum bio-oil yields of 44.5 ± 1.7 daf, wt% at 400 °C, and 59.9 ± 4.1 daf, wt% at 340 °C, for an intermediate pellet size of 4.84 ± 0.15 mm, were attained from the conversion of the low and high ash PWS (8.5 and 46.7 wt%), respectively. The low optimal reactor temperatures, as well as the high bio-oil yields, make valorisation via fast pyrolysis conversion promising. Due to the promotion of exothermic reactions for high heating rates, using smaller pellet sizes increased non-condensable gas yield, which corresponded to a decrease in the bio-oil yield

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Reduction of Heavy Metal in Sewage Sludge and Soil

Mehrotra et al. (2015) proposed a possibility of using simultaneous sewage sludge digestion and metal leaching (SSDML) process at the thermophilic temperature to remove heavy metals and suspended solids from sewage sludge. The SSDML process was carried out at 50 °C (thermophilic) by using ferrous sulfate or sulfur as the energy source in two reactors. The concentration of volatile suspended solids reduced by >40%, while that of heavy metals zinc, copper, chromium, cadmium and nickel decreased by >50% in both batches. Lead got leached out only when sulfur was used as the energy source. *Alicyclobacillus tolerans* was found to be the microorganism responsible for lowering the pH in both the reactors at thermophilic temperature. The indicator organism count was also below the maximum permissible limit making sludge suitable for agricultural use.

Mao et al. (2015) discussed the impact of temperature on Cr(VI) formation and reduction during heating of chromium-containing sludge in the presence of CaO. The result showed that CaO promoted Cr(III) oxidation, however, its influence is very dependent on heating temperature. From 200–400 °C, the presence of CaO facilitated formation of intermediate product Cr_2O_{3+x} containing Cr(VI) during dehydration of chromium hydrate, while Cr_2O_{3+x} would decompose as temperature over 400 °C, accompanied by part of Cr(VI) being reduced to Cr(III). From 500 to 900 °C, Cr(III) reacted with CaO to form a leachable $CaCrO_4$ product. This product was stable and a prolonged heating time did not reduce the amount of Cr(VI) significantly. At 1000–1200 °C, part of $CaCrO_4$ was reduced to $Ca(CrO_2)_2$ in 1 h. While extended heating time above 1 h resulted in the $Ca(CrO_2)_2$ being oxidized reversibly to $CaCrO_4$ at 1200 °C. Since $CaCrO_4$ is thermodynamically less stable over 1000 °C, MgO could induce $CaCrO_4$ to be reduced into $MgCr_2O_4$ at around 900 °C, lower than that for the reduction from $CaCrO_4$ into $Ca(CrO_2)_2$.

Thermal treatment is a promising technology for the remediation of mercury contaminated soils, but it often requires high energy input at heating temperatures above 600 °C, and the treated soil is not suitable for agricultural reuse. Ma et al. (2015) developed a novel method for the thermal treatment of mercury contaminated soils with the facilitation of citric acid (CA). When CA/Hg molar ratio was 15 as the optimum dosage, the mercury concentration in soils was successfully reduced from 134 mg/kg to 1.1 mg/kg when treated at 400 °C for 60 min and the treated soil retained most of its original soil physiochemical properties. Citric acid was found to provide an acidic environment which enhanced the volatilization of mercury. This method is expected to reduce energy input by 35% comparing to the traditional thermal treatment method.

Other Issues in Sewage Sludge and Biowaste Treatment

Wang et al. (2015) evaluated the dewatering performance and the characteristics of obtained products (hydrothermal sludge, hydrochar and filtrate). The sludge dewatering was conducted with hydrothermal treatment coupled with mechanical expression in two separate cells. The results showed that harsher hydrothermal treatment led to more water removal, and mechanical pressure became less significant as the temperature increased. The higher heating value correlated well with carbon content of sludge, which increased by 4.8% for hydrothermal sludge at 210 °C for 60 min and significantly decreased by 15.4% for hydrochar after 6.0 MPa for 20 min. The solubilization and decomposition of proteins, polysaccharides and DNA were determined to be temperature and residence time dependent, and the improvement of dewaterability was closely correlated to the variation of these biopolymers. The filtrates collected above 150 °C were found to be acidic.

Białobrzewskia et al. (2015) performed a mathematical model to simulate the sewage sludge-straw composting process integrating different heat generation capacities of mesophilic and thermophilic microorganisms. The model incorporates two microbial groups (mesophiles and thermophiles) characterized by different capacities of heat generation. The parameters modeled over a period of 36 d. The coefficients of metabolic heat generation for mesophiles were 4.32×10^6 and 6.93×10^6 J/kg, for winter and summer seasons, respectively. However, for thermophiles, they were comparable for both seasons reaching 10.91×10^6 and 10.51×10^6 J/kg. In the model, significant parameters for microbial growth control were temperature and the content of easily hydrolysable substrate. The proposed model provided a satisfactory fit to experimental data captured for cuboid-shaped bioreactors with forced aeration.

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