CHAPTER

ENERGY AND RESOURCE RECOVERY FROM SLUDGE: FULL-SCALE EXPERIENCES

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CHAPTER OUTLINE

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10.1 INTRODUCTION

> Historically, it was common to see the schematics that showed the water treatment scheme in detail and an arrow at the end that simply said "sludge to disposal."
>
> **Neyens et al. (2004)**

In the current scenario, the growing global urbanization of society coupled with increasingly stringent sludge reuse and disposal regulations and increasing public pressure are forcing both public and private sludge generators to reevaluate sludge management strategies (Liu and Tay, 2001). Conventionally, waste sludge is disposed via incineration, landfills or ocean disposal or is reused as a soil conditioner in agriculture. With the banning of ocean disposal and new stringent European landfill criteria, much more sludge is now beneficially reused both in agriculture and via a variety of thermal technologies (Matthews, 1996). 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 (Campbell, 2000). It is anticipated that upcoming sludge management efforts will accentuate the recovery and reuse of value-added crops from sludge (Rulkens, 2008). This interest in renewable energy has been driven by a combination of shrinking fossil fuel reserves caused by the rising demand for primary energy, fuel price spikes, climate change concerns, public awareness, and advancements in renewable energy technologies (Cao and Pawłowski, 2012; NACWA, 2010).

The two components in sludge that are technically and economically feasible to recycle are nutrients (primarily nitrogen and phosphorus) and energy (carbon) (Campbell, 2000). Several options are available for energy recovery from waste sludge. The most significant routes are anaerobic digestion of sludge with biogas recovery, co-digestion, incineration, and co-incineration with energy recovery, pyrolysis, gasification, supercritical (wet) oxidation, used in the production of construction materials, production of biofuels (hydrogen, syngas, and bio-oil), electricity generated using specific microbes, and the beneficial recovery of heavy metals, nutrient (nitrogen and phosphorus), protein, and enzymes (Tyagi and Lo, 2013).

10.2 SLUDGE CHARACTERIZATION

The sewage sludge is composed of a complex heterogeneous mixture of microorganisms, undigested organics such as paper, plant residues, oils, or fecal material, inorganic materials, and moisture (Degremont, 1979). The characteristics of primary and secondary activated sludge are summarized in Table 10.1.

Primary sludge is produced through a mechanical (screening, grit removal, and sedimentation) wastewater treatment process; it usually contains from 93% to 99.5% water and high ratios of suspended and dissolved organic matters. Waste-activated sludge (WAS), or secondary sludge, is produced during the biological treatment of wastewater and is composed mainly of microbial cells that are complex polymeric organic materials. The total solids (TS) concentration in secondary sludge ranges between 0.8% and 1.2%, which also depends on the type of biological treatment process employed (Tezel et al., 2011).

Table 10.1 Characteristics of Primary Sludge and Activated Sludge (Tchobanoglous et al., 2003)

Parameter	Primary Sludge	Activated Sludge	Composition
Total dry solids (total solids (TS)) %	5–9	0.8–1.2	• Nontoxic organic carbon compounds (approximately 60% on dry basis), Kjeldahl-N, phosphorus-containing components • Toxic pollutants: heavy metals (Zn, Pb, Cu, Cr, Ni, Cd, Hg, As: concentrations vary from 1000 mg/L to <1 mg/L), polychlorinated biphenyls, polyaromatic hydrocarbons, dioxins, pesticides, endocrine disrupters, nonyl-phenols • Pathogens and other microbiological pollutants • Inorganic compounds: silicates, aluminates, calcium, and magnesium-containing compounds • Water varying from a few percent to >95%
Volatile solids (VS) (% TS)	60–80	59–68	
Nitrogen (% TS)	1.5–4	2.4–5.0	
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	–	
Silica (SiO_2%TS)	15–20	–	
pH	5.0–8.0	6.5–8.0	
Grease and fats (%TS)	7–35	5–12	
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)	23,000–29,000	19,000–23,000	

WAS contains 59–88% (w/v) organic matter, which is decomposable and produces unpleasant odors. Only a small part of the sludge is solid matter in which over 95% is water. 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 (Orhon and Artan, 1994). The ash from waste sludge contains mainly minerals such as quartz, calcite, or microcline. These minerals are formed by elements such as Fe, Ca, K, and Mg. Furthermore, some heavy metals such as Cr, Ni, Cu, Zn, Pb, Cd, and Hg can also be found in sludge (Fonts et al., 2009).

The potential for energy recovery from sludge is a function of their composition, which is a mixture of organic (volatile) matter, inorganic matter (inert material), and associated water. The energy content of sludge is laid in the volatile solids (VS), which is subdivided into two components: readily degradable (50% in primary sludge and 25% in WAS) and not readily degradable (30% in primary sludge and 55% in WAS) (NACWA, 2010). Considering the energy values, 1 lb of dry biosolids has the energy content of 6000–9000 British Thermal Units.

10.3 METHODS FOR ENERGY AND RESOURCE RECOVERY

By using the thermochemical, biochemical, and mechanical-chemical methods, several sludge-derived resources including biogas, fuel gas, electricity generation, production of construction materials, nutrients, biofuels (syngas, biodiesel, and bio-oil), hydrolytic enzymes, polyhydroxyalkanoates (PHA) (for bioplastic manufacturing), and biofertilizers, biosorbents can be recovered. Fig. 10.1 shows the techniques of energy and resource recovery from waste sludge.

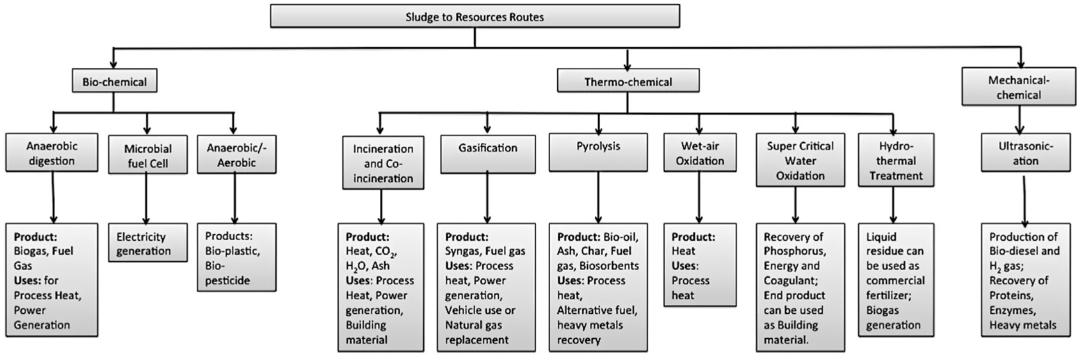

FIGURE 10.1

Routes of resource recovery from waste sludge (Tyagi and Lo, 2013).

10.3.1 ANAEROBIC DIGESTION

Anaerobic digestion is the most popular sludge stabilization technology currently on the market (Cao and Pawłowski, 2012). The process transforms sludge organic solids to biogas, which is a mixture of CH_4, CO_2, and traces of other gases, in an anaerobic environment (Reaction [1]) (Tezel et al., 2011):

$$C_cH_hO_oN_nS_s + yH_2O \rightarrow xCH_4 + nNH_3 + xH_2S + (c - x)CO_2$$

$$x = 1/8(4c + h - 2o - 3n - 2s) \qquad [10.1]$$

$$y = 1/4(4c - +h - 2o + 3n + 3s)$$

Biogas can be used as a source of energy to produce electricity and/or heat.

10.3.2 INCINERATION AND CO-INCINERATION

The main purpose of sludge incineration is the complete oxidation of organic compounds at a high temperature. In this process, biosolids are burned in a combustion chamber supplied with excess air (oxygen) to form mainly carbon dioxide and water, leaving only inert material (ash). This ash has to be disposed of or it can be used as a source to produce building materials (Guibelin, 2004).

10.3.3 GASIFICATION

Gasification involves the breakdown of dried sludge in an ash and in combustible gases at temperatures usually about 1000°C in an atmosphere with a reduced amount of oxygen (Jaeger and Mayer, 2000). Products of the process include heat (used to generate power and process heat) and syngas (synthetic gas). Gasification takes place at a high temperature (1400 to 1700°C) and high pressure (0.6–2.6 MPa) using pure oxygen as the oxidant (Spinosa, 2004).

10.3.4 PYROLYSIS

Sludge pyrolysis is an innovative method developed to manage sludge and energy, in which the sludge is thermally treated (350–500°C) under pressure and in an oxygen-deficient environment. In this method, the sludge is transformed into char, ash, pyrolysis oils, water vapor, and combustible gases (Stolarek and Ledakowicz, 2001; Khiari et al., 2004).

10.3.5 WET AIR OXIDATION

Wet oxidation is the chemical oxidation of sludge (by the addition of O_2) at a high temperature (150–330°C) and high pressure (6–20 MPa). The ZIMPRO process was the oldest process based on wet oxidation technology, developed in The Netherlands in the 1960s. The oxidation of sludge's organic matter produces water, carbon dioxide, and easily biodegradable organic compounds (acetic acid and fatty acid) (Weemaes and Verstraete, 1998).

10.3.6 SUPERCRITICAL WATER OXIDATION

Supercritical water oxidation (SCWO), which takes place at elevated temperatures and pressures (typically 25 MPa and 600°C), is a good solution for sludge disintegration. In this process, carbon and hydrogen from organic and biological constituents are oxidized to CO_2 and H_2O; nitrogen, sulfur, and phosphorus form N_2, SO_4^{2-}, and PO_4^{3-}, respectively; organic chlorides are converted to Cl^-; and heavy metals are oxidized to the corresponding oxides (Svanstrom et al., 2007). Although the cost of treatment is high, the value from the SCWO method in terms of sludge volume decrease together in excess of 90% recovery of energy, coagulants, and phosphate represent a value which will offset the cost of operation (Perez-Elvira et al., 2006).

10.3.7 HYDROTHERMAL TREATMENT

Hydrothermal treatment involves heating sludge in the water phase at temperatures between 150 and 450°C in the absence of oxygen or another oxidant. Sludge hydrolysis during hydrothermal treatment results in the production and accumulation of high concentrations of dissolved organic compounds in the liquid phase (Shanableh and Jomaa, 2001). Protein hydrolysis results in amino acids, lipid hydrolysis produces fatty acids, and the hydrolysis of fiber material and hydrocarbons leads to low-molecular hydrocarbon substances such as sugars. These compounds are particularly interesting as carbon resource not only in the production of biogas but also in the denitrification process and the biological removal of phosphorus from wastewater (Rulkens and Bien, 2004). The liquid residue of hydrothermally treated sewage sludge can be used as a marketable fertilizer because it is composed of three principal nutrients (N, P, and K) (Yoshikawa, 2010).

10.4 ENERGY AND RESOURCE RECOVERY

10.4.1 BIOGAS RECOVERY BY ANAEROBIC DIGESTION

Biogas produced during the anaerobic digestion of sewage sludge contains 60–70% methane, 30–40% carbon dioxide, and trace amounts of nitrogen, hydrogen, hydrogen sulfide, and water vapor.

Methane gas generated by anaerobic digesters is the main source of energy at a municipal wastewater treatment plant (WWTP). In most cases, the recovered methane is used to power gas engines or produce electrical and thermal energy for onsite use in the treatment plant. The cost of electricity for a treatment plant is about 80% of the total operational cost, and energy recovered through methane can cover about half of this cost (Deublein and Steinhauser, 2008). The Bio-terminator$^{24/85}$ is mesophilic anaerobic digestion technology developed by Total Solids Solution from research conducted at the University of Louisiana, United States. This process was found to be capable of destroying 85% of TS in 24 h at a reactor retention time of 24 h or less. A pilot-scale plant of 3.785-m^3 capacity was installed at Baton Rouge, Louisiana in 2005 and operated for 5 months (Burnett and Togna, 2007). The system was observed to remove 93% VS at 2 days' hydraulic retention time. Another commercial method, "Columbus Advanced Biosolids Flow-through Thermophilic Treatment (CBFT3), is a modification of thermophilic anaerobic digestion using a plug flow reactor. This process incorporates advanced reciprocating engines to produce electricity that supplies 40−50% of the plant electricity requirements. The overall energy efficiency of the process is 68−83% (Kalogo and Monteith, 2008).

A substantial increase in sludge mineralization and subsequent biogas generation can be achieved by employing a physical, chemical, thermal, mechanical, or biological pretreatment step such as microwave (MW) heating, ultrasonication, ozonation, enzymatic treatment, use of liquid jets, treatment with alkali or acids, high-performance pulse technique, or wet oxidation (Tyagi and Lo, 2011). With regard to the assessment of the feasibility of a pretreatment method, extra biogas production, total energy balance, final amount of sludge, and cost have to be taken into account and analyzed (Rulkens, 2008). Several pretreatment technologies such as Cambi (thermal), BioThelys (thermal), MicroSludge (physical-chemical), CROWN (ultrasonic), and Lysatec GmbH (mechanical) have been applied successfully at full scale in several countries (Kepp et al., 2000; Panter and Kleiven, 2005; Stephenson et al., 2005; Kruger and Hogan, 2005; Elliott and Mahmood, 2007).

The Cambi process was reported to increase net electricity production by 27% (Elliott and Mahmood, 2007). During full-scale municipal trials, Onyeche (2006) reported that high-pressure homogenization of WAS before anaerobic digestion increased gas production by 30%. Zabranska et al. (2006) reported long-term monitoring results from three full-scale installations of lysate thickening centrifuges. They reported 15−26% increases in biogas yield. A pilot-scale ozonation process (0.026 kg O_3/kg VS) to pretreat mixed primary and secondary sludge (weight by weight ratio of 1:3.5) was started in Japan by Kurita Water Industries. The process was capable of producing 36% more energy than the control anaerobic digester. The energy input (ozonation and pumping) and energy produced were estimated at 1923 kWh and 1736 kWh/dry metric ton (MT) sludge treated, respectively (Kalogo and Monteith, 2008; Goel et al., 2004). Xie et al. (2007) studied the effectiveness of ultrasonic treatment at a full-scale sludge digester in Singapore. The anaerobic digesters (4500 m^3 volume, sludge retention time (SRT), 30 days) were fed sonicated sludge (20 kHz; flow rate, 200 m^3/day). Over the 6-month study, the experimental system consistently produced a minimum of 200 m^3/day more gas than the control digester (methane production increased by 45%). Hogan et al. (2004) studied the feasibility of Sonix technology (20 kHz) for the pretreatment of WAS before anaerobic digestion at the demonstration and full-scale plants (Avonmouth, United Kingdom and Orange County, California, United States). They reported that Sonix technology was capable of improving biogas production (up to a 50% increase) and has a relatively short payback period of 2 years. The German company Hielscher (up to 48 kW) claimed to improve biogas yield by 25%. Another German company, Sonotronic, claimed that the integration of a high-output ultrasonic reactor (20 kHz) into existing biogas production systems increased biogas production (up to 50%) and the methane content of the biogas (to 70% of CH_4). Barber (2005) reported the outcomes of several full-scale part-stream ultrasound systems (Germany, Austria, Switzerland, Italy, and Japan). He observed a 22% increase in biogas production and VS reduction, and up to 7% improvement in sludge dewatering. The energy and mass balance study of the anaerobic digester (1200 m^3, 20 days SRT, flow rate 200 m^3/day, and 5% DS dry solids (DS)), treating the sludge sonicated at 2.5 W/m^2/K, shows that more energy is generated than consumed; ie, 1 kW of applied energy will generate seven times more electrical energy after losses. Moreover, the researchers suggested that a typical payback period for a full-scale ultrasound installation is 2–3 years.

Biogas is an excellent fuel for a large number of applications and it can be used more or less in all applications that were developed for natural gas. The biogas can be used for the production of heat and steam or electricity generation/cogeneration, as vehicle fuel, and for the production of chemicals.

Biogas can be used as a fuel to generate electrical power using engine generators, turbines, and fuel cells and as a fuel in gas vehicles (Bridger et al., 1962). An analysis accomplished by the Combined Heat and Power (CHP) partnership observed that if CHP were installed at all 544 wastewater treatment facilities in the United States (influent flow rates >5 million gallons/day and that operate anaerobic digesters), approximately 340 MW (340,000 kWh) of electricity could be generated, which is enough to power 261,000 homes (NACWA, 2010). According to the US Environmental Protection Agency, 2.3 million MT of carbon dioxide emissions annually (equivalent to 430,000 cars) could be offset if existing WWTP (with capacity over 5 million gallons/day) that employ anaerobic digestion installed energy recovery facilities. Harnessing the energy from biosolids offers energy security, reduced dependence on fossil fuels, and lowered greenhouse gas emissions (NACWA, 2010).

In several Swedish cities, use of sludge-derived biogas as biofuel in transportation sector is a well-established practice. The Henriksdal treatment plant produces and sells biogas to Stockholm's bus company. At least 30 buses in Stockholm are running on biogas (Salter, 2006). In the United States, various well-established energy recovery techniques are in use, including electricity and mechanical energy production and heat recovery through biogas generated from anaerobic digestion of waste sludge (Kalogo and Monteith, 2008). The use of methane as a source of hydrogen to generate energy with liquefied carbonate fuel has been effectively exhibited at King County, Washington's South treatment plant (Parry et al., 2004). Co-digestion of grease (from restaurant trap haulers) with sewage sludge is practiced in Watsonville, California, to improve biogas yield by over 50% (Cockrell, 2007). Grease is composed of energy-rich compounds such as fats, carbohydrates, and sugars (Bailey, 2007); thus, it is an appropriate substrate for biogas production during anaerobic digestion of sludge. The Sewerage Bureau of Tokyo Metropolitan Government (SBTMG) implemented several projects including the use of dewatered sewage sludge to produce fuel charcoal and sold for thermal power generation (Oda, 2007) and for electricity generation with a gas engine using syngas produced by the pyrolysis of sewage sludge (Takahashi, 2007). In China, biogas harvesting from sewage sludge is a common way to recover resources. The annual methane generation from all feedstocks including sewage sludge was assessed at 720 million cubic meters (Aalbers, 1999). In the United Kingdom, a new program for energy recovery was proposed by the government, including the generation of 20% of electricity from renewable sources by 2020 (Trumper, 2007). In 2005, 10.8% and 4.2% of all UK renewable energy was recovered by combustion and biogas production, respectively.

10.4.2 NUTRIENT RECOVERY

Sewage sludge contains considerable amounts of nutrients, especially phosphorus (0.5–0.7% TS) and nitrogen (2.4–5.0% TS) (Tchobanoglous et al., 2003); these nutrients exist mainly in the form of proteinaceous material. The breakdown and solubilization of sludge biomass and its subsequent conversion to ammonia and phosphates could be used to produce plant fertilizers such as magnesium ammonium phosphate (struvite), which can be applied directly to soil (SenterNovem, 2008; Liao et al., 2005a; Wong et al., 2006).

Much effort has been directed toward phosphorus recovery from sewage sludge via crystallization, which has been developed and implemented in Japan and The Netherlands (Stratful et al., 1999; Woods et al., 1999). Emerging commercial techniques for phosphorus recovery from waste sludge, including KREPO, Aqua-Reci, Kemicond, BioCon, SEPHOS, and SUSAN, are mainly based on physicochemical and thermal treatment to dissolve phosphorus and then recover it by precipitation. Phosphorus can be recovered from sludge as iron phosphate, calcium phosphate, phosphoric acid, and struvite (magnesium ammonium phosphate). The Aqua-Reci technology was developed in Sweden to recover both phosphorus and energy using combined SCWO following an extraction method (Stendahl and Jafverstrom, 2003). About 100% of phosphorus could be extracted with HCl or H_2SO_4 at 90°C and 2 h reaction time. Stendahl and Jafverstrom (2003) calculated that the total cost of the full-scale Aqua-Reci plant at Stockholm would be approximately US$946/dry MT sludge treated per year. The OSTARA process, another commercial technology to recover struvite from a phosphorus-rich sludge stream using magnesium chloride (80–85% P recovery), has been in operation (full-scale) at the City of Edmonton, Canada. The process has been in operation since May 2007, and is expected to produce between 200 and 250 MT of struvite per year (Kalogo and Monteith, 2008; Prasad et al., 2007). A full-scale process (45,000 m^3/day) for phosphorus recovery (>90% P recovery) as struvite (approximately 550 kg/day; equivalent to 0.01 kg struvite/m^3) was installed at the Lake Shinji East Clean Center in Japan (Ueno and Fujii, 2001). Seaborne technology, developed in Germany by Seaborne Environmental Research Laboratory (Berg and Schaum, 2005), a two-step acid–base leaching extraction method proposed by Kungl Tekniska Hogskolan, Swedish Royal Institute of Technology (Levlin and Hultman, 2004), and KREPO technique (pH 2, 100–110°C, 3.6 bars) (Hansen et al., 2000) and Kemicond technology (modified KREPO technique), are other efficient technologies applied at the pilot and full scale for phosphorus recovery. Crystalactor technology was applied at a full scale in The Netherlands. However, the cost of phosphorus recovery has been estimated at 22 times higher than the cost of mined phosphate rocks, and thus is not considered economical (Roeleveld et al., 2004). Phostrip technology recovers calcium phosphate from a phosphorus-enriched sludge processing side stream. A portion of the return sludge is pumped to an anaerobic tank where acetic acid may be dosed to the tank to increase the amount of phosphorus released to the liquid phase. The phosphorus-rich water is separated from the sludge and treated with lime to precipitate the phosphorus as calcium phosphate. In United States, at least four full-scale PhoStrip plants used the process in the mid 1980s. The cost of production is high compared with natural sources, but the value of the recovered calcium phosphate should increase as natural supplies decline (Kalogo and Monteith, 2008).

Since 1990, the Swedish government has emphasized the significance of nutrient recycling from sewage sludge. Thus use of sludge in agronomy is not a common practice despite the low concentration of contaminants in sludge compared with that in other countries (Bengtsson and Tillman, 2004). In 2000, the Swedish government investigation projected the target of recycling 75% of phosphorus from waste and sludge into productive soils by 2010 (SME, 2000). The Netherlands is well-known as one of the first countries to employ phosphorus recovery at a full scale (Stark, 2004). The Netherlands has aimed to replace 20% of its current phosphate rock consumption with recovered phosphate (Roeleveld et al., 2004). Around 32% of sewage sludge generated in The Netherlands is currently used in the cement industry and power stations (Uijterlinde, 2007). Germany is actively involved in advancing novel technologies for phosphorus recovery from sewage sludge; however, four pilot- or bench-scale technologies have been developed since 2002 (Berg and Schaum, 2005). Moreover, the dried biosolids products (OCEANGRO) are used as organic fertilizers by over 60 New Jersey golf courses and are registered with the New Jersey Department of Agriculture. The biosolids are used as a fertilizer to grow canola (used to make biodiesel fuel) at King County, Washington (Seattle) (Kalogo and Monteith, 2008). BioCon Technology was developed for phosphorus recovery as phosphoric acid. The sludge incinerated ash is leached with H_2SO_4, and resources including ferric chloride ($FeCl_3$), potassium bisulfate ($KHSO_4$), and phosphoric acid (H_3PO_4) are recovered by ion exchange (Hultman et al., 2003; Levlin and Hultman, 2004). However, BioCon Technology has been studied on a pilot-scale at a municipal WWTP near Aalborg, Denmark (Hultman et al., 2001).

The ammonia recovery process (ARP) is a technology developed in the United States and commercialized by the ThermoEnergy Corporation. In this process, an ion-exchange unit concentrates ammonia in the influent from approximately 1000 parts per million (ppm) to 15,000 ppm. The concentrated ammonia stream is then vaporized and the ammonia gas becomes in contact with sulfuric acid and crystallized as ammonium sulfate. The first ARP pilot plant was constructed at Oakwood Beach Water Pollution Control Plant, Staten Island, New York (Kalogo and Monteith, 2008).

10.4.3 HEAVY METALS RECOVERY

Heavy metals such as Zn, Cu, Ni, Cd, Pb, Hg, and Cr are principal elements restricting the use of sludge for land application owing to probable soil and ground water contamination, which ultimately affect human and animal health. Therefore, appropriate treatment of waste sludge is necessary before landfill disposal. Generally, metal-bearing sludges are treated to extract metal ions or stabilize the metals in solid form.

The effect of an ultrasonication-assisted acid leaching process on the separation and recovery of Cu and Fe from printed circuit board (PCB) waste sludge was studied by Xie et al. (2009). This technique was successfully implemented on an industrial scale in a heavy metal recovery plant in Huizhou city, China, from more than 2 years. The pilot-scale installation treated 5800 tons of waste sludge from PCB factories in 2007; 1000 tons of 98% copper sulfate and 3500 tons of 20% ferric chloride were produced. All of the copper sulfate was sold on the market and the ferric chloride was reused in the local PCB manufacturing industries. No secondary pollution was produced by the ultrasonication-assisted acid leaching method. This process has better separation and recovery efficiency, a low recovery cost, greater end-product quality, and zero process waste emissions (Xie et al., 2009). In another study (Li et al., 2010), a similar group reported significantly higher recovery rates of Cu (97.42%), Ni (98.46%), Zn (98.63%), Cr (98.32%), and Fe (100%) with a two-stage ultrasonically enhanced acid leaching process (pH 4.0, 100 min contact time, and 100 W power). The laboratory-verified process performance parameters (pH, ultrasonic power, and contact time) were successfully applied at a pilot-scale treatment and almost similar recovery rates were achieved for all of the studied metals as observed at a laboratory scale.

10.4.4 BIOFUEL PRODUCTION

Biofuels have gained worldwide attention because they have the potential to replace the nonrenewable petroleum fuels in the future. Emerging research is focused on biofuel recovery, especially bioethanol, biodiesel, syngas, biohydrogen, and bio-oil from biomass (Demirbas et al., 2011). Biofuels are produced from sources such as corn, soybeans, flaxseed, rapeseed, sugarcane, palm oil, sugar beet, raw sewage sludge, food scraps, animal parts, and rice (Singh, 2011). Using waste sludge as the substrate for biofuel production offers several advantages over the use of other biomass sources. It is a waste product and so is available at little or no cost, and the supply is plentiful because it is produced wherever there is a sizable human settlement (Massanet-Nicolau et al., 2010).

10.4.4.1 Hydrogen

Hydrogen is a promising alternative energy to fossil fuels. Hydrogen has high energy (122 kJ/g) that is 2.75 times greater than that of hydrocarbon fuel (Han and Shin, 2004). The possibility of producing hydrogen-rich fuel gas by thermochemical treatments of wet sewage sludge that include drying, pyrolysis, and gasification was studied by several researchers. Wet sewage sludge pyrolysis at high temperature (1000°C), combined with high heating rates, enhances the production of H_2-rich fuel gas (Dominguez et al., 2006). Moreover, a gaseous product of a much higher percentage of H_2 is produced from pyrolysis of wet rather than dry sludge (Manara and Zabaniotou, 2012). The extreme moisture content of sewage sludge generates high temperatures, and a steam-rich atmosphere consequently leads to in situ steam reforming of the volatile compounds and partial gasification of the solid char, which contributes to the production of hydrogen-rich fuel gas (Zhang et al., 2011). CO_2, CH_4, and H_2 concentration, low heating value of the produced gas, and aqueous yield are increased by the increasing moisture content, whereas CO concentration and tar yield are decreased (Manara and Zabaniotou, 2012).

10.4.4.2 Syngas ($H_2 + CO$)

Syngas, a mixture of carbon monoxide and hydrogen, may be used as a clean alternative to fossil fuels in generating electricity or for the production of liquid fuels such as synthetic diesel, dimethyl ether, and methanol (Lv et al., 2007). Syngas production is a two-step process. In the first step, the pyrolysis of sewage sludge at around 600°C in an oxygen-deficient atmosphere takes place, which leads to the production of carbon-rich char. In the second step, the char is gasified in the presence of oxygen or air and produces syngas. A commercial method, EBARA-fluidized bed gasification technology (Japan), co-treats municipal sludge with other solid wastes, including municipal solid waste, plastic waste, medical waste, and fly ash to recover the energy-rich syngas. As of September 2002, six TwinRec process lines were in operation and 14 more were under construction (Steiner et al., 2002). Another commercial method is KOPF gasification technology, including: a solar drying unit, a fluidized-bed gasification unit, a gas engine unit for energy recovery, and a postcombustion chamber (Kalogo and Monteith, 2008). The solar unit is used to dry the wet digested sludge to a solid content of between 70% and 85%. The fluidized-bed gasification unit operates at a temperature up to 900°C and a retention time of 30 min. The dried solids are converted into inert granules and combustible gas. The gas is recovered and cooled to a temperature below 150°C and dried. The gas engine unit generates about 70 kW of electricity. The postcombustion chamber is used to dispose of the surplus of gas that cannot be used. The gas is combusted at a temperature of 850°C. Most of the full-scale gasification installations are under operation in Europe, and mainly in Germany.

10.4.4.3 Bio-oil

Bio-oils, components of *n*-alkanes and 1-alkenes, aromatic compounds (that range from benzene derivatives to polyaromatic hydrocarbons, nitrogenated compounds, long-chain aliphatic carboxylic acids, ketones, esters, monoterpenes, and steroids), which are refined to high-quality hydrocarbon fuels, might have some advantages including facility of transport, storage, and combustion, and flexibility in marketing (Dominguez et al., 2003). Furthermore, the bio-oil is a possible source of light aromatics (for example, benzene, toluene, and xylene), which control a greater marketplace value than do raw oils (Tian et al., 2011).

Sludge pyrolysis (liquefaction) at intermediate temperatures of around 425–575°C (heating rate around 100°C/min) allows the dominant production of bio-oil, the yield of which amounts to 30–40 wt% of sewage sludge (Cao and Pawłowski, 2012). In 1980, a pilot-scale study was carried out to produce bio-oil from waste sludges using thermochemical liquefaction, in which liquid sludge (20% TS) was heated at 300°C and 10 MPa pressure for about 90 min, generating a heavy oil, char, gas, and reaction water. The technology was patented as the Sludge-to-Oil Reaction System (STORS). Typically, oil yields ranged from 10% to 20% and char from 5% to 30% by weight. Conventionally, liquefaction of sludge is always carried out in an electric or gas furnace (Dominguez et al., 2003).

The commercial EnerSludge demonstration plant was installed at Perth, Australia. Overall, 45% energy in the biosolids was converted to bio-oil; however, the plant was discontinued after 16 months of operation because it was not considered cost-effective (GVRD, 2005). In another STORS process, which was commercialized by ThermoEnergy (2007) at high pressure and elevated temperatures (275–315°C, 11,400–14,800 kPa, and 1–3 h), the sludge (20% DS) was converted into a fuel consisting of oil with 90% of the heating value of diesel and a solid (char) similar to coal. The recovered bio-oil could be used to generate electricity and/or heat using an engine. A general cost estimate of STORS technology for a small (10,000 p.e. (population equivalent), 292 dry MT/year), medium (100,000 p.e., 2920 dry MT/year), and large (1 million p.e., 29,200 dry MT/year) population was provided by Molton et al. (1986). They estimated that the energy used in the process was 1410, 1394, and 1394 kWh/dry MT, respectively, and the electricity from oil produced was 1898, 1480, and 1480 kWh/dry MT for the small, medium and large population, respectively. However, there is currently no full-scale installation in operation (Kalogo and Monteith. 2008).

10.4.4.4 Bio-diesel

Limited fossil fuel reserves and environmental benefits of biodiesel (decrease in acid rain and emissions of CO_2, SO_x and unburned hydrocarbons during the combustion process; easy biodegradability; less toxicity; and safety in storage and handling) increase the significance of biodiesel (Gogate and Kabadi, 2009). Biodiesel is the esters of simple alkyl fatty acids that can be produced from various lipid sources by a trans-esterification reaction with alcohol in the presence of a base, acid, enzyme, or solid catalyst. Municipal sewage sludge is gaining traction worldwide as a lipid feedstock for biodiesel production because it is available in abundance and contains significant amounts of lipids, which can make biodiesel production from sludge lucrative. These energy-rich lipids include phospholipids, monoglycerides, diglycerides, triglycerides, and free fatty acids in the oils and fats (Kargbo, 2010).

Studies (Dufreche et al., 2007) show that combining lipid extraction processes in 50% of all existing municipal WWTP in the United States and trans-esterification of the extracted lipids could produce approximately 1.8 billion gallons of biodiesel, which is about 0.5% of the yearly national petroleum diesel demand. Currently, the estimated cost of production is US$3.11/gallon of biodiesel.

Nevertheless, this cost should be reduced to levels that are at or below the current petro diesel costs of US$3.00/gallon (Kargbo, 2010). Currently, the estimated cost of production of biodiesel from dry sludge is US$3.11/gallon of biodiesel (Mondala et al., 2009; Susanne, 2010) compared with US$3.00/gallon for petro diesel (as of January 2010). To be more reasonable, it is necessary to reduce the cost to levels that are equal to or under petroleum diesel costs.

According to a case study in South Korea, the price of the lipids extracted from sewage sludge (SS) was approximately US$0.03/L, which was lower than that of all current biodiesel feedstocks (Kwon et al., 2012). The researchers revealed that the production of biodiesel using lipids extracted from SS could be economically feasible because of the remarkably high yield of oil and low cost of this feedstock compared with conventional biodiesel feedstocks. The yield of oil from SS, 980,000 L/ha per year, is higher than that from microalgal and soybean oils, 446 and 2200 L/ha per year, respectively. The disposal cost of 1 ton of wet SS paid by the Korean government is US$58.3 and the drying cost of 1 ton of wet SS is US$57.17. Dried SS is usually sent to the coal power plant and cement manufacturer and its cost (ie, 1 ton of dried SS) is US$10. Thus, biodiesel production from lipids extracted from SS would be the most economical. This economic feasibility would be synergetic with an inexpensive and reliable biodiesel conversion process (Kwon et al., 2012).

10.4.5 CONSTRUCTION MATERIAL

Reuse of waste sludge for construction materials can reduce the problems of disposal while offering a renewable substitute for the depletion of nonrenewable resources (Tay et al., 2004). Sewage sludge containing both organic carbon-containing complexes and inorganic composites represents a source of valuable materials. Substantial work has been carried out for the manufacture of valuable products by the thermal solidification of inorganic sludge composites, particularly in Japan. Dried sludge or incinerator ash is used as a primary material in manufacturing construction material. Solidification occurs at high temperatures up to 1000°C. Waste heat is available for the drying process. Depending on specific process modifications and operating conditions, various types of products can be made, such as artificial lightweight aggregates, slags, and bricks (DRRSS, 2002; Wang et al., 2008).

Upon mixing with clay or on their own, biosolids ash can be used to make bricks that are similar in appearance and physical properties to standard building bricks (Tay and Show, 1997; Wiebusch and Seyfried, 1997). In Japan, biosolids ash has been used to make bricks for over a decade (Okuno and Takahashi, 1997). The first full-scale sludge brick plant commenced in 1991 in Tokyo with a production capacity of 5500 bricks per day using 15,000 kg of incinerated sludge ash. More important, no heavy metal leaching was observed from the finished bricks, even in adverse environments with pH levels as low as 3 (Spinosa, 2004). Anderson et al. (1996) added sewage sludge ash from a fluidized bed incinerator to a series of common commercial brick; they reported encouraging results that directed a UK brick company to use this material as a potential substitute for the addition of sand to the bricks. At the University of Leeds, United Kingdom, Forth (2007) produced a building block, “Bitublock,” made by mixing waste products such as recycled glass, sewage sludge, metal slag, and incinerator ash with a sticky binder called bitumen. Bitublock was considered to be almost six times stronger than traditional concrete block. Waste sludge can also be used to produce pumice, which consists of a highly vesicular rough texture (characterized by a rock being pitted with many cavities, known as vesicles, at its surface and inside). It can be used for the underlayer of athletic grounds because it has the characteristic of draining excess water and holds sufficient moisture.

Generally volcanic gravel is used for this purpose; thus, pumice can be a good alternative to less available volcanic gravel (Spinosa, 2004). Okuno and Takahashi (1997) reported the commercial-scale manufacture of bricks consisting of 100 wt% ISSA (Incinerated Sewage Sludge Ash). They stated that important parameters for the starting ash were an average particle size of <30 μm, loss on ignition of <1 wt%, CaO content <15 wt%, and an optimum maximum temperature of 1070–1080°C. The bricks complied with all relevant Japanese standards. However, during service life, problems with moss growth, efflorescence, and ice formation were observed which were linked to water absorption. A silicon-resin coating was applied that eliminated these performance problems. However, the coating resulted in a significant increase in manufacturing costs compared with conventional clay bricks. As landfill costs continue to rise, this will become a more significant factor in determining the economic viability of ISSA-based products. According to Wiesbusch et al. (1998), leaching tests on ISSA-containing bricks revealed concerns about the leaching of Cl^-, SO_4^{2-} and certain heavy metals, which led the authors to increase the brick-firing temperature from 1000–1060°C to 1100–1200°C.

The production of Portland cement using waste sludge is another way to use valuable inorganic and organic compounds of the sludge (Taruya et al., 2002). The waste sludge can be used in three different forms: as incinerated ash, dewatered sludge, or dried sludge powder. Of the three forms, use of dewatered sludge directly into Portland cement kilns seems to be the most appealing because this process does not require new incinerators or generate additional running costs. At a high operating temperature, toxic organic pollutants in the sludge are completely oxidized and heavy metals are immobilized in the cement (Rulkens, 2008). Thus the sludge can be a used as a raw material in Portland cement manufacturing, and subsequently can reduce the burden from natural resources such clay and limestone (sources of CaO, SiO_2, and F_2O_3) (Spinosa, 2004). According to previous studies (Paya et al., 2002; Tay et al., 2002; Lin et al., 2012), cement-like materials made from sludge can replace ordinary Portland cement for up to 20% by weight.

Waste sludge can also be reused to manufacture artificial lightweight aggregate (ALWA). ALWA can be used as planter soils, fillers for clearance between kerosene storage tanks and room walls, flowerpot additives, heat-proofing panels, replacement for water-infiltrating pavement, substitute of anthracite media in rapid sand filters as well as in walkways pavement (Spinosa, 2004). A 500-kg/h plant for producing ALWA commenced operations in 1996 at the Nambu plant in Tokyo. Compared with commercial lightweight aggregates, ALWA has better sphericity, lesser specific gravity, and low compressive strength. Concrete made with the sludge–clay aggregates had lower density and hence a higher strength to mass ratio compared with that produced from conventional granite aggregates. On the basis of their research findings, Tay et al. (2004) recommended that the sludge–clay aggregates with up to 20% clay content are suitable for structural applications, whereas aggregates with up to 50% clay content could be used for other general applications in which strength is not a critical requirement. Leaching test results showed that the peak levels of all health-based contaminants were within the respective safety limits specified in the World Health Organization (WHO) guidelines for drinking water. Compliance with WHO safety limits indicates that the use of these sludge–clay aggregates should not have a significant effect on human health or the environment.

Slag, a marble-like mineral of semicrystalline structure, is a possible solution to volume reduction and the immobilization of heavy metals in sludge. Water-cooled slag and air-cooled slag are two types which can be produce from waste sludge and can be used as an alternative to natural coarse aggregate, including ready-mixed concrete aggregate, road bed materials, concrete aggregate and back-filling material, interlocking tiles, permeable pavement, and other secondary concrete products

(Spinosa, 2004). GlassPack, a vitrification process (developed by Minergy Corporation, United States), uses the organic fraction of biosolids as a renewable fuel source to produce an inert glass aggregate product from the inorganic (ash) fraction. Wet sludge (approximately 20% solids) is predried to <15% moisture; the dried solids are then subjected to temperatures between 1330 and 1500°C, at which the ash component melts into molten glass.

Japan may be considered a pioneer country in the production of construction materials from sewage sludge. Sludge is used to produce construction materials at full-scale plants (Ozaki et al., 1997). Incinerated sludge ash is also used in Columbus, Ohio, as a water-absorbent surface amendment in sports fields and horse arenas (USEPA, 1994). Ash from thermal oxidation installations are using to manufacture bricks by municipalities in Virginia and Georgia, and as a source of phosphorus by the city of Cincinnati, Ohio (Welp et al., 2002). In China, sewage sludge is also used in to manufacture of bricks and other building materials (Wang, 1997).

Thus a promising output was reported worldwide regarding the use of waste sludge as a construction material. Nevertheless, despite the development of technically feasible processes, most of the techniques are not economically viable because of the higher production cost (compared with the market price). Therefore, the commercialization of sewage sludge—based construction materials (ie, scale-up of economically feasible technologies and market development) are major challenges.

10.4.6 ELECTRICITY PRODUCTION FROM SLUDGE BY MICROBIAL FUEL CELLS

Electricity production from sludge using microbial fuel cells (MFC) has been considered a beneficial way to reuse sludge. A mixed bacterial population can be used in MFC to produce electricity while achieving the biodegradation of organic wastes. Many different bacterial species including *Escherichia*, *Shewanella*, *Clostridum*, and *Desulfovibrio* have been reported to reduce metallic ions (eg, manganese, ferric, uranium, and cupric) while oxidizing available carbon substrates by the redox mechanism (Lovely, 1993; Oh and Logan, 2005; Du et al., 2007; MFC, 2013). Rabaey and Verstraete (2005) described the mechanisms of waste treatment in MFC reactors. Microbes in the anodic chamber of an MFC oxidize added substrates and produce electrons and protons in the process. Electric current generation is made possible by keeping microbes separate from oxygen or any other end-terminal acceptor other than the anode, which requires an anaerobic anodic chamber. Typical electrode reactions are shown in Eqs. [10.2] and [10.3] using acetate as an example substrate.

$$\text{Anodic reaction: } CH_3COO^- + 2H_2O \xrightarrow{\text{microbes}} 2CO_2 + 7H^+ + 8e^- \qquad [10.2]$$

$$\text{Cathode reaction: } O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \qquad [10.3]$$

The whole reaction is the decomposition of the organic substrate to carbon dioxide and water with simultaneous electricity generation as a by-product. Based on this electrode reaction pair, an MFC bioreactor can generate electricity from the electron flow from the anode to cathode in the external circuit (Du et al., 2007).

Various types of commercially available fuel cells include low-temperature (including phosphoric acid, proton exchange membrane, and alkaline types) and high-temperature (molten carbonate and solid oxide types) fuel cells. Overall fuel cell efficiency varies by type between 47% and 87%. The voltage of a biofuel cell is normally on the order of several hundred millivolts. Power densities have been reported on the order of a 50- to 100-W/m^3 reactor (Rabaey et al., 2005). Only phosphoric acid and molten carbonate fuel cells have been studied at full scale. Fuel cell capacities in North America range from 200 kW to 1 MW. Although the operating costs of fuel cells can be low, on the order of $0.01/kWh, capital costs currently are high compared with other technologies (Kalogo and Monteith, 2008).

10.4.7 BIOPLASTIC

PHA is polyester of hydroxyalkanoic acid and is well known to be biodegradable and thus an environmentally friendly alternative to petroleum plastics (Lee and Yu, 1997; Akaraonye et al., 2010; Thomson et al., 2010). Poly-β-hydroxybutyric acid and its copolymer, poly (3-hydroxybutyrate-*co*-hydroxyvalerate), are the most widespread PHAs, whereas other forms are possible (Chua et al., 1999). PHA is produced in nature by the bacterial fermentation of sugar or lipids. PHA in microorganisms, particularly in bacteria, serves as a carbon and energy reserve and/or as a sink for redundant reducing power or electrons in stressful states (Anderson and Dawes, 1990; Lee, 1996). PHA-accumulating microorganisms are found in activated sludge. Polyphosphate-accumulating organisms accumulate PHA by taking up volatile fatty acids (VFA) under anaerobic conditions. PHA production by activated sludge has the following advantages (Satoh et al., 1999): (1) By using activated sludge, waste organic materials can be recovered and reused as biodegradable plastics; (2) the cost of PHA production can be reduced by using waste sludge as feedstock because the waste sludge is easily available in plenty; (3) PHA that is not produced by known pure culture can be obtained by using activated sludge instead of pure culture (Satoh et al., 1992).

PHAs are appealing as packaging films and disposable products (ie, utensils, diapers, cosmetic containers, bottles and cups) owing to their biodegradability (Reddy et al., 2003). In medicine, PHA can be used as functionalized nanobeads or microbeads for diagnostic and therapeutic applications, for soft- and hard-tissue repair and regeneration, and as conduits and carrier scaffolds for nerve repairs, drug delivery systems, devices for joints and wound dressings, drug eluting stents for cardiovascular applications, and heart valves in heart tissue engineering (Misra et al., 2006; Philip et al., 2007).

The current cost of producing microbial PHAs is about US$4–6/kg, which is almost 10 times higher than petroleum plastic (Chua et al., 1999; Akaraonye et al., 2010). The cost of carbon sources has triggered slow growth experienced by the PHA industry. For example, the cost of substrate or carbon sources accounts for about 50% of the cost of microbial PHA (Law et al., 2001). Even with genetically engineered *Escherichia coli*, the carbon source is about 31% of PHA's production cost (Ma et al., 2000). According to Brar et al. (2009), the major technical difficulties with bioplastic production from wastewater sludge are optimizing the organic loading rate (OLR) and the economically lower yields. This requires extensive studies of enhancing OLR and efficacy in using mixed substrates (sewage sludge and agroindustry wastewater sludge) with mixed cultures.

Micromidas LLC is developing a biological process which will use carbon and other nutrients in sludge to generate biodegradable plastic. The resulting plastic will have a lifespan of months instead of the centuries needed to breakdown petroleum-based plastics. They are in the process of developing a trailer-mounted pilot unit that can be taken to a resource recovery facility to be tested on a larger scale (Moss et al., 2013).

10.4.8 BIOFERTILIZERS

Amino acid–chelated trace elements (AACTE) fertilizer is recognized as an environmentally friendly fertilizer for cotton, fruit, and other cash crops in China (Zhang et al., 2003); however, its production is restricted by limited protein sources such as animal hair, hooves, horn, and leather (Lu et al., 2007). Liu et al. (2009) developed a novel technology for sewage sludge use. Bacteria proteins in sewage sludge were extracted to generate AACTE fertilizer using several chemical methods. Initially, sewage sludge was hydrolyzed under hot HCl solution to obtain a protein solution. Then, the protein solution was further hydrolyzed into amino acids under hot acidic conditions. After that, the raw amino acid solution was purified through activated carbon decolorization and glacial acetic acid dissolution. Finally, the purified amino acids were used to produce AACTE fertilizer by chelation with trace elements.

Under optimal hydrolysis conditions, 78.5% of protein was extracted from the sewage sludge and the amino acids yield was 10–13 g/100 g dry sludge. The AACTE fertilizer produced was observed to be in agreement with China Standard for Amino Acids Foliar Fertilizer (GB/T 17,419-1998) (Lu et al., 2007).

10.5 OVERALL STATUS OF SLUDGE REUSE FOR ENERGY AND RESOURCE RECOVERY

There is general consensus among wastewater treatment experts worldwide that waste sludge is not a waste but a source of valuable resources. Major factors behind this consent are sustainability and environmental concerns (resource depletion, soil pollution, and global warming), the hike in energy prices, stringent directives for sludge disposal, and increasing pressure and protests from environmental authorities and the public domain (Kalogo and Monteith, 2008).

Japan may be considered a pioneer in the production of construction materials from sewage sludge. Sludge is used to produce construction materials at full-scale plants (Ozaki et al., 1997). The SBTMG implemented several projects including the use of dewatered sewage sludge to produce fuel charcoal and sold for thermal power generation (Oda, 2007) and for electricity generation with a gas engine using syngas produced by the pyrolysis of sewage sludge (Takahashi, 2007). Since 1990, the Swedish government has emphasized the significance of nutrient recycling from sewage sludge. Thus, the use of sludge in agronomy is not a common practice despite the low concentration of contaminants in sludge compared with other countries (Bengtsson and Tillman, 2004). In 2000, the Swedish government projected the target of recycling 75% of phosphorus from waste and sludge to productive soils by 2010 (SME, 2000). In several Swedish cities, use of sludge-derived biogas as a biofuel in the transportation sector is a well-established practice. The Henriksdal treatment plant produces and sells biogas to Stockholm's bus company. At least 30 buses in Stockholm are running on biogas (Salter, 2006).

In the United States, various well-established energy recovery techniques are in use, including electricity and mechanical energy production, and heat recovery through biogas generated from the anaerobic digestion of waste sludge (Kalogo and Monteith, 2008). The use of methane as a source of hydrogen to generate energy with liquefied carbonate fuel has been exhibited at King County, Washington's South treatment plant (Parry et al., 2004). Co-digestion of grease (from restaurant trap haulers) with sewage sludge is practiced in Watsonville, California, to improve the biogas yield by over 50% (Cockrell, 2007). Grease is composed of energy-rich compounds such as fats, carbohydrates, and sugars (Bailey, 2007); thus it is an appropriate substrate for biogas production during anaerobic digestion of sludge. Incinerated sludge ash is using in Columbus, Ohio, as a water-absorbent surface amendment in sports fields and horse arenas (USEPA, 1994). The ash from thermal oxidation installations is used for brick manufacture by the municipalities of Virginia and Georgia; and as a source of phosphorus by city of Cincinnati, Ohio (Welp et al., 2002). The dried biosolids products (OCEANGRO) are used as organic fertilizer by over 60 New Jersey golf courses and registered with the New Jersey Department of Agriculture. Moreover, the biosolids are used as a fertilizer to grow canola (used to make biodiesel fuel) at King County, Washington (Seattle) (Kalogo and Monteith, 2008).

In China, biogas harvesting from sewage sludge is a common method of resource recovery. Annual methane generation from all feedstock including sewage sludge was assessed at 720 million cubic meters (Aalbers, 1999). Moreover, sewage sludge is used in the manufacture of bricks and other building material (Wang, 1997). The Netherlands is well known to be one of the first countries to employ phosphorus recovery on a full scale (Stark, 2004). The Netherlands has aimed to replace 20% of its current phosphate rock consumption by recovered phosphate (Roeleveld et al., 2004). Around 32% of sewage sludge generated in The Netherlands is currently used in the cement industry and power stations (Uijterlinde, 2007). In the United Kingdom, a new program for energy recovery was proposed by the government, including the generation of 20% of electricity from renewable sources by 2020 (Trumper, 2007). In 2005, 10.8% and 4.2% of all UK renewable energy was recovered by combustion and biogas production, respectively. Germany is actively involved in advancing novel technologies for phosphorus recovery from sewage sludge; however, only four pilot or bench-scale technologies have been developed since 2002 (Berg and Schaum, 2005).

In New Zealand, the city of Napier is implementing the production of sludge compost using primary sludge from the Awatoto wastewater plant and wood chips (MacDonald et al., 2007). The main goal of this project is to use the sludge compost as a soil conditioner and a source of fuel for energy production. Furthermore, Malaysia is performing research to evaluate the potential of using dried sewage sludge as a raw material to produce clay-sludge bricks (Liew et al., 2004).

10.6 SUMMARY

Building sludge-derived resources recovery systems will help to produce environmentally benign products, reduce dependency on nonrenewable resources, thus facilitating the conservation of natural resources, decrease human health risks and environmental pollution (by complete eliminating pathogens, reducing the risk of soil and groundwater contamination from heavy metals and other emerging contaminants associated with landfills and land application of sludge, reducing the greenhouse gas emissions associated with burning petroleum fuels), and offer routes to the sustainable management of waste sludge (ie, environmentally friendly, economically feasible, and socially acceptable).

The major issue with resource recovery from waste sludge is related to the manufacturing cost of value-added products compared with the market price. Thus, the cost-effective production of value-added products with supply chain management and environmental compatibility must be ensured during the development of different processes. Several developments have failed mainly owing to the high capital and operation and maintenance costs (Kalogo and Monteith, 2008). Moreover, the method must generate a few or several low-volume and high-value chemical products as well as low-value and high-volume liquid transportation fuel, while producing electricity and process heat for its own use and which would be possibly adequate for the sale of electricity. The high-value products increase profitability, the high-volume fuel fulfills national energy demands, and the power generation decreases costs and avoids the release of greenhouse-gases (Speight, 2011).

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