Chapter 18
Management/Utilization of Wastewater Treatment Sludges*

18.1 Introduction

Sludge is the largest by-product of the pulp and paper industry and disposal of sludge is a major solid waste problem for the industry (Battaglia et al. 2003; Geng et al. 2006; Suriyanarayanan et al. 2010; Krigstin and Sain 2005; Mladenov and Pelovski 2010). The nature of sludge generated from paper industries mainly depends on the raw materials used in different unit processes. The quantity of sludge generation varies with the type of pulping and papermaking or both (Springer 1993). Sludge generated from the industrial sludge contains a large number of ingredients, some of which are toxic. Solid waste is generated from the both large and small categories of paper mills. Solid waste from paper industries is generated usually in various stages of paper production. The production of chemical pulp generates various fractions of solid waste:

- Inorganic sludge (i.e. dregs and lime mud) from the chemical recovery
- Bark and wood residues from woodhandling
- Sludge from the biological wastewater treatment plant (i.e. inorganic material, fibers, and biological sludge)
- Dust from boilers and furnaces
- Rejects containing mainly sand from woodhandling
- Fly and bottom ashes from the fluidized bed boiler

Dregs and lime mud are separated from the chemical recovery cycle in order to keep the amount of inert material and nonprocess chemicals in the cycle at an acceptable level and thus secure high reaction rates in the chemical recovery system.

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P. Bajpai, *Biotechnology for Pulp and Paper Processing*,
DOI 10.1007/978-1-4614-1409-4_18,

Solid waste disposal is usually to landfill, although incineration is becoming increasingly widespread. Prior to any land application of solid residues, the levels of chemicals of concern need to be routinely demonstrated to fall below realistic regulatory levels. Kenny et al. (1997) have reported that Canadian pulp and paper mills with activated sludge wastewater treatment system produce primary sludge of 31 kg(od)/tons of pulp while the secondary (biological) sludge generation is 16 kg/tons. A typical floatation deinking plant produces 80–150 kg of dry sludge per tons of recycled pulp (Latva-Somppi et al. 1994). The amount of sludge generated by a recycled fiber mill depends very much on the type of furnish being used and the end product being manufactured. For example, a recycled tissue mill and a recycled newsprint mill may use the same old newspaper as furnish, but the higher brightness and lower dirt requirements of the tissue will result in a lower yield and higher sludge generation.

The composition of sludge depends on the raw material, manufacturing process, chemicals used, final products, and the wastewater treatment technique. In case of recycled papers, it also depends on the type of paper used and the number and types of cleaning stages used in the recycling operation. For example, sludge from mixed office wastepaper (MOW) may contain high levels of clay and other types of fillers, printing inks, stickies from envelope adhesives, as well as fibers and paper fines. In fact, sludges from MOW recycling operations may contain as much as 2% ash from fillers in the wastepaper. Sludge solids produced by pulp and paper mills typically include a majority fraction of fiber. Depending on the mill ink, sand, rock, biological solids, clay/fillers, boiler ash, grits from recausticizing, etc. may make up the other fractions. Because of the constituents that may exist, along with the water fraction, typical sludge analysis can vary widely. So, it is very important to characterize the sludge carefully for determining the best method for sludge disposal.

18.2 Dewatering of Sludge

Sludge is usually disposed of through landfilling, incineration, land spreading or through alternate uses. All these approaches have one feature in common: the sludge must be as dry as possible. Hence, dewatering the sludge to as high a solids level as possible is important for both economical and environmental reasons.

The primary sludges can be dewatered easily as these are high in fiber and low in ash. The most difficult are the solids from the high-rate biological treatment systems. The primary sludge most difficult to dewater is that containing groundwood fines. Primary sludges are normally tertiary or quaternary pulp and paper mill rejects, but often consist of quality fibers having a high monetary value. As the percentage of secondary sludge increases, the dewatering characteristics deteriorate, resulting in decreased cake solid contents. Tissue mills, NSSC plants, and recycle paperboard plants have problems with dewaterability of combined sludges.

Sometimes, it may be desirable to dewater the primary sludge separately from the secondary sludge. One example is a situation in which the secondary sludge can be disposed of through land application. Blended sludges are not usually suitable for such disposal. Another example is a situation in which the primary sludge can be used to produce a by-product or can be reused within the production process, but the blended sludge cannot be used. If the combined consistency is less than 4–5%, sludges must be predewatered. It actually helps the dewatering process by reducing solution volume while increasing solid content for further dewatering, absorbing fluctuations of inlet solids consistency while stabilizing the output consistency, increasing outlet solids content and solids capture efficiency, and reducing overall polymer consumption.

Predewatering technologies which are commonly used include rotary sludge thickeners (RSTs) and gravity thickeners. Other technologies in use include gravity table thickeners, dissolved air floatation (DAF) clarifiers, and belt presses. Centrifuges, V-presses, coil vacuum filters, and fabric vacuum filters are also used but these are not very common. The floatation thickener used on secondary sludge can achieve approximately 4% solids, giving it an advantage over the gravity thickener, which can achieve only about 2%. The advantages of gravity thickeners include: simplicity, low operating costs, low operator attention and a degree of sludge storage. Conditioning chemicals are not normally required and there is minimal power consumption. However, these advantages are often offset by potential septicity/odor, less dewatering capability (as compared to other technologies) and large space requirements. These disadvantages have limited the use of gravity thickeners in recent installations. An RST is a rotary screen where water is removed by gravity and tumbling action. RTSs have been installed in many mills as predewatering units before the screw presses. This type of predewatering device is capable of increasing consistency to between 4 and 10% depending upon the proportion of secondary sludge and the percentage of solids from the secondary and primary clarifiers. In a gravity table filter, sludge is drained on a rotary wire. Drainage is assisted by moving paddles. The paddles are required to prevent wire pluggage. Gravity tables and RSTs produce sludges of similar consistency. Gravity tables are normally placed over screw presses to allow feeding by gravity. As with RSTs, polymers are applied before the table filter.

With DAF clarifiers, secondary sludge is floated with dissolved air, usually with the aid of some dewatering chemicals. Sludge is skimmed from the surface of the clarifier and the underflow re-treated in the aeration pond or the primary clarifier. In the DAF process, solids can be increased to 3–6% for secondary sludges. The actual performance is frequently dependent upon the type of chemical applied and the dosage rate. DAF units also have the potential to eliminate odor problems. Few mills rely solely on DAF units for sludge pre-dewatering (Kenny et al. 1997). Few activated sludge treatment plants use DAF units in combination with RSTs. One mill in Canada uses coil filters and V-presses to dewater primary sludge (Kenny et al. 1997). After pre-dewatering of the primary sludge, the secondary clarifier sludge and pre-dewatered primary sludge are mixed in a paddle mixer and then discharged for final dewatering on screw presses. No dewatering chemicals are required. Vacuum filter dewatering of biological sludges has been phased out of service in North America. Problems with poor capture rates, blinding and landfilling difficulties have eliminated this option.

In order to obtain good dewatering efficiency, sludge from wastewater treatment plants is frequently conditioned, using chemical or physical means to alter the floc structures of the sludge, i.e. imparting sufficient stiffness and incompressibility to the structures so that water entrained in the sludge can rapidly be drained through filtering or other means (Benitez et al. 1993; Wu et al. 1998). The functions of conditioners are to improve the sludge dewatering properties, to reduce specific filtration resistance, and to enhance the dewatering efficiency. These increase the solids content after dewatering. There are four mechanisms through which chemical conditioners added to sludge at wastewater treatment plants act: compression of the electrical double layer, neutralization of charges, retention of precipitates, and the bridging effect. These actions destroy the stability of the existing flocs, causing them to re-aggregate and precipitate into a tighter sludge filtration cake, thus enhancing dewatering (Huang and Chang 1997). In general, following chemicals are used for conditioning, regardless of the type of equipment: lime, ferric chloride, and polymers. The three can be used separately or in combination. Ferric chloride has the disadvantage of being highly corrosive but is a very effective conditioning agent. The sludges that are difficult to dewater require high polymer addition rates. Wet air oxidation has also been used as a conditioning process to aid sludge dewatering and has been commercially applied in the paper industry (Mertz and Jayne 1984) where filler recovery was a side benefit. However, the brightness of the filler recovered was lower than that of the filler grade clay and the installation experienced considerable down time and high maintenance costs.

Polymers are typically added to flocculate sludge during wastewater treatment. Banerjee (2009) has reported that cyclodextrins (CDs) boost the performance of these polymers by increasing the cake solids and drainage rates of belt- or screw-pressed biological or primary sludge. These benefits are obtained at very low CD dosage. CDs also decrease the specific resistance to filtration (SRF) and increase the capture rate of solids during belt pressing. In three different full-scale trials, a combination of higher cake solids, better drainage, better filtrate clarity and lower polymer use was obtained. The CD application for sludge dewatering has been implemented at the Mississippi mill and has provided stable benefits of a 30% reduction in polymer costs for several months. Several successful trials at other facilities in the United States have been run successfully and additional implementations are anticipated. From a cost standpoint, the CD is approximately twice the cost of the polymer. It displaces a much higher proportion of the polymer, so the cost:benefits are attractive. Finally, CDs are biologically derived products in that they are prepared from starch. Sludge-conditioning polymers are derived from hydrocarbons, so that the displacement of polymers by CD carries both economic and socio-political benefit. The cost of α-CD is about three times higher than that of a typical sludge-conditioning polymer, but it is applied at very low doses so the increase in overall chemical cost is relatively small. This cost is more than offset by the savings realized from the reduced polymer dosage. The benefits of the CD are incremental; the CD essentially boosts the performance of the polymer(s) applied with regard to cake solids, drying rate, and capture efficiency. The cost:benefits are site-specific, but they are especially attractive at locations where sludge disposal costs are high. Finally, the CDs are biologically derived products. Sludge-conditioning polymers are derived from hydrocarbons, so their partial replacement with CDs carries both economic and environmental benefit.

Taiwan researchers (Perng et al. 2006) have studied the application of nanosilica for paper mill dewatering. The study was conducted in a paper mill in Taiwan which produces cultural and industrial paper products and which applies sedimentation and a single-stage activated sludge (AC) process to treat its mill effluent. The primary sludge from sedimentation and the waste biosludge from the AC stage were collected for the experiment. A conventional cationic polymer and a nano-silica preparation were respectively used as a dewatering agent and co-agent to see whether the dewatering efficiency could be enhanced. Sludge dewatering efficiencies were quantified using the SRF and capillary suction time (CST). A 23-factorial experimental design was used to delineate the effects and interactions of the sequence of polymer addition and the dosages. Analyses of the factorial design on the CST and SRF tests showed that both the primary sludge and biosludge had similar treatment behaviors. All three variables under investigation were significant, but none showed interactions with each other. The biosludge had a poorer dewatering efficiency than did the primary sludge on the CST and SRF tests. They found that the cationic polymer should be added first, followed by the anionic nano-silica. The reverse sequence of addition was largely deleterious to the dewatering of the primary sludge. Both the cationic polymer and nano-silica showed close weighting factors on the dewatering efficiency.

The commonly used dewatering devices used in the paper industry are rotary vacuum filters, centrifuges, V-presses, twin-wire presses, and screw presses. In some situations, the primary dewatering device is followed by a press to further increase the solids content. The vacuum filter had been the most popular device. Solids capture in vacuum filter is 90–95%, and the cake produced is about 20% solids. In order for the filter cake to discharge properly from the filter, 10–20% long fiber (>100 mesh) must be present in the sludge (Miner and Marshall 1976). Vacuum filter cakes containing combined sludge solids can be further dewatered on V-presses to approximately 35–40% consistency. A V-press is just two disks providing a converging nip that applies pressure to the sludge to squeeze out the water. Vacuum filters can be equipped with either fabric media or steel coils. Fabric media are often used in situations when fiber content is low, the ash content is high, or the solids are otherwise difficult to dewater on a coil filter. The power costs for operating the large vacuum pump required by a vacuum filter are quite high. Vacuum filters are being replaced by belt presses, which seem to perform as well if not better, at lower operating cost.

Voith Paper has developed Thune, a new design of screw press for dewatering pulp and paper mill sludge (Norli and Smedsrud 2006). The trial was taken at the new Adolf Jass Schwarza mill at Rudolstadt Germany in 2005. The new screw press achieves high torque distributed evenly along the axis by integrating the inlet and discharge housings and the screen supports into the machine frame. The centerline of the press is kept low in order to minimize deflection at high loadings, the height above mountings being only 270 mm. The operating cost is kept low and the machine has been designed to facilitate maintenance and servicing. Above all the new press achieves a higher dewatering per screen area than comparable sludge presses. The Thune SPS70 screw press at Schwarza handles all fine and sludge for dewatering, fed by a Meri BlueDrain gravity table. A Meri Sediphant is used to predewater cleaner reject and prescreened sewer matter. Dynamic torque control ensures a uniform consistency of the discharge. Voith Paper dewatering center at Tranby Norway have also installed a smaller system at Orbro Kartong in Sweden, with a Meri Elephant filter and a Thune screw press.

Disk centrifuges have found little application in the paper industry. They have been tried as thickening devices but experience has been unsatisfactory. Basket centrifuges have been used to a limited extent for sludges that are very difficult to dewater, but they operate in a batch mode rather than continuously. Usually, it is desirable to use the continuous decanter scroll centrifuge. Special scroll units have been developed for secondary sludge, and they are usually preferred over the basket centrifuge. Scroll centrifuges dewatering combined paper industry sludges generally produce cakes of 20–40% consistency at solids capture efficiencies of 85–98% from sludges conditioned with polymer. As the centrifuges operate on the basis of density difference separation, the sludges which are much denser than water, such as high-ash sludges, provide the best application of centrifuges. Specially designed scroll centrifuges can dewater secondary sludge from 2 to 11% solids with 99.9% capture efficiency (Reilly and Krepps 1982). However, it required 6–8 kg polymer per tons of sludge for conditioning. Centrifuges have a relatively low capital cost but can be expensive to operate due to requirement of chemical conditioning agents, their high power requirements, and their maintenance costs. Dissatisfaction with centrifugation has been attributed to the following: (a) generation of poor quality supernatant that could cause a buildup of fines in the treatment system, (b) susceptibility of centrifuges to plugging with pieces of bark, and (c) the severe screw conveyor abrasion experienced at many mills.

V-presses have been applied successfully to the dewatering centrifuge and vacuum filter cakes containing as much as 30% biological solids. However, the combined sludges normally encountered require sufficient conditioning for vacuum filtration or centrifugation to render them amenable to V-pressing (Miner and Marshall 1976). V-pressing can be performed to raise the solids content of the sludge high enough for incineration (Stovall and Berry 1969). V-presses generally produce primary sludge cake consistencies of 30–45%. Either a V-press or a screw press would precede most bark boilers burning bark and sludge. The sludge would enter the press at 15–25% solids and be subjected to a pressure of 690 kPa to raise the solids to the 30–45% suitable for incineration (McKeown 1979).

Pressure filters are the most powerful dewatering devices available. For combined sludge, cake of 30–35% consistency can be produced with solids capture efficiency of 95–100% (Miner and Marshall 1976). However, it is necessary to precoat the filter cloth to facilitate cake discharge and minimize the frequency of media cleaning. Diatomaceous earth, flyash, cement dust, etc. can be used for precoating. Media cleanliness has been indicated as a crucial parameter in determining the pressure filter cycle time. Pressure filtration also requires conditioning of the sludge before filtration. On pure secondary sludge, 35–40% cake solids can be achieved with a conditioning agent and a pressure of 200–250 psi. The main drawback of the pressure filter is that it is a batch operation and requires a lot of operator attention. Continuously operating automatic units have also been developed, but they are mechanically complex and therefore subject to many maintenance problems.

Moving belt press (Twin-wire press) has received intensive industry interest in the past. Many paper mills have installed moving-belt presses. On primary or combined sludges, moving-belt presses have generated cakes of a consistency comparable to that of two-stage dewatering with V-presses, and with similar or somewhat higher conditioning costs and generally lower power consumption. Polymers are commonly used for the sludge conditioning, and some processes use dual-polymer systems. The cake solids are 20–50% for the primary sludge whereas they are 10–20% for the secondary sludge. Capture efficiency is very high for belt presses, about 95–99% of the solids fed. Requirement of operator attention is low. These presses require power only to drive the belt, thus they are energy-efficient. Another advantage is their ability to operate on secondary biological sludge. However, the major operating problem is belt life, which is only few months. The usual cause of failure is puncture of the belt by incompressible objects in the sludge. The press is also subjected to corrosion due to hydrogen sulfide gas that is sometimes generated if there is any sulfur content in the sludge.

The latest development in sludge-dewatering is screw press of new design. These presses produce cake solids of 50–55% when operated as the only sludge dewatering device, solids capture ranges from 70 to 88% with no polymer addition on primary sludge (Toole and Kirkland 1984). Biological solids adversely affect solids recovery. Polymer can be used to improve efficiency but it has little or no effect on final sludge consistency; therefore is often not used on primary sludge. With secondary sludge, polymer is used. These presses appear to be energy-efficient. Screw presses are replacing twin-wire presses as the dewatering technology of choice for the pulp and paper industry.

18.3 Methods of Disposal

The pulp and paper industry disposes of its dewatered solids by landfilling, incineration, land spreading, or through alternate uses (Monte et al. 2009).

18.3.1 Landfill Application

Landfill has been the most common method till recent past for disposal of sludge, etc. (Gavrilescu 2004; Monte et al. 2009). However, the major factors to be considered when planning for landfill site include:

- Environmental suitability of area for landfill
- Geology of the area
- Environmental impact of run off water from the site
- Impact on ground water
- Composition and volume of the sludge
- Transportation cost

Mills favor landfilling whenever disposal sites are readily available and handling costs are low (Russel and Odendahl 1996). Landfilling is preferred because of the relatively low capital investment and the availability of mill owned land. In recent years, however, regulatory agencies have recognized the potential for far-reaching adverse environmental effects from landfilling activities. This has resulted in the tightening of regulations and requirements for more monitoring, environmental impact assessments, closure plans, and public consideration.

Normal sanitary landfill practices should be observed in constructing an industrial landfill. Some of the requirements that must be met are as follows (McKeown 1979):

- The disposal site should be a minimum distance above groundwater
- All subsurface conduits – such as culverts, gas and water lines – should be removed
- The site should be above the flood plain and be protected from flooding
- The site should be a minimum distance from a public well, highways and watercourse, and
- The nearest property line should be a certain distance away. After a site is chosen, according to the listed criteria, it should be used in accordance with good operating procedures for sanitary landfills.

Studies of the specific requirements for the design of papermill landfills are described by several researchers (Wardwell et al. 1978; Holt 1983; Ledbetter 1976). Modern landfill will require a liner design. A leachate collection system is required plus FML liners and a clay liner. In daily use, intermediate cover is usually not required, but a final cover will be, and it must be impermeable, properly sloped, vented, and have the ability to support vegetation.

Most of the environmental effects from landfills arise from the runoff of liquid leached from the waste, that is, the leachate. Leachate is generated at solid waste landfills as a result of physical, chemical, and biological activity within the landfill. Leachate characteristics are effected by

1. Precipitation
2. Run-off from and run-on into the landfill
3. Groundwater flow into the landfill
4. Evapotranspiration
5. Consolidation and water generated during the decomposition of the waste

These factors depend on local conditions such as climate, topography, soils, hydrogeology, the type of cover on the filled sections, and the type of waste. Leachates from pulp and paper industry landfills are known to contain conventional pollutants as well as metals, volatile organic compounds, phenolic compounds, volatile fatty acids, and some base neutral compounds (NCASI 1992). A NCASI study (1992) found that metals were usually present at fairly low concentrations. Volatile organic compounds were detected; toluene being the most common with a median concentration of 35 μg/L which is well below the Canadian Council of Resource and Environment Minister’s goal of 300 μg/L for protection of aquatic life. The only base/neutral compounds found in detectable quantities, more than once were bis-(2 ethyl-hexyl)-pthalate and di-*n*-octyl pthalate. Pthalates are used in plasticizers, defoamers, and lubricating oils. Several kinds of phenolic compounds may be found in pulp mill landfill leachates including cresol isomers, phenols, and chlorinated phenols. Volatile fatty acids are produced from the decomposition of organic matter under anaerobic conditions and are common to leachates from much type of landfills. Acetic acid and propionic acid were found in the highest concentrations in pulp and paper mill landfills. A comparison of the average TOC and COD concentrations and the total UFA concentrations showed that UFAs contributed from 7 to 100% of the organic material in kraft mill landfill leachates (NCASI 1992). These leachates if not properly collected and treated may contaminate groundwater or surface water bodies. When landfills are on relatively permeable soils such as sand or gravel, leachate migration may cause contamination over areas many times longer than the area of the landfill. This can also occur over impermeable surfaces such as bed rock where the leachate can flow quickly toward a receptor. Groundwater contamination is a concern if the groundwater is a drinking water source or if it flows to a surface water body. If groundwater contamination directly affects the drinking water supply, the liability implications for the landfill owner/operator may be enormous. In addition to impairment of drinking water quality, leachate contamination of ground or surface water may result in the impairment of biological communities, aesthetics and recreational uses. Recognition of these potential effects, together with public awareness of landfilling issues dictates the necessity for a thorough EIA of new landfill sites.

In Canada, while the regulatory framework does not typically require an EIA for pulp and paper landfill proposals, many of the components of an EIA are fundamental to a successful permitting process. The key components include establishing a site development and approval plan, conducting effective public consultation throughout the process and undertaking solid technical studies and impact assessment analysis in support of the project (Russel and Odendahl 1996). The mill will need to decide on the specific scope of work based on the environmental conditions of the site, the community needs and the input from local regulatory agencies. Regardless of scope or approach, the mill as a proponent of a new landfill development must recognize the long-term commitment associated with landfill effects and adopt a management approach which incorporates public involvement with solid technical design and assessment.

A cost-effective approach has been developed and applied to a landfill in Ontario (Russel and Odendahl 1996). Essentially, a control chart method is used where warning and control limits are established for selected leachate indicators. Leachate indicators are selected based on the ratios between background and leachate concentrations, with the highest ratios indicating the most appropriate indicators. The leachate indicators selected should also represent different chemical groups such as metals, nutrients, ions, and organic compounds. Before landfill operation, the selected leachate indicators (three to five chemical constituents) are monitored monthly and the concentration differential is used to establish the warning and control limits. The landfill is monitored monthly during the operation and the concentration differential is plotted on a graph for each leachate indicator with the warning and control limits. If the value is within the warning limit, no action is required, however if the value is above warning or control limits, an established response is implemented to determine the cause and if necessary, initiate mitigative measures. The use of control charts for tracking water quality is beneficial as it is easily interpretable by the public and the mill's environmental managers.

The main disadvantages linked with the landfill is the possible risk of contamination of land and ground water due to which most of the developed countries are banning landfill in near future.

18.3.2 Incineration

The solid wastes rich in organics are incinerated mainly to reduce its volume and ultimate disposal in a feasible way which is easier and cheaper to landfill. Sludge is mainly burnt in fluidized bed and grate boilers. Burning of sludge is also associated with several limitations such as high capital investment, need of auxiliary fuel due to high moisture content, emissions of dioxin, NO_x, heavy metals, etc. in addition to other problems like:

- Storage
- Handling
- Low combustion efficiency
- Opaque stack gas
- Sticky ash formation

The following three types of incineration are in practice in the industry:

(a) Burning in an incinerator specifically designed for the sludge
(b) Burning in the bark boiler
(c) Burning in a power boiler that also burns fossil fuel

Burning the sludge in the bark boiler, which is a hogged fuel (combination fuel) boiler, seems to cause few problems except for reduced steam generation and reduced boiler efficiency (Miner 1981). Incineration in the bark boiler appears to be acceptable for sludge incineration if such a boiler is available on the mill site and if it can take the increased water load. Dewatering to higher levels, 45–50% solids, will make bark boiler incineration an even more attractive and will minimize the effect on boiler operation.

Combustion properties of a sludge are generally related to the amount of fiber present. Energy available is usually inversely related to the ash content. High ash values (up to 50% on dry basis) correlate with relatively low heating values. Sulfur values are important as related to emissions. Dewatering of the sludge stream will be required to increase solids up to some minimum level before combustion will be beneficial or even breakeven. Self-sustained combustion is available with some sludges generated depending on the moisture and organic levels. Cost and benefit evaluations can be made that will indicate the moisture level for optimum performance. Removal of additional water to increase solids above 50% requires a different method similar to paper passing from the press section to the dryer section on a paper machine (Busbin 1995). Thermal drying with hot gases or air can be done in a conveyor dryer, cascade system, or a stand alone drying unit. Reduced water content obviously helps improve efficiency and also can improve long-term storage options through reduced microbial growth.

The sludge product may be available in several forms depending on the method of combustion and the boiler used. Dewatered sludge straight off a screw press will be lumpy and after moving through several conveying operations begin to break up into a fuel that is fine, uniform and fibrous in nature. Sludge may also be processed further into briquettes or pellets (David 1995; Nichols and Flanders 1995; Sell and McIntosh 1988) to improve handling, storage or combustion characteristics. Blending dewatered sludge with other fuel (chip fines or saw dust) can help improve conveying characteristics. Pelletizing has come to the forefront as a method to convert combustible solid waste into a usable fuel. Waste to energy via pellet fuels needs to be examined more closely and regarded more highly as a successful solution to landfill crisis. They are quickly becoming a very viable and profitable alternative (Bezigian 1995).

Various types of combustion methods are available which include traveling grate boilers, vibrating grate boilers, other hog fuel boilers, bubbling bed combustors, circulating fluidized boilers, stage combustors, rotary kilns, and pyrolysis/pulse combustors (Kraft and Orender 1993; King et al. 1994; Fitzpatrick and Seiler 1995). The practicality of the above would be based on the sludge characteristics (contaminant contents, fuel size, volatility, ash characteristics, heat content, etc.) and to a great degree the volume to be fired (Busbin 1995). Operating experiences with stoker firing of TMP clarifier sludge with wood waste and combustion of the wastewater clarifier underflow solids in a hog fuel boiler with a new high energy air system have also been reported (King et al. 1994; La Fond et al. 1995). Combined cycle fluidized bed combustion of sludges and other pulp and paper mill wastes to useful energy has been suggested (Davis et al. 1995). Pulp and paper companies can improve the cost of operation by using proven, readily available power plant and combustion equipment and systems to efficiently convert the energy available in mill wastes to useful thermal energy and electrical power. By using the combined cycle concept, either as the combustion turbine combined cycle or the diesel combined cycle, the firing of wood waste and sludge provides net energy gain for the operation of facility rather than merely a means of disposal.

Other alternatives of recovering energy from the sludge have also been tried. A sludge gasification plant has been tested to generate the clean fuel (AghaMohammadi et al. 1995). Steam reforming as an alternative method for disposal of waste sludge has been suggested (AghaMohammadi and Durai-Swamy 1995). A novel method of thermal treatment of contaminated de-inking sludge has been proposed which is based on the application of the low-high-low temperature (LHL) regions during the combustion (Kozinski et al. 1997). The LHL approach allows for the simultaneous encapsulation of heavy metals within solid particles, removal of submicron particulate, and destruction of polycyclic aromatic hydrocarbons before they are emitted into the atmosphere. The encapsulation of the heavy metal layers surrounding the heavy metal-rich cores of the ash particles may prevent the metals from leaching under acidic conditions.

Sludge can be easy to burn with the right combustion technology. Knowing that the right technology is very fuel-specific and having the technology characterization customized for site-specific conditions is essential to make proper combustion technology choices. Incineration is not practical for high-ash sludges. Stringent air pollution emission requirements for combination boilers have diminished the amount of incineration practiced. One of the Finnish mills incinerate sludge if the solids content is over 32%, and landfills the sludge if it is less than 32% (Kenny et al. 1995). Operation of the boiler must also be considered when the sludge is not available as a fuel. Several points of consideration include the combustion temperature, fuel feed systems, and boiler rating. Older boilers burning sludge as an alternative fuel should be able to simply return to earlier operating states.

Some of the chlorinated organics not eliminated through process modifications could be trapped on the sludge from the external treatment process(es). The disposal of pulp and paper mill sludges, which may contain chlorinated organic compounds, represents an increasing problem. However, if those sludges could be dried to 90% dry content, in an energy-efficient manner, they could provide high enough flame temperature upon combustion in order to destroy the organic chlorides entrapped in the sludges. In addition, this approach could improve mills' fuel self-sufficiency.

18.3.3 Land Application (Composting)

Two factors viz., continued decrease in availability of landfill space and increase in energy cost in incineration, have forced the pulp and paper mills internationally to look for the land application of the same as a low cost disposal method. In composting process microorganism break down the organic matter of the sludge under aerobic conditions. It is suitable both for biosludge and sludge from primary clarifier.

Much work has been done with land application of pulp and paper mill sludge in the last 2 decades. In Canada, several mills are routinely doing land application and several have conducted serious field trials. QUNO Inc. Thorold, Ontario, Canada has experience with land application of primary, secondary, and deinking sludges (Pridham and Cline 1988). Primary and deinking sludges have been found to have similar characteristics – low nitrogen and high fiber content. Conversely, secondary sludges (biosolids) have relatively high nitrogen and phosphorus content and low fiber content making them more suitable for land application. Tests at QUNO found that the heavy metal content of the combined paper mill sludge was equivalent to that of the cattle manure, and about one-tenth that of municipal sludge. The sludge has been successfully used as a replacement for manure in agricultural applications, as well as for land reclamation projects of old sand pits, coal/clinker sites and a former foundry site. Work has been completed with Alberta pulp and paper mills in conjunction with the Alberta Research Council on land application (Macyk 1993). Land spreading trials have been completed on both agricultural and forest cut-block sites. Research is also being conducted by the Alberta Newsprint Corporation and Alberta Research Council to evaluate the environmental effect of land spreading conventional and deinking sludge (Pickell and Wunderlich 1995). Preliminary research indicated that the procedure should not present any problems in regard to soil quality or plant growth. Trials with land spreading around the mill site have been successfully completed by applying the sludge on top of a gravel base. Alberta Research Council has also completed research on ash and sludge land spreading in conjunction with the Slave Lake Pulp Corporation (SLPC) (Pickell and Wunderlich 1995). Grass yield on the test plot site at SLPC indicated as much as five times the yield of control plots. SLPC has had favorable results with sludge application on the surrounding agricultural area. Previously, landfilled sludge has been reclaimed and distributed to the farming community and applied using manure spreaders.

There has been considerable interest in use of paper mill biosolids and ink waste in agricultural land for many years (Pridham and Cline 1988). Sludges function only as amendments and not as fertilizers because they do not contain the elemental analysis required of a fertilizer (Atwell 1981). For a soil amendment, the carbon nitrogen ratio should be 20:1–30:1. An average composition of seven different paper mill combined sludges from ten different mill types was 26:1, so this criterion is being met. The calcium/magnesium ratio should be above 6:1; many combined sludges fail to meet this criterion but the addition of lime to the sludge fulfills it. Sludges are good soil amendments for sandy soils. Detailed analysis of the seven combined sludges did not indicate a heavy metal problem (McGovern et al. 1983). Trials have been conducted in which fly ash and either primary sludge or secondary sludge were applied to crop land. The fly ash–sludge blends were as effective as commercial fertilizer. In these same trials, lime mud applied to agricultural land performed better than dolomite limestone used for the same purpose (Simpson et al. 1983). Australian Newsprint mills Ltd. (ANM) used small quantities of biosolids on vegetable and horticultural gardens with good results and no observed detrimental effects (Hoffman et al. 1995). Several farmers have also used the material on small pasture areas and on orchards, but no objective evaluations have been carried out. Because of the high level of farmer interest, ANM carried land spreading trials on crops and pastures (Hoffman et al. 1995). The biosolids were utilized on a farm land close to mill. For this, a desk study and a survey of local farmers were conducted. It was found that biosolids would be readily used by farmers, if it could be demonstrated that it was a viable fertilizer, that it was safe to apply to the environment and the cost was competitive with existing practices. This study also confirmed that about 2,000 ha/year of land would be required to dispose of the material. It identified the area of interest of land for economic disposal as areas of crops and pasture land within 20 km of the mill and luceme flats where disposal could take place in winter. In 1992, a field experimental program started with a large area experiment on oats at a location known as Waitara. Biosolids were found to be slow to release their nutrients and produced an effect similar to fertilizer without producing adverse environmental effects. Rates of 16–64 tons/ha were required to substitute for normal rates of conventional fertilizer. ANM also conducted trials to spread the biosolids on forest land (Hoffman et al. 1995). Trials started in the Carabost and Green hills State Forests, near Tumbarumba. The major disadvantage with forest spreading over agricultural land spreading is the higher cost of transport to the disposal site. So, the cost of transport would normally make forest spreading unattractive. However, if the solid could be back loaded on log trucks then the economic disadvantage decreases. In Canada, Greater Vancouver Regional District (GVRD) and the University of British Columbia's Forest Sciences department embarked on a 3-year research program at UBC's Malcolm Knapp Research Forest in Maple Ridge to determine the environmental and silvicultural application of recycling pulp and paper sludge and treated sewage sludge as an organic forest fertilizer called Nutrifor (Pickell and Wunderlich 1995). The second phase of the program introduced Nutrifor as a viable fertilizer for forestry and other users.

Scott Paper Ltd. in New Westminster conducted a full-scale land application project with GVRD in which paper mill sludge is combined with municipal sludge and then applied to a tree farm in the Fraser Valley (Pickell and Wunderlich 1995). In 1990, the GVRD, Western Forest Products Ltd. and the IBEC Aquaculture participated in a fertilization project in which various mixtures of pulp mill wastes, sewage sludge and fish mort silage were applied to forest sites in Southern British Columbia near Port McNeil on Vancouver Island (Taylor et al. 1992). Initial results indicate a rapid response by young conifers to organic fertilization. In 1992, a project cosponsored by Nutrifor was completed at Malaspina College where 600 dry tons (2,500 wet tons) of sludge were applied over an area of 26 ha in the Malaspina College Research Forest on Central Vancouver Island (Braman 1993). Full-scale projections were made using data obtained from the trials to determine cost per tons of sludge for each of three application methods (Braman 1993). The lowest cost method of spreading the sludge was found to be dry application. Projected cost could be reduced to $56/wet tons to apply approximately 36,000 wet tons onto 400 ha.

Seattle, Washington has a sludge management plan which calls for the development of a number of alternative methods (Pridham and Cline 1988). Since halting ocean disposal in 1972, the system has made compost, undertaken strip mine reclamation and is said to have been one of the first to use biosolids in forestry. An innovative application is the growing of hops for the beer industry. Seattle is making use of about 101,000 dry tons/year at 20% moisture. The effects of lands spreading wastewater sludges from pulp and paper mills were investigated by examining (a) the fate of chlorinated organic materials in land spread sludge and (b) the impact of sludge on plant growth and wild life (Sherman 1995). The results indicated that high-molecular-weight chlorolignins were rapidly absorbed by soil or humic matter and organic chlorine was slowly released as inorganic chloride. There was no detectable release of new monomeric chlorolignin-related chloro-compounds. Even under severe extraction conditions, the extractability of low-molecular-weight chloroaromatic compounds decreased rapidly (half lives of 6–70 days), apparently the result of biodegradation and biologically mediated chemical binding into the soil humic structure. No persistent biotransformation products were detected. Sludge applications produced an increase in plant growth (grass, hay, corn, trees). Studies of wildlife on sludge-amended soils did not detect any adverse effects on the health of individuals or on reproductive parameters. Criteria have also been proposed for the land spreading of solid waste (Springer 1993). Briefly, the proposed criteria are:

1. The soil sludge mixture must not have a high content of heavy metal that can be taken up by growing plants
2. The soil-waste pH should be 6.5 or higher
3. Excess nitrogen should not be applied beyond that normally taken up by the crop in one season
4. The sludge applied should be free of living pathogenic organisms
5. Solids must be applied in such a manner that they are not available for direct ingestion by domestic animals or humans

Land application is not a trouble-free technology however (Springer 1993). The most commonly noted problems are odors, groundwater contamination, heavy metals, and specific organic toxics. Other problems are noise, surface water contamination, pathogens, and excessive nitrogen application. The process of applying sludge is dirty and noisy, so if there are houses in the vicinity, potential difficulties will arise. Actually, public and user acceptance has been very good because sludge is applied mostly to rural areas close to the mill and in some cases on mill-owned land.

Pulp and paper mill sludges are usually amenable to well-controlled composting techniques. Markets for compost include land application for agriculture, horticulture, land reclamation, landscaping, and individual consumer use. One mill has had considerable success with marketing its composted sludge. This mill presently composts about 50% of its sludge. The mill sells the compost to a limited number of distributors who market the material in an area within a 250-mill radius from the mill. Initiation of new composting operations within the industry has slowed considerably since the mid-1980s. Lack of sufficiently large, locally available markets for compost and regulatory concerns about the possible presence of chlorinated dioxins and furans in industry sludges are two common reasons for the limited utilization of this management alternative. Recent industry initiatives to reduce the presence of dioxin in sludges are likely to relieve some regulatory concerns about land application of sludges.

A mill in the northeastern United States began working with a third party company to produce synthetic topsoil using sludge (Weigand and Unwin 1994). The process involves the homogenization of sludge with varying proportions of sand, gravel, and fertilizer to produce a synthetic soil. More than a dozen landfills have used the soil as part of the final cover. It also has use in other applications requiring vegetative cover. The pulp fiber content of the synthetic soil probably allows for an increased resistance to erosion before the establishment of vegetative cover.

18.3.4 Recovery of Raw Materials

Paper industry sludges usually contain significant percentages of both cellulose fiber and paper making fillers such as clay and titanium dioxide. Attempts have been made to reduce sludge volume by reclaiming the fiber or filler or both for reuse (Weigand and Unwin 1994). There are several methods to recover raw materials from sludge. One of the most common is to recycle primary sludge back into the mills' fiber processing system. Recycled paperboard mills commonly use this technique. Some manufacturers of unbleached and bleached pulp and paper have also practiced recycling primary sludge back to the mill with limited success (Rosenqvist 1978). Segregated effluents from paper machines, bleach plants, and various cleaning and screening operations can be good targets for fiber reclamation because they usually lack contaminants such as bark or causticizing waste solids. Using some fractionation scheme for the sludge may also provide recovery of fiber alone. The complexity of fiber recovery systems varies widely and depends on the nature of the constituents in the sludge. Mills producing bleached pulp sometimes add recovered fiber to the unbleached pulp entering the bleach plant. This strategy allows for both the reclamation of unbleached fiber and the brightening of previously bleached fiber which may have dirtied by exposure to contaminants in the wastewater. Some mills have associated the reuse of fiber recovered from sludge with increased deposits of pitch on equipment. Use of fractionation system helps to recover filler. Most systems for which pilot- or full-scale data are available have employed a thermal oxidation technique for destroying the organic fraction of the sludge to yield filler in the form of ash (Weigand and Unwin 1994). Experiments with calcination systems have revealed that controlling the kiln temperature 816 and 843°C helps to avoid formation of fused agglomerates which can cause the recovered filler to be excessively abrasive. Wet air oxidation can be also used to recover filler materials from sludge. One U.S. mill is practicing this process on a full scale (Weigand and Unwin 1994). Wet air oxidation is an oxidation reaction carried out in a liquid environment under high temperature and pressure. This process is capable of reducing sludge volume through oxidation of the organic fraction to yield an ash composed of inert materials, e.g., filler clay, titanium dioxide and calcium carbonate for reuse in the papermaking process. Initial experience with the operation of WAO unit for filler recovery revealed problems with Ca-sulfate and Ca-oxalate scale deposition. Both pilot- and full-scale systems have demonstrated some problems with low brightness of the recovered filler. In Turkey, primary sludge has been successfully used in the manufacture of hardboard (Ozturk et al. 1992). Full-scale studies using sludge at a 1:4 ratio indicate that the use of 28 bdt/day of waste primary sludge mill save $455,000/year on wood costs and $130,000/year on electricity costs.

18.3.5 Production of Ethanol and Animal Feed

Ethanol is a common additive in automobile gasoline. Traditionally, it is produced by fermentation of starches and syrups. Interest has been shown to produce ethanol from agricultural waste, municipal solid waste, and pulp and paper mill sludge in order to reduce production cost and to make ethanol more widely available. Laboratory and pilot scale studies to produce ethanol from wood-based feedstocks have used acid and enzymatic hydrolysis followed by fermentation of the resulting sugars into ethanol (Goldstein and Easter 1992; Alterthum and Ingram 1989; Lee and McCaskey 1983). Primary sludges can be used as feedstock for ethanol production because they are widely available in sufficient quantity and that they have little economic value. In University of Florida, Dr. Ingram's group has conducted research on conversion of cellulose and hemicellulose fractions of wood-based feedstocks into hexose and pentose sugars followed by fermentation to ethanol using a genetically engineered strain of *Escherichia coli* (Ingram and Conway 1988). The advantage of this process is that it can ferment both the pentose and hexose sugars into ethanol thereby increasing the overall yield.

Sludge has been also used for production of animal feed. There are two methods for using sludge in animal feed. One method involves production of single cell protein. Cell protein is present in secondary sludge and derives from the fermentation of fibrous sludge. It is possible to dry these proteins and incorporate them into feed mixtures. In the United States, one mill used a process to convert secondary sludge into saleable protein product for use in animal feed. Mechanically, dewatering secondary sludge to 12% solids with further dewatering by feeding a mixture of sludge and oil to specially designed multiple effect falling film evaporators produced a 45% protein material. Centrifugation of the evaporator discharge gave 83% dry solids, 1% water, and 16% oil. Targeted markets for the finished product included feed for cattle and poultry and use in agricultural composting. However, acceptance of this product in the market was not sufficient to support continued production.

The second method incorporates sludge directly into animal feed mixtures (Weigand and Unwin 1994). This method exploits the presence of carbohydrates which are primarily in the form of cellulose and other nutrients present in primary or combined sludges. Research in the early 1970s included experiments on the palatability and digestibility of sludge-augmented feed mixture on goats, sheep, and cattle. It was found that the digestibility of sludge relates directly to the carbohydrate content and inversely to the ash and lignin content. Hardwood pulp residues were found to be more digestible than softwood residues (Millet et al. 1973).

18.3.6 Pelletization of Sludge

The reasons for producing sludge pellets are:

1. Volume reduction
2. Odor control
3. Recovery of fuel value
4. By-product applications

The most common reason for production of pellets is for use as an alternative fuel. One mill transports dewatered sludge to an off-site pellet mill for drying and formation into pellets. The mill purchases the finished pellets as a fuel supplement. The finished pellets contain 15–20% moisture and 10% ash. They have a heating value of 14.7×10^6 J/kg (Weigand and Unwin 1994).

Two companies are now manufacturing pellets by using mixtures of sludge and nonrecyclable paper (Bajpai et al. 1999). These pellets are being marketed as an alternative fuel compatible for use in most stoker and some pulverized coal boilers. The amount of sludge in these pellets can range between 10 and 66%. It is possible to control the fuel value of the pellets by manipulating both the sludge content and the grade of nonrecyclable paper used. The fuel values of the finished pellets are in the range of 14–23 × 10^6 J/kg. The regulatory agencies require evaluation of alternative fuels for by-products of combustion before widespread use of the fuel. Companies involved in both production and use of sludge and NRP fuel pellets have indicated that regulatory reaction to trial run data has generally been positive. NCASI has developed a proprietary process to convert combined sludge from a recovered paper deinking mill into a granular product. The product has been used as a carrier material for agricultural as well as home and garden pesticides and can compete with other common pesticide carrier materials composed of clay, vermiculite, diatomaceous and cob products. Claims for the product indicate that it is superior to some of these conventional carriers because it is dust-free and attrition-resistant (Weigand and Unwin 1994). The company's production facility has a capacity of 180 tons/day of the granular product.

Kitty littre, poultry littre, and large animal bedding have all used pelletized sludge. One U.S. mill processes all of its primary sludge into several varieties of animal litter sold to a distributor for marketing. The litter production process is proprietary. It involves sanitizing and deodorizing primary sludge followed by drying and pelletization. Kitty litter is the primary product manufactured, but other products include large animal bedding, pet bedding and bedding for laboratory animals. Grocery stores market kitty litter and feed stores market bedding products. Bedding sells in 25- and 50-lb bags and 1,000 lb totebins (Weigand and Unwin 1994). Several other companies have studied the feasibility of using sludge to produce kitty or poultry littre. In these cases, they have usually demonstrated production of a quality litter product from primary sludge. Initial capital costs, distribution and marketing issues and incompatibility with company business strategies have inhibited some companies from persuing this byproduct alternative.

18.3.7 Manufacture of Building and Ceramic Materials and Lightweight Aggregate

Sludge use in building products has followed three general techniques. One method is the use of sludge as a feedstock to a cement kiln. Raw materials used to produce cement can include calcium carbonate, clay, silica, and smaller amounts of aluminum and iron. Some sludges contain significant quantities of these materials. Two companies have extensively investigated this alternative and one mill currently practices this on full scale (Bajpai et al. 1999). The mill sends all its primary sludge and all its coal boiler ash to the cement manufacturer. This is a combined total of approximately

100 tons/day. For the kiln involved, this amount of material represents only about 2% of the total feed stock.

Another alternative is the use of sludge in cementitious products. Lot of work has been done on the use of organic fibers including wood pulp in cementitious composites. The advantages include increased durability and pumpability as well as reduced shrinkage-related cracking (Thomas et al. 1987). Two studies undertaken to assess the performance characteristics of composites which included paper industry sludge concluded that a composite material potentially useful in building blocks, wallboards, panels, shingles, fire retardants, and filler materials for fireproof doors could result from combining Portland cement with sludge from deinking mill (Thomas et al. 1987). It was found that mixtures including Portland cement, ash, sand, and sludge yielded a compressive strength comparable to conventional concrete and superior flexural strength (Thomas et al. 1987).

Sludge has been also used in the production of LWAs (Weigand and Unwin 1994). Aggregate is a term describing a collection of materials used as a filler in construction materials. Aggregates find use in cementitious products such as concrete, masonary, building blocks, and asphalt. Sand and gravel or both are typical aggregate materials mixed with cement to produce concrete. LWA refers to a select group of materials which allow for reductions in final density while maintaining acceptable strength properties. Products which sometimes incorporate LWA include concrete block, architectural panels, and decorative stone.

18.3.8 Landfill Cover Barrier

Paper industry sludges have been found to show low hydraulic conductivity (permeability). This finding has led to research by many groups on the potential utilization of sludge as hydraulic barrier layer in landfill cover systems. In 1987, NCASI completed construction of four pilot-scale field test cells designed to allow investigation and comparison of the performance of hydraulic barrier layers made from sludge and made from clay (Weigand and Unwin 1994). Results obtained from these cells during the first 5 years of operation indicate that the sludge barriers perform as well or better than the clay barriers. Experience with the use of paper industry sludge as daily, interim and final cover for paper industry and municipal landfills is available. Worthy of special mention is the experience of one organization. To demonstrate the utility of paper mill sludge as landfill-capping material, this recovered fiber processing mill constructed six test cells to compare the performance of primary sludge combined sludge and clay as hydraulic barriers (Weigand and Unwin 1994). Data from these test cells sufficiently supported a petition to the Massachusetts Department of Environmental Protection for a full-scale demonstration project. The project involved capping a 2 ha municipal landfill with combined mill sludge. To date, monitoring of cap performance indicates that the demonstration has been successful.

18.3.9 Other Uses

Pyrolysis, gasification, and supercritical water oxidation have been studied as a way of reducing sludge volume. During pyrolysis, oil like liquids and gases are formed which have fuel value. Study has been conducted on pyrolysis of cellulose-based waste materials but there is not much published information on experience with pyrolysis of pulp and paper industry wastes (Weigand and Unwin 1994). Pilot studies have been conducted on the application of this technology to wood chips, recycle mill sludge, and bleached kraft mill sludge. There is no report on a full-scale experience with the pyrolysis of sludge. Supercritical water oxidation has undergone research as a waste management technology for approximately 10 years. The process involves the decomposition of organic and some inorganic materials in the aqueous phase above the critical point of water (374°C and a pressure of 22×10^3 kPa). In this state, organic materials become much more soluble in water and oxidize readily. The principal of supercritical water oxidation except that wet air oxidation maintains subcritical conditions. No full-scale supercritical water oxidation units are currently in operation. Laboratory scale research has been conducted on supercritical water oxidation of pulp and paper mill sludge. This work used an 80 cm^3/min bench top system. Operating limits for the reactor were 600°C and 25.5×10^8 kPa. Residence time in the reactor ranged from 10 s to 10 min. In the experiments, a 99% reduction of total organic carbon was possible. The problems anticipated with large-scale and or full-scale systems involve (1) corrosion of equipment particularly for low pH and high chloride concentration wastes and (2) deposition of salts or pyrolytic chars which could lead to plugging or increased cleaning requirements.

In Canada, Ensyn Technologies has developed a rapid thermal processing (RTP) reactor which heats biomass to an extremely high temperature (400–900°C) for 0.5 s at atmospheric pressure with no oxygen (Rodden 1993). RTP is also called fast cracking and is similar to the catalytic cracking process used by the oil industry. The rapid heating of the biomass cracks the chemical bonds and produces a liquid bio-oil. Rapid cooling prevents the completion of chemical reactions. The feed stock can vary: pulp sludge, wood waste, rice husks, and agricultural residue. The bio-oil created from the process has been used as a fuel oil substitute. Destructive distillation as a resource recovery process for solid waste was evaluated during 1982–1984 at Marcel Paper Mills, Elmwood Park, New Jersey (USA) (FioRito 1995). The results indicate that the process is environmentally friendly and has the edibility to provide substantial energy savings utilizing organic solid waste as its sole source of fuel. The technology is able to fractionate the biomass content of municipal and industrial wastewater sludge to a combustible gas and inert char in an environmentally safe manner. Full-scale operation of the process was carried out on sewage and deinked paper mill sludge at installations in California and New Jersey.

The expense of solids disposal could be eliminated by destroying the microorganisms in the excess secondary sludge and recycling the material through the treatment process. Springer et al. (1996) used a simple mechanical device – a kady mill to breakdown the microorganisms in the excess sludge allowing all of the material to be recycled to the treatment process. The kady mill combines the effects of high shear and temperatures, both of which are required for efficient cell destruction. Based on 60 days of operating data, it was found feasible to operate an activated sludge plant in extended aeration mode by recycling sludge that has been lysed in a kady mill. This process could be an alternative wastewater treatment system for use in the pulp and paper industry. The system would be most suitable for use in mills operating well within EPA permit discharge limits for BOD. This system operated with an average COD-removal efficiency of 80%, compared with 87% removal for the conventional system. Both systems operated with an influent COD of 260 mg/L. The sludge-lysis-and-recycle process operated free of bulking problems. This process appears to be an economically attractive alternative to conventional treatment if higher BOD values can be accommodated.

The biosolids generated by activated sludge process can also be anaerobically digested to reduce its volatile solids and generate energy in the form of methane gas (Krogmann et al. 1997).

Hammond and Empie (2007) have reported that secondary wastewater sludge can be added to the black liquor gasification process at a paper mill to produce a combustible fuel gas. The gas is fed to a combined cycle boiler plant and turbogenerator system to generate electricity.

Anaerobic digestion is found to be an effective alternative for sludge management in pulp and paper treatment plants (Guiot and Frigon 2006). Waste characteristics, organic loading rate, hydraulic retention time (HRT), temperature, pH, mixing, and the presence of inhibitory matters are shown to affect the rate of anaerobic digestion. An increase in temperature increases the digestion rate and lowers the HRT and digester volume, resulting in higher amounts of treated waste loads. Biogas recovery in anaerobic digestion avoids odor release and lowers greenhouse gas (GHG) emissions from landfill diffusion and from burning fossil fuels. The solution is believed to provide 100% digestion of the sludge generated, thus offering an improved means of disposal, green energy and lowered GHG discharges. Methane and carbon dioxide are also generated during the process. Purified methane from sludge digestion can be used as natural gas, which can replace fossil fuel and reduce GHG emission. Anaerobic digestion is believed to be a cost-effective approach in the valorization of waste sludge, especially when the cost of natural gas is high.

A method of treating paper mill sludge treatment as raw material for the manufacture of animal bedding won a National Recycling Award for EnviroSystems, Cheshire, UK (Anon 2005). The sludge is dried down to 90% dry material and broken in small pieces, and then is heat-treated. The finished product is called EnviroBed and is being used as bedding for 50,000 dairy cows in the UK. Sludge from Bridgewater Paper and Shotton Paper is being processed at EnviroSystems plant in Cheshire. A second plant at Brent Pelham, Hertfordshire, is being supplied by material from Aylesford. EnviroSystems is looking for additional supplies of suitable paper crumble, with 40–45% organic matter or above and without a high moisture content.

The wastewater sludge of Neenah Paper, Neenah, WI, USA, is recycled into useful forms, including electrical power and glass aggregate (Anon 2004). 5,000 tpy of paper sludge are recycled using a system installed by Minergy Corp, also located in Neenah. Solids are melted in a glass furnace, destroying organic compounds. The inorganic mineral waste exits the furnace as liquid glass which is used in the manufacture of floor tiles, abrasives, roofing shingles, asphalt and decorative landscaping materials. Via a steam generator furnace heat produces electricity which dries the wastewater solids. The recycling process provides many environmental benefits, in Neenah Paper's case preserving green space and reducing landfill use. The company has developed an online tool for individuals and businesses to calculate the environmental benefits of using recycled paper.

Oxycair is an innovative treatment technology developed to treat various types of wastewaters, which has been shown to generate substantial savings over conventional treatment costs (Gagnon and Haney 2005). The technology uses patented processes, is based on concurrent physical mechanisms taking place within multiple reactor vessels and uses no chemicals. The destructive mechanisms include physical destruction, thermic stabilization, air supersaturation, oxidation, explosive decompression, cavitation, and microbubble oxidation. The technology has been tested at both laboratory and industrial scale, transforming excess sludge stream into a nearly sterile stream rich in dissolved oxygen and the nutrients and micronutrients contained in bacterial cells. This stream can be returned directly to the bioreactor as a nutrient supplement. Oxycair is a service provided by WR3 Technologies Inc., Canada.

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