Emerging Biodrying Technology for the Drying of Pulp and Paper Mixed Sludges

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Effective sludge management is increasingly critical for pulp and paper mills due to high landfill costs and complex regulatory frameworks for options such as sludge landspeeding and composting. Sludge dewatering challenges are exacerbated at many mills due to improved in-plant fiber recovery coupled with increased production of secondary sludge, leading to a mixed sludge with a high proportion of biological matter that is difficult to dewater. Various drying technologies have emerged to address this challenge of sludge management, whose objective is to increase the dryness of mixed sludge to above critical levels (∼42% dryness) for efficient and economic combustion in the boiler for steam generation. The advantages and disadvantages of these technologies are reviewed in this article, and it is found that many have significant technical uncertainties and/or questionable economics. A biodrying process, enhanced by biological heat generation under forced aeration, is introduced that has significant promise. A techno-economic analysis of the batch biodrying process at a case study mill showed an annual operating cost savings of about $2 million, including the elimination of landfilling practices and supplemental fuel requirements in the boiler. It was shown that if a biodrying residence time of less than 4 days can be achieved, payback periods of 2 years or less can result in many mills. The potential for the development of a continuous biodrying reactor and the fundamentals of its mathematical modeling are thus presented. Compared to the batch reactor configuration, it is expected that the continuous process would result in improved process flexibility and controllability, lower investment and operating costs due to shorter residence times, and an improved potential to fit into the crowded pulp and paper mill site.

Keywords Biological drying; Combustion; Mixed sludge management; Pulp and paper industry; Techno-economic analysis

INTRODUCTION

Pulp and paper mills produce large quantities of mixed sludge, especially mills that have implemented activated sludge treatment (AST). The two main alternatives for dealing with mixed sludge from pulp and paper mills include (a) increasing sludge dryness by mechanical dewatering and combusting it in a boiler to generate steam and/or power and (b) landfilling. In recent years, landfilling of mixed sludge has dramatically decreased. A survey of the Canadian pulp and paper industry sector in 1995 and 2002 indicated that landfilling of pulp and paper mixed sludge and solid residues in 2002 had decreased by 50% compared to 1995 values.[1] Landspeeding and composting have been selected as the preferred sludge management strategies at some mills. For various reasons, including in particular rising energy costs and complex regulations related to landspeeding and composting, many mills are currently seeking to dispose of their sludge by combustion, and mills already employing this method want to improve their operating efficiencies.

With improvements in fiber recovery processes in recent years and incremental increases in pulp production, mills are generating less primary (fibrous) sludge and more secondary (biological) sludge. The mixture of primary and secondary sludge is called “mixed sludge.” The mechanical dewatering of mixed sludge with a high proportion of secondary sludge is difficult and can result in lower and variable dewatered sludge drynesses. This results in operating challenges and increased costs for all sludge management options, particularly at mills that combust sludge.

Canada has promulgated the Kyoto protocol and has targeted significant reductions in greenhouse gas (GHG) emissions. Mixed sludge from the pulp and paper industry is an important source of GHG emissions when landfilled. However, mixed sludge can reduce fossil fuel requirements and GHG emissions if combusted to produce steam and/or power. With the emergence of GHG trading markets, it is expected that there will be additional economic driving forces for efficient sludge combustion at pulp and paper mills.

It is critical, therefore, to develop an efficient way to increase the dry matter content of mixed sludge from pulp and paper mills to values above critical levels for safe and economic combustion.

Biological drying (“biodrying”) represents an important opportunity for the treatment of mixed sludge to consistently
raise the dry solids content so that the sludge can be economically disposed of in boilers for the generation of steam and/or power. In this article, the biodrying technologies that have been employed for other types of sludges are reviewed, and the key issues relevant to the biodrying of pulp and paper mixed sludge are presented.

**MATERIAL CHARACTERISTICS AND TREATMENT METHODS**

**Pulp and Paper Mill Mixed Sludge**

A typical pulp and paper mill wastewater treatment system consists of two treatment systems: primary (mechanical) and secondary (biological) treatments. In the primary wastewater treatment system, solid particles are removed by gravity, settling/clarification, and flotation.[2] The primary sludge mainly contains fibers (cellulose, hemicellulose) and fillers. Primary treatment is followed by biological treatment, often an activated sludge treatment (AST) system, in which wastewater organic matter is broken down by means of aerobic biodegradation.[2] The combined sludge from primary and secondary treatment consists of a muddy mass of microorganisms, fibrous materials, lignin, mineral components (limestone and phosphorous), clay, inert solids rejected during the recovery process, ash, and water.[3,4] The possibility of recycling this sludge to the process is limited, and landfilling is increasingly restricted due to mounting environmental pressures and high costs. Therefore, combustion can provide a competitive disposal method, as long as the dry solids content of the sludge is maintained above the critical level for good combustion. Previous publications have reported that the critical level of dryness of combustible materials in order to guarantee stable conditions in the boiler is about 42%.[5,6]

At most mills, the mechanical dewatering process (alone) is neither feasible nor economically viable for the target dryness levels sought for efficient sludge disposal by combustion.[7] Figure 1 qualitatively describes the four types of water that can be present in mixed sludge. The constant drying rate (free water removal) is followed by the first (interstitial water removal) and second (surface water removal) falling rates. In the falling rate periods, a much higher external heat/mass transfer coefficient is required to remove the moisture arriving at the surface of the sludge. Free and interstitial water can be mechanically removed by an efficient dewatering process, but surface and intercellular (bound) water require more extensive treatment techniques.

The heating value of mixed sludge on dry basis is 14–19 MJ/kg, which is relatively close to the values of wood or peat,[8] although the sludge must be dried to above critical values for good combustion. Table 1 summarizes typical characteristics of mixed sludge produced in a kraft pulp mill.

**Mixed Sludge Disposal Techniques**

Table 2 provides a summary of the advantages and disadvantages of sludge management techniques commonly used by pulp and paper mills.

A benchmark survey of Canadian pulp and paper solid waste residues management revealed that the amount of ash generated in power boilers in 2002 was 37% greater than in 1995. This is an indication that sludge landfilling has dramatically decreased, and mills have become increasingly reliant on on-site energy sources, such as burning bark and mixed sludge.[1]

**Sludge Combustion**

Exponentially increasing fossil fuel prices are increasingly driving pulp and paper mills to valorize mixed sludge and burn it in power boilers for steam and/or power generation. To some extent, the acceptance of sludge to energy is related to the development of renewable energy alternatives, fuels, and the subsequent reduction of greenhouse gases. Carbon dioxide emissions from the pulp and paper biomass combustion are considered neutral and are not counted in greenhouse gas emissions.[9]

A 4% increase in moisture content of the fuel in a boiler can result in a 38°C drop in boiler combustion temperature, which in turn greatly affects boiler performance.[5,6] Thus,

**TABLE 1**

<table>
<thead>
<tr>
<th>Characteristics of mixed sludge from a typical kraft mill (mixed sludge/bark ratio = 2)</th>
<th>Sludge elemental analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge dryness (%)</td>
<td>Bark dryness (%)</td>
</tr>
<tr>
<td>19–25</td>
<td>33–50</td>
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</tbody>
</table>
at mills where mixed sludge is burned, supplementary fuel (natural gas, oil, or coal) is typically required. The calorific value of mixed sludge could be similar to some wood species and peat if it is dried to above 40% dryness. It has been reported that for an average size mill producing 850 dry tons of product, about 34% of the purchased fossil fuel could theoretically be substituted by the effective heating value of mixed sludge of sufficient dryness. This estimate was based on a sludge generation rate equivalent to 128 tons of dry sludge per day, the effective heat value of sludge at 5.5 MJ/kg and mill energy consumption of fossil fuel at 6.0 GJ/ton dry product.

The energy content of pulp and paper mixed sludge is doubled when the dry solids content is increased from 20% to about 50%. As can be observed from Fig. 2, further drying (to >50% dryness) brings little value to the energy content of the sludge. Therefore, if drying of sludge to about 50% can be accomplished in an efficient way, it can result in significant economic benefit to boiler operations. Figure 3 describes the inverse relationship between the efficiency of the boiler and the moisture content of the biomass being burned.

### TABLE 2

<table>
<thead>
<tr>
<th>Disposal technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfilling</td>
<td>- Established</td>
<td>- Greenhouse gas emissions</td>
</tr>
<tr>
<td></td>
<td>- Simple disposal</td>
<td>- Transport offsite</td>
</tr>
<tr>
<td></td>
<td>- No complex treatment</td>
<td>- Increasing environmental restrictions</td>
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<td></td>
<td></td>
<td>- Increasing high cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Odor problem</td>
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<tr>
<td>Landspreading</td>
<td>- Improves soil characteristics</td>
<td>- Odor problem</td>
</tr>
<tr>
<td></td>
<td>- Returns some nutrients and carbon to environment</td>
<td>- Transportation &amp; spreading equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Regulatory complexity and requirements</td>
</tr>
<tr>
<td>Composting</td>
<td>- Produces saleable product</td>
<td>- Capital costs associated with facilities</td>
</tr>
<tr>
<td></td>
<td>- Destroys pathogens</td>
<td>- Reliable market for product</td>
</tr>
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<td></td>
<td>- Low energy consumption</td>
<td>- Long residence time required for treatment</td>
</tr>
<tr>
<td></td>
<td>- Well established at the full scale</td>
<td>- Mostly batch operation (except VCU technology)</td>
</tr>
<tr>
<td>Recycling to the process</td>
<td>- Reclaims value in new products</td>
<td>- Transportation of the product</td>
</tr>
<tr>
<td></td>
<td>- Reduces burden on other sludge disposal</td>
<td>- Reduces product quality (mostly paper quality)</td>
</tr>
<tr>
<td></td>
<td>techniques</td>
<td>- Limited to specific board and paper products</td>
</tr>
<tr>
<td>Combustion</td>
<td>- Energy recovery</td>
<td>- Sludge pretreatment process sometimes required</td>
</tr>
<tr>
<td></td>
<td>- Significant volume reduction of wastes</td>
<td>- High capital costs (if the boiler does not already exist in the mill)</td>
</tr>
<tr>
<td></td>
<td>- Displaces fossil fuels (at appropriate dryness level)</td>
<td>- Operating risk (if moisture content is too high)</td>
</tr>
<tr>
<td></td>
<td>- Reduces GHG emissions</td>
<td>- High maintenance cost</td>
</tr>
<tr>
<td>Thermal processes</td>
<td>- Energy is derived from waste heat sources</td>
<td>- Ash management required</td>
</tr>
<tr>
<td></td>
<td>- Potential for profitable operation</td>
<td>- Equipment corrosion</td>
</tr>
<tr>
<td></td>
<td>- Sludge kept onsite</td>
<td>- Complex technology (due to process integration)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Not yet proven commercially</td>
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<tr>
<td></td>
<td></td>
<td>- High capital cost</td>
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</table>

**DRYING OF PULP AND PAPER MIXED SLUDGE**

**Conventional Drying Technologies**

For the various reasons cited above, the pulp and paper industry is seeking to develop efficient techniques to dry
mixed sludge that can guarantee the economic viability of sludge combustion. In recent years, a number of sludge drying innovations have entered the market whose objective is to provide economic solutions that address the problem of low and variable solids content of dewatered mixed sludge in the pulp and paper industry. Following is a critical review of mixed sludge drying techniques and relevant studies.

Chen et al. [3] provided an overview of pulp and paper sludge dewatering and possible drying alternatives. Direct, indirect, and combined drying alternatives were reviewed for the drying of activated sludge from the pulp and paper industry. However, based on the preliminary assessment, it was concluded that it is necessary to develop a new drying process that can be economically feasible and thermally efficient. [3] Banerjee et al. [14] and Beckley and Banerjee [15] developed an impulse drying method to dry mixed sludge from pulp and paper mills. The mixed sludge is briefly exposed under pressure to a hot surface. This technique enhanced drying compared to a pure thermal drying approach but implies high temperatures and a complex technology. [14,15] Vaxelaire et al. [16] studied the convective drying of activated sludge and PVC with ambient air at temperatures of 41–60°C. The results showed that the activated sludge was very difficult to dry compared to PVC because of a crust that forms. [16] Kudra et al. [3] studied the hydrodynamics and drying kinetics of pulp and paper sludge via a lab-scale batch pulsed fluid bed dryer, where high drynesses (88% w/w) of the disintegrated mixed sludge was achieved. The hydrodynamics considered included the development of pressure drop, minimum pulsed-fluidization velocity, dynamic bed height, and mass flow rate coefficient equations. However, there is no information available at full scale. Hippinen and Ahtila [4] reported an experimental approach for the drying of activated sludge under partial vacuum by means of waste energy streams. Waste heat sources are widely available in pulp and paper mills, particularly since recent environmental legislation and restrictions have prompted mills to minimize water consumption, which leads to an increase in the temperature of water in the system. The warm water needs to be cooled in order to be reused in the process, and one possibility would be to use this energy to dry activated sludge. It was concluded that partial vacuum drying of mixed pulp and paper sludge can provide a competitive solution to this challenge. However, this conclusion was made based on laboratory-scale experimentation. [4] Leonard et al. [17] investigated the influence of three operating variables, i.e., inlet air temperature, superficial velocity, and humidity, on wastewater sludge drying kinetics, and concluded that the temperature of the inlet air was the main operating parameter affecting the kinetics of drying. It was also reported that the drying of activated sludge was mainly controlled by external limitations. It is worth mentioning that all the above-mentioned conclusions of various studies were made either in lab scale or without economic consideration.

A comprehensive review of available drying technologies was conducted for the CANMET Energy Technology Centre in Canada including fluidized bed dryers, rotary dryers, paddle dryers, superheated steam pneumatic dryers (GEA exergy steam dryer), belt dryers, integrated sludge dewatering and drying systems (J-VAP and DryVac), integrated sludge drying and combustion systems, the TLG sludge drying process, the Dry-Rex dryer, the SmartSoil Biodyrting technology, solar dryers, and cyclonic dryers. [11] The main advantages and disadvantages of each are summarized in Table 3 and suggest that the majority of these technologies suffer from technical uncertainty and offer questionable economic benefits. Therefore, new efficient drying technologies for mixed sludge continue to be sought. One such innovation is biodrying technology, which provides both economic and environmental benefits.
<table>
<thead>
<tr>
<th>Disposal technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluidized bed dryers</td>
<td>Direct drying, Gentle, fast and uniform drying at low temperature, Low space requirements</td>
<td>High initial capital costs, Requires off-gas handling and cleaning equipment, High degree of auxiliary equipment required</td>
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<tr>
<td></td>
<td>High degree of product dryness</td>
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<tr>
<td>Rotary dryers</td>
<td>Provides for drying and granulation in one step</td>
<td>Large floor space requirement</td>
</tr>
<tr>
<td></td>
<td>Allows for reclamation of waste heat, Versatile in configuration</td>
<td>High capital and maintenance costs, Back-mixing to avoid sludge agglomeration required</td>
</tr>
<tr>
<td></td>
<td>Well-suited for heavy products</td>
<td></td>
</tr>
<tr>
<td>Paddle dryers</td>
<td>High ratio of heat transfer surface area to overall dryer volume, Self-cleaning of the intermeshing paddles, Low space requirement</td>
<td>Relatively high complexity of equipment</td>
</tr>
<tr>
<td></td>
<td>Low capital and installation costs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Well-proven, commercially available technology</td>
<td></td>
</tr>
<tr>
<td>Superheated steam pneumatic dryer</td>
<td>Compact design, Short product residence time, Low floor space requirements</td>
<td>Back-mixing of dried product with wet feed, Relatively high specific energy consumption, Turbulent drying conditions and high capital cost</td>
</tr>
<tr>
<td></td>
<td>80–90% energy recovery from the drying process possible, Closed-loop steam cycle</td>
<td></td>
</tr>
<tr>
<td>Belt dryers</td>
<td>Ability for low-grade energy usage, Low air temperatures required (30°C to 90°C), No back-mixing of dried product with wet feed required</td>
<td>Large floor space requirement, Relatively high degree of auxiliary equipment, High complexity of equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High maintenance and long residence time</td>
</tr>
<tr>
<td>Integrated sludge dewatering and drying systems</td>
<td>Indirect sludge drying</td>
<td>New technology, No installation for pulp and paper mixed sludge</td>
</tr>
<tr>
<td>Integrated sludge drying and combustion systems</td>
<td>Surplus heat generation, Cyclone furnace is used for incineration</td>
<td>Treatment of boiler flue gas required, High degree of auxiliary equipment, Large floor space requirement</td>
</tr>
<tr>
<td>TLG dryer</td>
<td>Low-temperature drying, No loss of energy, Surplus heat generation, Low degree of auxiliary equipment required</td>
<td>Relatively high floor space requirements, Manufactured in only two sizes (1.6 and 20 tons per day)</td>
</tr>
</tbody>
</table>

(Continued)
Biologically Enhanced Drying

In biodrying processes, the drying of sludge is augmented by biological heat in addition to forced aeration. The major portion of biological heat, naturally available through the aerobic degradation of organic matter, is utilized to evaporate surface and bound water associated with the mixed sludge. This heat generation assists in reducing the moisture content of the biomass without the need for supplementary fossil fuels, and with minimal electricity consumption. The advantages of employing sludge as a fuel include low cost, displacement of fossil fuels, and supply dependability (not seasonal or variable).

Two prominent parameters must be considered relative to moisture removal rate in the biodrying process: inlet air flow rate and exit air temperature. Airflow is necessary to remove water from the matrix, and air temperature affects the moisture holding capacity of air.[18–20]

Microbial activity produces a rise in temperature within the porous matrix. Biological activity is mostly due to the presence of bacteria categorized into three major groups:[21] i.e., psychrophiles (active at −5 to 20°C), mesophiles (active at 5 to 48°C), and thermophiles (active at 42 to 68°C). Forty to 50% of the biologically generated heat in the solid matrix is utilized by microorganisms to guarantee their preservation, growth, and multiplication. The rest is distributed throughout the porous matrix, and serves to enhance the evaporation of interstitial and bound water.[22]

The metabolic reaction can theoretically proceed at high moisture levels, but the oxygen supply that sustains the microbial activity necessary for aerobic decomposition can be diminished under high moisture conditions. Nakasaki et al.[23] reported that optimum moisture content for microbial activity is 45–65% w/w. This has been confirmed elsewhere.[24] In contrast to the composting process, in the biodrying process a compromise is made between the rate microbial activity and preserving the heating value of the remaining dried sludge.

Recent Studies on Biodrying Processes

Klaus[25] studied the effect of operating variables on the biodrying process for municipal sludge, i.e., the ratio of sewage sludge to flocculating agent, the throughput of the sludge, the temperature of the inlet air, as well as the residence time on the controllability of the biodrying process. By controlling these variables, it was possible to optimize the biodrying operation. Additives were added as conditioning agents to the sludge.[25,26] Nellist et al.[27,28] reported that fast biodrying determines low biological stability and vice versa. A similar result was confirmed by Adani et al.[19] Choi et al.[29] concluded that high moisture removal can be achieved in a full-scale, well-insulated biodrying reactor.[29] Adani et al.[19] reported that the biological stability provided by the biodrying process could minimize odors and biogas production of municipal waste sludge. Hansjoer et al.[30] developed a method for the continuous biological drying of garbage residues and sewage sludge. The technique involved continuous measurement of the carbon dioxide gas content in the exhaust air along

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<td>Dry-Rex dryer</td>
<td>–Low-temperature air (30°C to 90°C)</td>
<td>–Powerful vacuum system required for large air volumes</td>
</tr>
<tr>
<td></td>
<td>–Accelerated drying process</td>
<td>–Many moving parts</td>
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<td></td>
<td>–Fully automated process</td>
<td>–Long residence times result in higher capital cost</td>
</tr>
<tr>
<td></td>
<td>–Very little process equipment</td>
<td>–Economically feasible for mills having large sludge production</td>
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<tr>
<td></td>
<td>–Bi-directional aeration through forced convection</td>
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<td></td>
<td>–Enhanced by biologically heat generation</td>
<td></td>
</tr>
<tr>
<td>SmartSoilTM Biopile</td>
<td>–Efficient heat transfer rates</td>
<td>–Very high capital cost</td>
</tr>
<tr>
<td></td>
<td>–Dries difficult (very wet) substrates</td>
<td>–Complex system</td>
</tr>
<tr>
<td>Carver-Greenfield</td>
<td>–Natural energy from sun</td>
<td>–Not generally applied in the P&amp;P industry</td>
</tr>
<tr>
<td>Solar dryers[67]</td>
<td>–Direct drying</td>
<td>–Large space requirement</td>
</tr>
<tr>
<td></td>
<td>–Better contact</td>
<td>–Odor problem</td>
</tr>
<tr>
<td></td>
<td>–Short residence time</td>
<td>–Regional and seasonal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>–Not proven commercially</td>
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<tr>
<td></td>
<td></td>
<td>–Wet sludge feeding problem</td>
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<th>TABLE 3</th>
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<tr>
<td></td>
<td>–Short residence time</td>
<td>–Not generally applied in the P&amp;P industry</td>
</tr>
<tr>
<td>Cyclonic dryers[68]</td>
<td>–Direct drying</td>
<td>–Large space requirement</td>
</tr>
<tr>
<td></td>
<td>–Better contact</td>
<td>–Odor problem</td>
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<tr>
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</table>
a closed transport track in order to control the air supply, so that the carbon dioxide gas content in the exhaust air was kept within a range of 0.05 to 0.4% by volume.\cite{30} Sugni et al.\cite{31} reported that biodrying could be a good solution for municipal solid waste management, allowing for the production of fuel with attractive energy content. It was possible to mitigate the heterogeneity and temperature gradient of the dried sludge by inverting the airflow direction.\cite{31} Lhadi et al.\cite{32} studied the evolution of organic matter and the humification process during the co-composting of the organic fraction of municipal solid waste and poultry manure with two different particle sizes (0.2 and 1 cm). The results suggested that hemicelluloses were readily degradable compared to cellulose and lipids. It was also pointed out that degradation phenomena were more marked for mixtures with lower particle sizes.\cite{32} The techno-economic analysis of Laflamme-Mayer et al.\cite{33} illustrated that biodrying could be an attractive alternative for those pulp and paper mills that are seeking to eventually achieve zero-effluent operations when compared with other alternatives such as low sludge production and retrofit of hollow-fiber membranes into the aeration basin.\cite{33}

Therefore, biodrying shows considerable potential as a management strategy for high-moisture organic residuals. To our knowledge, to date there is no literature regarding implementation of biodrying processes for treating pulp and paper mixed sludge. Certainly, the complexity of the mixed sludge is one of the formidable challenges, which requires a specific reactor configuration with a precise control system that needs to be carefully addressed in any technology development.

**BIODRYING PROCESS UNDER DEVELOPMENT AT ÉCOLE POLYTECHNIQUE**

The concept of biodrying is explored by examining the fundamentals of modeling and transport phenomena, with an emphasis on the advantages of a continuous biodrying reactor configuration versus batch operation. A novel biodrying technology has been under development over the last few years.\cite{34} The novelty of the biodrying process lies in the fact that the driving force for drying is naturally present in the porous matrix (self-heating process) due to the metabolic degradation that differs this technology from the conventional drying technologies.

**Batch Biodrying Process**

Frei\cite{18} studied the drying of mixed sludge using a 1-m$^3$ batch biodrying reactor (1.75 m $\times$ 0.75 m $\times$ 0.75 m) for three mixed sludge/woodwaste dry mass ratios (1:1, 1:0.5, and 1:0.25). The optimum pneumatic condition for the biodrying process performance was achieved using a ratio of 1:0.5 of mixed sludge/wood waste. Measured temperatures and pressures in the porous matrix were used to estimate permeability using Darcy’s law. The maximum matrix temperature reached was around 65°C, and sludge carbon losses were estimated at between 5.5% and 18% over the three experimental runs. As biodrying progressed, the carbon loss increased linearly to about 20% (Fig. 4).

The matrix permeability (ability of the porous matrix to transmit air flow through pore spaces) increased significantly during forced aeration periods $[-+00]$ when the center conduit was injecting (+) air, the two side conduits would be extracting ($-0$) air, as drying progressed, and conversely, the permeability decreased during extracted air periods ($+0-0$), due to the rewetting phenomenon (Fig. 5), where reversing the air flow direction rewetted the sludge, resulting in the rehydration of solids by humid air, which increased microbial activity and subsequently led to a high drying rate.

Furthermore, the drying rate more or less followed the same trend as the average internal temperature (Fig. 6). The increased outlet air temperature (as a consequence of the microbial activity) allowed the air to hold greater quantities of moisture, thus increasing the drying rate.

Roy\cite{20} performed batch biodrying experiments with the goal of optimizing the batch biodrying process. It was concluded that low air flow rates favor biodegradation, although less progress on biodrying can be achieved, whereas at higher air flow rates, biodegradation is limited due to the fact that the biomass is cooled. The natural biological heat provided by microbial activity was recognized to be the major source of energy in the novel biodrying system. It was found that the biological energy produced in a batch biodrying system for mixed sludge varies from 23 to 39 W/kg. Similar results have been reported by Mote and Griffis\cite{35} (20–28 W/kg-DM) and Harper et al.\cite{36} (20–38 W/kg-DM).
Performance variations were attributed largely to the initial sludge properties. It was determined that the drying rate was mostly a function of air flowrate and of outlet air temperature. The outlet air temperature was a function of biological activity close to the air outlets. Three distinct drying periods were identified and correlated to the microbial population growth periods (Fig. 7).

- The exponential rate period (P1), characterized by an exponential increase in the drying rate, was mostly a function of the acclimatization of the microbial mass (increase of cell counts from $10^6$ CUF/g to $10^8$ CUF/g) comparable to microbial populations reported by Haug.\[37]\]

- The declining rate period (P2), characterized by an exponential decrease in the drying rate triggered by a lack of organic substrate/nutrient availability.

- The stable rate period (P3), which began following nine days of the biodrying process and was characterized by a stable drying rate, was mostly a function of the air flow rate.

It was also found that in the batch reactor configuration, air flow inversion favored biodegradation rather than biodrying. Inverting the air flow direction causes the water front to switch direction, and water removed from the wet portion of the matrix is deposited in the dry area.\[18,20,31,35]\]

Techno-Economic Analysis of the Batch Biodrying Process

In most cases, the economics of biomass to energy conversion is sensitive to the size and configuration of the main process from which the waste is generated, as well as to the value of the fuel used to produce steam and electricity for the main process. The value of the mixed sludge relative to its thermal content, and the overall efficiency of energy recovery inherent to the mixed sludge to energy process will dictate the economic viability of a particular technology.

Frei et al.\[38\] considered the techno-economic analysis of a $7 \times 18$ m (height and width, respectively) batch biodrying system applied to the drying of pulp and paper mixed sludge. The length of the reactor can be modified because there is little variation in drying with length. The residence time was assumed to be 7 days. The sensitivity analysis of three scenarios showed that in the worst case, the long residence times required for biodrying would allow the dryness of the sludge to reach 45%, while the ratio of mixed sludge/woodwaste was 1:1. The implementation of the best scenario can yield 60% dryness when the ratio of mixed sludge/woodwaste is 4. A short residence time and a short investment payback period were the main advantages of this scenario. A savings of more than $2 million in annual operating costs was realized for the base case model, whereas the payback period was about 2.5 years. It was also
concluded that the feed dryness and the residence time have the greatest effect on the performance of the system. Moreover, the mixed sludge/woodwaste ratio and the porous matrix temperature were other influential factors.

As can be seen in Fig. 8, the feed dryness had the largest impact on the yearly saving and the project payback. While performing the sensitivity analysis, other variables, such as residence time and sludge/woodwaste ratio, were kept constant at values of 7 days and 2, respectively. The minimum payback period was observed to occur at 24% of feed dryness.

Figure 9 illustrates the effect of residence time on the annual savings and payback period. Long residence times yielded little annual savings but greatly increased the payback period. For instance, by tripling the residence time, the system installation cost was doubled.

Roy et al. [39] considered a full-scale biodrying system comprising two 625-m³ reactors of 5 m in height, 5 m in width, and 25 m in length. The effect of final material dryness on capital and operational costs as well as on the system performance was investigated. Among three scenarios with different types of bulking agents and air flow rates, the best scenario was found to be the one with the maximum aeration (32 cfm), with dried mixed sludge as the bulking agent.

Aeration rate had an influential effect on the capital costs of the biodrying system. For instance, doubling the air flow rate (from 16 cfm to 32 cfm) reduced the capital cost of the system by half. Utilizing treated sludge as bulking agent instead of bark also reduced capital costs for final material dryness values greater than 43%.

Greater air flow rates, such as 32 cfm/m³, provided acceptable payback periods that could eventually minimize mill-specific system sizing. Proper sizing of the biodrying system would significantly lower capital costs to achieve payback periods in the range of 1.5–2 years, which, in the current economic context, appears to be the industrial standard for this type of project.

Figure 10 represents the trend of system performance for different scenarios. It can be observed that after 4 days of biodrying process, using treated material as bulking agent provides greater final dryness. However, this will not have a significant impact on the viability of the biodrying process. Furthermore, doubling the air flowrate (from 16 cfm to 32 cfm) doubled the return on investment.

From the results discussed above, it is clear that batch biodrying is a process that is technically sound and economically viable. Some of the promising achievements that encourage further consideration of biodrying include the short payback period, high annual savings, significant reduction in fossil fuel consumption, environmental benefits, and self-heating system. Although the results confirm the applicability and operability of the batch biodrying technology, a number of shortcomings were identified,
such as inflexibility, relatively long residence times, the space requirements at mill sites, short-circuiting, and the possible occurrence of anaerobic conditions.

**Continuous Biodrying Process**

VCU (Vertical Composting Unit), a New Zealand-based company, has developed a continuous composting reactor that works based on a “plug flow” principle, as shown in Fig. 11. Shredded mixed municipal sludge flows from the top to the bottom of the reactor. The compost is removed daily from the bottom. The biological heat generated can raise reactor temperatures up to 40–70°C, which destroys pathogens present in municipal sludge waste. It is claimed that this system is energy efficient and does not require agitation, bio-filtration, external heating, or air injection. With minimal moving components, maintenance, and operating costs, the continuous vertical reactor appears to function well according to both economic and operational aspects.[40] However, the physical characteristics of mixed sludges from the pulp and paper industry differ from municipal sludge.

In addition to the fibrous components (cellulose, hemicelluloses, lignin, and other types of carbohydrates), there are also mineral materials either from papermaking process (clay, fillers) or wastewater treatment system (mainly phosphorous, limestone, and nitrogen), microorganisms (tiny biological flocs), and heterogeneous bark or wood waste residues as bulking agent. Therefore, the description of the manner of biological reaction in the biodrying process is highly complex; however, the batch experiments demonstrate that the mixture will dry well through biological heat generation under forced aeration.

The schematic of the proposed continuous biodrying reactor is illustrated in Fig. 12. Airflow is blown through the porous matrix, in order to remove the moisture and water within the reactor. One of the most critical process requirements is good pneumatic conditions along the reactor such that pressure drops across the porous matrix are acceptable and maximum microbial activity can be guaranteed for enhanced drying purposes. In addition to the appropriate pneumatic requirement in each compartment, the air flow rate down the length of the reactor will also be governed by outlet air relative humidity.

The reactor is divided into four nominal compartments. The wet mixed sludge is fed to the reactor top (compartment I) and flows downward by means of gravity. In the first compartment, the high forced aeration removes the free and interstitial water, leaving the surface and bound water, making the porous matrix more susceptible to biological reaction (biodrying). Maximum air flow rates will likely be required in the first compartment, which is expected to result a similar trend of drying rate and
temperature rise shown in Fig. 7 (P1). The drying of surface water takes place at the exposed surface of the particles by convection in compartments I and II. It has been reported that migration of bound water through the solid matrix occurs by molecular diffusion having a flux proportional to the gradient of the chemical potential of the bound (water) molecules. [41]

Once the moisture content is decreased to a thin film of surface water, oxygen from the air must penetrate the thin biofilm to reach the microorganisms. This is most likely to happen in the second and third compartments, where the moisture content favors biological reaction, which helps to evaporate surface and bound water. Consequently, the maximum biological activity will increase the drying rate as well as porous matrix temperature, similar to phase 2 (P2) in Fig. 7. Cooling down the system, however, would limit the metabolic activity. Therefore, the air flow rate is gradually decreased to the control strategy proposed level. A similar process for forced aeration composting has been described elsewhere. [42,43] Diaz et al. [42] reported that excessive aeration cools the porous matrix and leads to large nitrogen (N) losses, while inadequate aeration prevents the proper development of stabilizing temperatures. In compartment IV, the temperature decreases and the second falling rate period will occur, during which it is believed that the biological activity will dramatically decrease due to a lack of sufficient moisture, nutrients, and oxygen, as the last compartment at the bottom of reactor is supplied with minimum aeration. In operational point of view, the behavior of process in compartment IV is more likely to follow phase 3 (P3) in Fig. 7.

**Expected Profiles of Moisture Content, Air Temperature, and Air Superficial Velocity**

Figure 13 shows the expected profiles of average dryness, matrix temperature (or air temperature in the case of local thermal equilibrium), and air superficial velocity. At the beginning of the process, it is expected that free and interstitial water will be removed rapidly due to a high aeration rate. This drying trend continues until the end of compartment II, where there is no more free and interstitial water left, but only a thin layer of surface water. The porous matrix temperature is expected to follow more or less the same trend as dryness, except that in the first two compartments, the temperature of the matrix increases very slowly due to the high moisture content and aeration (which cools down the matrix), compared to compartments III and IV, where there is a decline in the aeration rate and high exothermic metabolic reaction.

Air superficial velocity, which is directly related to the porosity and permeability of the porous matrix, is expected to be almost the same in compartments I and II. The main reason for this expectation is that the inlet air flow rate will not change significantly in the first and second compartments because it is required to remove free, interstitial, and some portion of surface water. Since oxygen must penetrate through the biofilm to reach the microorganisms, the aeration rate must satisfy the efficient metabolic activity. As permeability is expected to increase when drying progresses, more void spaces will be available, and therefore the superficial velocity will decrease.

It should be emphasized that these trend descriptions were hypothesized to be reasonable but experimental verification will reveal the actual process parameter variations.

**Modeling as a Design, Optimization, and Scale-Up Tool**

Extensive characterization of biodrying behavior using a strictly experimental approach constitutes a formidable challenge due to the excessively large number of variables such as air velocity, inlet air temperature, inlet air humidity, feed dryness, particle size and distribution, ratio of bulking agent, and residence time. Modeling can provide a deterministic approach for controlling the rate of drying and different types of drying kinetics during mixed sludge biodrying. Such a capability could help to provide the knowledge to optimize the biodrying process, to minimize the experimental trials, and to establish the scale up criteria in a reasonable way, without having to resort to an extensive plan of experimental tests.

Modeling is a useful tool that can help to enhance the design of the continuous biodrying reactor. It can be used to establish and explore the optimum design criteria. It can predict the biodrying performance and, most importantly, provide dynamic coupling between mass and heat transfer mechanisms, which cannot be clearly identified through extensive experiments.

Considering the operational obstacles and extremely high costs associated with performing extensive experiments at different scales, there is an additional incentive to simulate the biodrying process mathematically. Through modeling, one can seek the compromise between the extent of biological reaction, in order to achieve the target dryness
The third category in the modeling involves empirical models of the process parameters related to mass and heat or momentum transfers. For instance, the ideal gas law can be employed for air and water vapor, specific heat capacities can be assumed to have a linear relationship with moisture content, and porosity or permeability can be correlated to the moisture content from the experimental data, and so on.

By repeatedly working on these three categories that describe the modeling task, models will be constructed and solved numerically in order to find the distribution of temperature, moisture content, and drying rate. One last step is required before simulations can be performed, which appears explicitly in Fig. 14. It involves accurately determining the constraints and boundary conditions for the specific configuration of the biodrying system. In the case of the continuous biodrying reactor, one of the immediate process constraints is fully saturated air at the outlet of gas flow, which will allow all the process variables to be set accordingly.

Physical Modeling of the Continuous Reactor

As mentioned above, models for composting sludges with forced aeration have been described extensively in the literature. Heat balance analyses were presented by Bach et al., Harper et al., Koenig and Tao, Bari et al., and mass balance evaluations were provided by Robinzon et al., Batista et al., and Straatsma et al.

To illustrate, the following mass balance equations for moisture content and oxygen have been reported with the goal of providing simultaneous coupling between mass and energy balances:

\[
\frac{dM_b}{dt} = \frac{G_a[H_s(T_a) - H_s(T)] - \gamma H_b O/BVS \frac{d(BVS)}{dt}}{\rho_{db} V_r}
\]

where \( M_b \) is the material moisture content (kg H2O/kg-DS), \( t \) is the time in (s), \( G_a \) is the mass flow rate of inlet dry air (kg/s), \( H_s \) is the saturated humidity of outlet air (kg H2O/kg-dry air), \( T \) is the temperature of the matrix (°C), \( T_a \) is the ambient temperature (°C), \( \gamma \) is the metabolic yield of water (kg H2O/kg-BVS removed), and \( \rho_{db} \) is the bulk density of the porous matrix (kg/m³).

The metabolic reaction of oxygen is written as follows:

\[
\frac{dM_{O_2}}{dt} = \frac{G_a(X_{O_2, a} - X_{O_2, exit}) - \gamma H_b O/BVS \frac{d(BVS)}{dt}}{\epsilon V_r \rho_a(T)}
\]

where \( BVS \) is the mass of biodegradable volatile solids (kg), \( V_r \) is the working volume of the reactor (m³), \( X_{O_2} \) is the concentration of oxygen (kg-O2/kg-dry air), \( \epsilon \) is the porosity of the porous matrix, and \( \rho_a \) is the density of dry air (kg/m³).
Concerning the energy balance, the following model can be cited:\textsuperscript{[45]}
\[
\frac{d(mmT)}{dt} = GH - G\Delta H_{\text{f}} - UA(T - T_a) + \frac{d(BVS)}{dt}H_c \tag{3}
\]
where \(m\) is the mass of the porous matrix (kg), \(c\) is the specific heat capacity of the matrix (KJ/kg\(^\circ\)C), \(G\) is the mass flow rate of air (kg/s), \(H_{\text{f}}\) and \(H_a\) are the inlet and exit gas enthalpies (KJ/kg), \(H_c\) is the combustion heat of the substrate (KJ/kg), \(U\) is the overall heat transfer coefficient (heat loss) (kW/m\(^2\)\(^\circ\)C), and \(A\) is the surface area of the reactor (m\(^2\)).

There have been several models reported for the rate of biological reaction, including first-order reactions,\textsuperscript{[52,54–56]} Monod-type reactions,\textsuperscript{[57–59]} and empirical models.\textsuperscript{[47,60–63]} Although these models adequately fit with most biological reaction applications, there are some limitations associated with employing them. For instance, some models require temperature corrections and heat conversion factors. A broad review of these correction factors can be found elsewhere.\textsuperscript{[45]} Recently, Roy et al.\textsuperscript{[64]} employed a thermodynamic approach to estimate biological heat generation in a biodrying system and found results that were in a good agreement with the literature.\textsuperscript{[38,39]} Biological heat can also be automatically monitored.\textsuperscript{[37,53,54,65–66]}

These models could be used in a lumped manner for each compartment. It might be possible to employ these models with some correction factors or dimensionless numbers, which could subsequently represent forced convection and highlight the differences between composting and biodrying. However, it should be noted that the aeration rate in the biodrying process is 10–30 times higher than that of the composting process.\textsuperscript{[37]} As a result, if lumped models will probably be first considered in our work, we believe that an adequate and space-dependent description of the transport phenomena governing the continuous biodrying process will ultimately require the development of distributed models based on partial differential equations.

**Expected Dominant Transport Phenomena**

At the top of the reactor, there are three phases; free and interstitial water, the solid matrix, and gas flow (air and water vapor). Free and interstitial water are separated from the particles and begin to move downwards due to gravity, but the high airflow rate evaporates them quickly. As the free and interstitial water are removed, microorganisms actively start their growth, reproduction, and metabolic reactions. At the end of the second compartment, the air flowrate is decreased to facilitate the biological activity. In terms of energy transfer in compartment I, it is reasonable to neglect the term related to the biological heat production. This will simplify the mathematical analysis of the modeling in this compartment. Convection in the pore space and conduction in the solid phase are the dominant factors in the energy balance in compartment I. Darcy’s law for porous media may be used for describing the flow of the gas and liquid phases.

In the middle of the reactor (compartments II and III), moderate aeration influences the convective and diffusion terms of the gas phase, and microbial activity causes the heat source term to be dominant. Therefore, all these terms will be present in the heat transfer equations. Further considerations must be made to simplify the equation. Nevertheless, as the porous matrix is being dried, surface and unbound water move toward the surface of the particles by capillary forces. The porous matrix of mixed sludge contains interconnecting and varying pores and varying particle sizes. Capillary forces that occur due to the meniscus of thin layers of surface water across each pore between the solid particles, provide the driving force for water to move through pores to the surface of the solid particles.

At the bottom of the reactor, only minimum aeration is supplied. The mixed sludge has already been dried and microbial activity faces a number of challenges. The first is a low moisture content that makes it difficult for microorganisms to continue reproduction, growth, and degradation. The second is a low aeration rate, which cannot supply sufficient oxygen for microorganisms. The third problem involves the development of undesirable anaerobic conditions in the porous matrix that can cause variations in the mixed sludge dryness at the bottom of the reactor. In addition to these three deficiencies, insufficient permeability or porosity might be a real challenge due to the load of wet sludge and compaction. All these considerations must be taken into account in order to establish mass and energy balances. Other phenomena like short circuiting, bridging, and/or channeling might also occur. However, none of these obstacles can be confirmed yet as there is no experimental data available or similar work described in the literature.

**Comparison of Continuous Biodrying Reactor with Batch Reactor**

According to the results described previously, the batch biodrying process has significant potential as a suitable solution for drying pulp and paper mill sludges with minimum energy requirements and side impacts. Nevertheless, the continuous biodrying reactor offers several advantageous performance features over the batch system:

- The movement of mixed sludge is assisted by gravity.
- Different aeration rates along the vertical reactor provide better controllability and performance, and may achieve higher dryness levels within a short residence time.
Uniform sludge treatment and drying can be achieved via the continuous vertical reactor configuration which is more difficult to achieve with the batch system.

The lack of space on-site is a major problem for most pulp and paper mills, yet the vertical configuration has a reduced footprint and favors retrofit installation at crowded mill sites.

The continuous reactor requires fewer shutdowns, cleanings, and startups.

The continuous reactor is more flexible and can accommodate different operating variables as well as sludges with different characteristics.

It is possible to design for different capacities and performance by installing continuous vertical reactors in series or in parallel.

Utilizing bark as a bulking agent can be minimized in continuous biodrying due to the fact that part of the treated sludge can be recycled and mixed with the wet sludge, providing higher initial dryness, uniform porosity, faster start up of biological reaction, and a decrease in the residence time.

CONCLUDING REMARKS

The challenges of mixed sludge disposal in the pulp and paper industry, including current disposal and drying techniques, have been reviewed in this article. Various problems and restrictions associated with landfilling have triggered the search for new energy efficient technologies for the drying of mixed sludge to be burned in power boilers.

The biodrying technology presented here was shown to be an attractive technique for sludge drying. In summary, the main advantage of the biodrying technology compared to conventional drying technologies is that heat is generated within the porous matrix as a consequence of microbial activity, which enhances moisture removal when coupled with forced aeration. Another advantage of the biodrying technology is that the mixed sludge can be dried while largely preserving its calorific value.

Based on preliminary batch biodrying process, the techno-economic feasibility of batch biodrying technology has been proven, and a vertical continuous biodrying reactor configuration proposed. The continuous reactor has potential to provide a more cost-effective solution with minimum external thermal energy requirements for sludge management at pulp and paper mills. The design configuration of the continuous biodrying reactor was described, including virtual reactor compartments with adjustable air flow rates to achieve a target mixed sludge dryness. The fundamentals of mathematical modeling of the continuous reactor were briefly discussed and a critical review of the mass and energy balances in aerated composting processes presented. Such a mathematical simulation coupled with experimental verification would yield significant scientific benefits, unique reactor configurations for a given mixed sludge characteristic, and contribute to the goal of advancing the efficient drying of mixed sludge. The dominant transport phenomena in different zones of the biodrying reactor were described and the expected velocity, temperature, and mixed sludge dryness profiles along the length of the reactor were presented.

NOMENCLATURE

- A: Surface area of the reactor (m²)
- BVS: Mass of biodegradable volatile solids (kg)
- c: Specific heat capacity of the matrix (KJ/kg°C)
- G: Mass flowrate of air (kg/s)
- G₆: Mass flowrate of inlet air (kg/s)
- Hₖ: Combustion heat of the substrate (KJ/kg)
- Hᵢ: Inlet gas enthalpy (KJ/kg)
- Hₒ: Outlet gas enthalpy (KJ/kg)
- Hₛ: Saturated moisture of outlet air (kg H₂O/kg-dry air)
- Mₘ: Moisture content (kg H₂O/kg-dry solid)
- m: Mass of porous matrix (kg)
- T: Temperature of matrix (°C)
- Tₐ: Ambient temperature (°C)
- t: Time (s)
- U: Overall heat transfer coefficient (kW/m²°C)
- Vᵣ: Working volume of the reactor (m³)
- Xₒ₂: Concentration of oxygen (kg O₂/kg-dry air)
- y: Metabolic yield of water (kg H₂O/kg-BVS removed)

Greek Letters
- ε: Porosity of the matrix (dimensionless)
- ρₐ: Density of dry air (kg/m³)
- ρₜₜ: Bulk density of porous matrix (kg/m³)

Acronyms
- AST: Activated sludge treatment
- BC: Base case
- CUF: Colony forming units
- DM: Dry matter
- DS: Dry solid
- GHG: Greenhouse gas
- PVC: Polyvinyl chloride
- VCU: Vertical composting unit

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