Needs Assessment for Sludge Processing Technologies in Ontario

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September, 2017

Table of Contents

Acknowledgements

The authors appreciate the efforts of the following individuals who assisted with data acquisition and analysis:

Gregg Archer, M.A.Sc Candidate CEE

Bill Mclaren, Research Assistant CEE

Adam Schneider, Research Assistant CEE

In addition the contributions of the following individuals that served as an industrial advisory to the project are recognized:

Michael Payne, Black Lake Environmental

Mike Newbigging, XCG Consultants Ltd.

Don Hoekstra, Ontario Clean Water Agency

Jose Bicudo, Region of Waterloo

Vince Pillegi, Ontario Ministry of Environment and Climate Change

The Ontario Ministry of Environment and Climate Change (MOECC) and the Ontario Clean Water Agency (OCWA) are recognized for providing datasets that were employed in this study.

List of Figures

List of Tables

Executive Summary

Sludge handling and biosolids disposition are important activities that are associated with wastewater treatment and represent a significant economic activity. This report addresses a study that was conducted to:

- establish current sludge handling and biosolids management practices in the province of Ontario,
- review current and innovative technologies for biosolids reduction and energy generation,
- assess the opportunities for innovative technology implementation.

In the first phase of this study, the sludge handling technologies currently employed and the quantity and quality of biosolids generated between 2014-2016 were characterized. Information was gathered from the Ontario Ministry of Environment and Climate Change (MOECC), the Ontario Clean Water Agency (OCWA) and through direct contacts with WWTPs. The current use of sludge handling technologies was categorized by functionality including thickening, stabilization and dewatering and the disposition practices of the produced biosolids were characterized.

The use of separate thickening processes was reported at 16% of WWTPs and these were employed at plants with design hydraulic capacities (DHCs) greater than 10,000 m^3/day. Stabilization was implemented at 77% of the surveyed WWTPs with 52.8 % of them using aerobic digestion and 36.7% employing anaerobic digestion. Anaerobic stabilization is most commonly employed in WWTPS with DHC values greater than 10,000 m^3/day while aerobic stabilization is predominantly employed at the remaining plants. Dewatering is primarily employed at large WWTPs (DHC > 10,000 m^3/day) representing 13% of all WWTPs. A majority of biosolids are employed for agricultural use and this is followed by landfilling and incineration for final disposition. There was no apparent relationship between the DHC of the WWTPs and disposition practices.

The distribution of WWTPs producing liquid and dewatered biosolids was characterized. It was found that WWTPs generating 1000-5000 m^3 of liquid biosolids/year and 1000-5000 tonnes of dewatered biosolids/year respectively were most common. Liquid

biosolids typically had solids concentrations in the range of 1~4% over the range of DHC from 100 to 100,000 m^3/day. The solids content of dewatered biosolids ranged between 20%-30%. There is evidence of a number of WWTPs that might benefit from enhanced dewatering to increase solids content and hence reduce the volume of biosolids produced.

The quality of biosolids was assessed with respect to parameters that may influence technology selection and disposition alternatives. The pathogen indicator content was found to be consistently within regulatory requirements for current disposition practices although improved quality would be needed if more diverse alternatives were to be desired. Three general patterns of metals concentrations were identified including those of low concern (arsenic, cadmium, cobalt, chromium and lead), medium concern (mercury, nickel and zinc) and highest concern (copper, selenium and molybdenum). The concentrations of highest concern metals met NASM requirements but may prevent the biosolids from being employed as composts. Dewatered biosolids typically had lower metals concentrations as compared to liquid biosolid and in general met Category B requirements for compost.

Phase 2 of the project involved gathering of information on innovative technologies for sludge processing. A keyword search of research publications yielded 262 reports that demonstrated the primary development of innovative technologies occurs in East Asia, Europe and North America. Most reports described bench and pilot scale testing and there were limited reports of full scale demonstration of selected stabilization, thermal reduction, heat drying, resource recovery and dewatering technologies. Globally, innovations in stabilization (34%), conditioning (27%) and dewatering (16%) technologies were most prominent. The most frequently reported developments in Canada were in the category of stabilization.

The largest number of reports within the stabilization category addressed innovation in biological processes. Anaerobic digestion processes had the dominant number of biological treatment reports with a focus of pre-treatment technologies for enhanced digester performance and process enhancements respectively. A limited number of reports on innovations on aerobic digestion were identified although these may be most feasible for many of the smaller WWTPs in Ontario.

Innovations in chemical conditioners were most frequently reported as there is a focus on reduced costs of dewatering and increased solids content of dewatered biosolids. The corresponding interest in dewatering was indicated by a substantial number of reports describing innovation in electro-dewatering, physical, and passive technologies. Collectively, innovations in conditioning and dewatering represent a significant opportunity due their potential to respond to a number of drivers that are expected to impact sludge handling in the future.

A total of 39 commercially available innovative sludge processing technologies were documented in this study. Innovations in sludge stabilization were found to represent 44% of the commercial reports and most of the companies are located in either North America or Europe with 77% of the technologies demonstrated at full scale. The market for development of anaerobic digestion technologies is highly developed and Canadian-based companies are active in this category. Most companies focusing on thermal reduction were identified to be located in the United States and Europe. Thermal reduction technologies tend to only be employed at large WWTPs. Phosphorous and fertilizers are the most common resources targeted for recovery by commercial technologies and Canadian companies (Lystek and Ostara) are active in this area.

The potential for implementation of innovative technologies was assessed on the basis of a number of drivers that are anticipated to influence decision making on sludge processing technologies and biosolids disposition practices. For each driver, innovations that would assist WWTPs to respond to the driver are suggested.

Energy/Greenhouse Gases

- Development of anaerobic digestion technologies that are viable in smaller WWTPs. There are a number of commercially available technologies that can provide enhanced anaerobic digestion but they have primarily focused on medium and large scale WWTPs. A number of sludge pretreatment technologies have been developed but there has been limited implementation.
- Advanced thermal reduction technologies that are capable of energy recovery/and or fuels production while allowing recovery of nutrients. Current thermal

technologies that are employed in the province may provide some energy recovery but solids destruction appears to be the primary objective for these systems. Innovations in sludge drying could further increase the viability of thermal reduction technologies.

- High efficiency aerobic digestion technologies with reduced energy consumption. There are a large number of aerobic digesters employed at small and medium sized WWTPs that tend to be energy intensive. Relatively few reports on innovation in aerobic digestion and few innovative commercial aerobic digestion technologies were identified.

Changing populations

In large (and growing) WWTPs:

- Enhancements in sludge conditioning/thickening and dewatering that are typically employed at large WWTPS and which increase process efficiency and produce dewatered biosolids of higher solids content. There has been considerable activity in this regard in the research literature (i.e. electro-dewatering) but the number of implementations in Ontario are modest.
- The implementation of advanced thermal reduction technologies increases in viability at large scale. As the number and scale of large WWTPs increases with growth in populations the number of opportunities for implementation of these technologies will increase.
- The implementation of digestion enhancements that increase capacity (i.e. sludge pretreatment technologies) will be of interest to larger WWTPs with increasing sludge production. Thermal hydrolysis technologies have been implemented internationally but there has been little uptake in Canada.
- The implementation of technologies that provide higher quality products (i.e. disinfection) will diversify the disposition opportunities and may increase local usage.

In small WWTPs:

- Passive technologies that require minimal operator attention.
- Low cost thickening and dewatering technologies that reduce haulage and disposition costs.

Reductions in Agricultural Land Availability

- Enhanced conditioning, thickening and dewatering technologies. For larger WWTPs there would be a benefit in obtaining higher solids content products to reduce haulage costs. The development of technologies that support smaller WWTPs would increase implementation in these facilities. There is currently little use of these technologies in small WWTPs.
- The implementation of advanced thermal reduction technologies in large WWTPs will reduce the demand for agricultural land for biosolids disposition.
- The implementation of digestion enhancements that increase solids destruction (i.e. sludge pretreatment technologies) will reduce the demand for agricultural land for biosolids disposition.
- Implementation of technologies capable of producing biosolids of higher quality (i.e. reduced pathogen content) to support alternative disposition practices.

Changes in Septage Disposition

- Development of thickening and dewatering technologies that address septage solids in small WWTPs.

Changes in Landfill Regulations

- Development of thickening and dewatering technologies in small and medium size WWTPs that support increased winter storage to reduce the need for landfilling.

Increased Emphasis on Resource Recovery

- Further innovation and implementation of technologies capable of recovering phosphorous and nitrogen. Commercial technologies exist in this regard but their implementation to date has been modest.
- Advanced thermal reduction technologies that are capable of energy recovery/and or fuels production while allowing recovery of nutrients. The growth of larger cities may provide the conditions that are supportive of use of these technologies. Enhancements in supporting technologies such as drying would increase the viability of thermal reduction technologies.
- Integration of resource recovery with technologies that achieve increased solids destruction. For example, recovery of nutrients from dewatering return streams downstream of advanced anaerobic digestion processes.

Increasingly stringent regulations on wastewater discharges

- Passive technologies that require minimal operator attention in small WWTPs that are most impacted by recent regulatory initiatives.
- Low cost thickening and dewatering technologies that reduce haulage and disposition costs.
- High efficiency aerobic digestion technologies with reduced energy consumption. Aerobic digesters employed at small and medium sized WWTPs tend to be energy intensive.

1 Project overview

Sludge handling and biosolids disposition are essential activities associated with municipal wastewater treatment and require substantial capital and operating expenditures (Kelessidis & Stasinakis 2012). A recent report has indicated that the global biosolids market value in 2016 was $118.35 Million it is estimated to reach $161.06 million by 2022 (Global Biosolids Market, 2017). The growth in this industry can be considered both a cost for municipalities but also an opportunity for the technology provider sector.

Municipalities have traditionally been under pressure to efficiently operate facilities and, more recently, pressures around greenhouse gas emissions have become more prominent. The implementation of innovative technologies is one approach that might be employed by municipalities to meet goals in this regard. There is however little system-wide data available to characterize sludge handling practices in Ontario and the current status of implementation of innovative technologies.

This report seeks to achieve the following objectives

I. Document the current status of sludge processing in Ontario
II. Review innovative technologies for sludge treatment
III. Critically evaluate the potential for technology innovation to address key drivers influencing sludge processing and biosolids management in Ontario

These objectives were framed within the context of the following drivers that may be anticipated to impact upon sludge processing and biosolids management in the future.

- Energy/greenhouse gases
- Changing populations
- Reductions in agricultural land availability
- Changes in septage regulations
- Changes in landfill regulations
- Increased emphasis on resource recovery
- Increasingly stringent regulations on wastewater discharges.

These drivers are explored in greater detail in Chapter 4 of this report and are referred to, where appropriate, throughout the report.

Chapter 2 details the current status of sludge handling in Ontario. A profile of sludge handling technologies that are currently employed in Ontario is presented. Subsequently, the characteristics of biosolids generated between 2014-2016 in terms of quantity and quality (i.e. metal and pathogen indicator content) are described. The data employed in this analysis was gathered from the Ontario Ministry of Environment and Climate Change (MOECC), the Ontario Clean Water agency (OCWA) and from individual municipalities that were approached directly.

Chapter 3 documents innovative technologies for sludge treatment that were identified either in the research literature or are being marketed as commercial technologies. A keyword search of peer reviewed journals was initially employed to identify innovative technologies that have been reported over the last 10 years. These technologies were categorized in term of geographic location, state of development, scale of application, and treatment process type. In addition information on recently commercialized technologies that are being marketed at full/pilot scale, with an emphasis on Canadian based companies was gathered. Commercial technologies were identified through a review of technical reports, conference papers and correspondence with industry contacts.

Chapter 4 collectively reviews the current sludge handling practices within Ontario along with the overview of innovative technologies to identify opportunities for enhancement of sludge handling in Ontario. This analysis is presented in the context of drivers that are likely to affect sludge handling and biosolids management in the future.

2 Current status of sludge processing in Ontario

This section documents the results of a data gathering exercise that was conducted to establish the current status of sludge handling in Ontario. Information on the major classes of sludge treatment technologies that are currently employed in Ontario wastewater treatment plants (WWTPs) were collected and summarized. In addition biosolids production over the period 2014- 2016 in Ontario was characterized. The quantity of sludge generated from all responsive WWTPs and their corresponding design hydraulic capacity (DHC) were assessed. Measured values of important biosolids properties (i.e. solids content, pathogen indicators, metals) were collected, analyzed and sorted by relevant indicators such as WWTP DHC and related regulations (i.e. CP1 NASM).

Section 2.1 presents the methodologies employed for data collection. Section 2.2 describes the current technologies implemented in the province for sludge handling. Section 2.3 presents an analysis of biosolids quantity and quality with respect solids content, *E.coli* content and metals concentration. Section 2.4 summarizes conclusions that were arrived at regarding the current status of sludge handling in Ontario.

2.1 Data collection methodology

This section details the methodology used in collecting information for this portion of the project. A database of information on technologies employed for liquid and sludge treatment along with the WWTP DHC and biosolids disposition practices was obtained from the Ontario Ministry of Environment and Climate Change (MOECC). The data provided was somewhat dated and where possible, the data were updated with information obtained from other sources including websites and direct communication with plant operators. Further, the data provided appeared to have been self-reported by the plants and there were inconsistencies in terminology used to describe technologies and biosolids disposition. Where possible, some of the responses were consolidated to reduce the number of categories employed to characterize practices. Quantitative information describing biosolids production, solids content, pathogen and metal concentrations were provided by OCWA and through direct contacts that were made with individual municipalities.

According to information provided by the MOECC, 486 WWTPs operate within the province and they are operated by either the municipalities (253), OCWA (183) or private companies (50). In this study, 51% of the WWTPs plants that are operated by OCWA (93/183) provided data on sludge handling during 2014-2016. A total of 177 plants that are operated by municipalities or private operators with a hydraulic capacity greater than 1000 m^3/day were contacted directly. A total of 77% of the contacted plants (136/177) provided data or annual reports to facilitate data collection. It should be noted that data from indigenous communities and from WWTPs that employ lagoons for wastewater treatment were not included in this data collection. In the former case, these plants are not regulated provincially and hence identification of them was challenging. The latter plants do not generate biosolids on a regular basis and hence information on biosolids generation was sporadic and difficult to interpret. Various data formats including EXCEL files of regular operational data, annual reports to the MOECC, reports from certified labs, regional master plans and documents from consulting companies were provided.

Several challenges were encountered while conducting the data collection and analysis. It was not possible to obtain an exhaustive data set as not all of the municipalities or WWTPs that were contacted responded to the requests for data. Further, the data that was provided by the various sources was not always complete. For example, some sources provided a complete package of data that included all information required for this study. However, a number of the WWTPs/operators only provided a portion of the requested data.

In some cases the format of the data that was provided created challenges when integrating with data provided by other facilities. For example, regulatory requirements for land application of biosolids requires the concentrations of *E.coli* to be reported as a geometric mean of dry weight based values when the solids content is greater than 1% and wet weight based values when the solids content is smaller than 1% (OMOECC 2002, OMOECC 2012). However, in many cases it was not clear which bases were employed for reporting purposes. In addition, most of the reported data were single values that often reflected the averaging of a number of samples. Often, the number of tested samples and standard derivations were not provided. The averaging period was also inconsistent as some municipalities provided monthly/bi-weekly values whereas others provided yearly average values. Thus, statistical analysis of the sludge quality data was not conducted in this study.

Despite the above mentioned challenges, the dataset that was generated for this study was large and included a majority of the large biosolids generators in the province. Further it included a wide range of plant sizes and geographic locations. It is believed that the data set is of sufficient quality to provide insight into the status of sludge handling and biosolids management in the province.

2.2 Summary of sludge treatment technologies

This section presents a summary of the technologies implemented for sludge treatment and they are categorized by the number of implementations and the design hydraulic capacity (DHC) of the WWTPs. The data analysis was conducted primarily on the basis of information provided by MOECC that was updated with information provided by individual municipalities. In total, information from 486 WWTPs in Ontario regarding implemented technologies for sludge treatment process was provided.

The sludge treatment processes at the plants were categorized on the basis of their role in thickening, stabilization, dewatering and the end disposition of the product biosolids. For each category, the total numbers of technology implementations were summarized, aiming to quantify the distribution of technologies within each category. In addition, a more detailed classification of the implemented technologies was completed by sorting them according to the DHC of the wastewater treatment facility. The DHC values were divided in to 5 ranges, namely a) < 100 m^3/day, b) 100~1000 m^3/day, c) 1000~5000 m^3/day, d) 5000~10000 m^3/day and e) >10000 m^3/day. In each DHC range, the technologies employed for thickening, stabilization, dewatering and the disposition of the generated biosolids were assessed.

2.2.1 Thickening processes

Figure 2-1 presents a summary of the current implementation of thickening processes in the province. It can be observed that 16% of all WWTPs (78 out of 486) in Ontario reported the use of a separate thickening process before stabilization for sludge treatment. Thickening tanks (24), gravity belt thickeners (14) and rotary drum thickeners (9) were the most frequently reported technologies used for sludge thickening. A large number of WWTPs did not report implementing thickening before stabilization and 209 WWTPs provided N/A as responses and 166 plants only use lagoons to treat the influent wastewater. Lagoon-based plants would not be expected to employ thickening continuously due to the intermittent nature of sludge production.

WWTPs that employed anaerobic digestion for stabilization and did not employ thickening were highlighted in Figure 2-1. This mode of operation would typically result in relatively inefficient use of anaerobic digestion capacity. It is likely that these plants use co-thickening of waste activated sludges in the primary settlers and this was not identified in the source database. These WWTPs may represent an opportunity for enhanced digestion as operation with mechanical thickening would provide reduced volumes of sludge and hence, extended digester retention times, increased biogas production and associated volatile solids destruction.

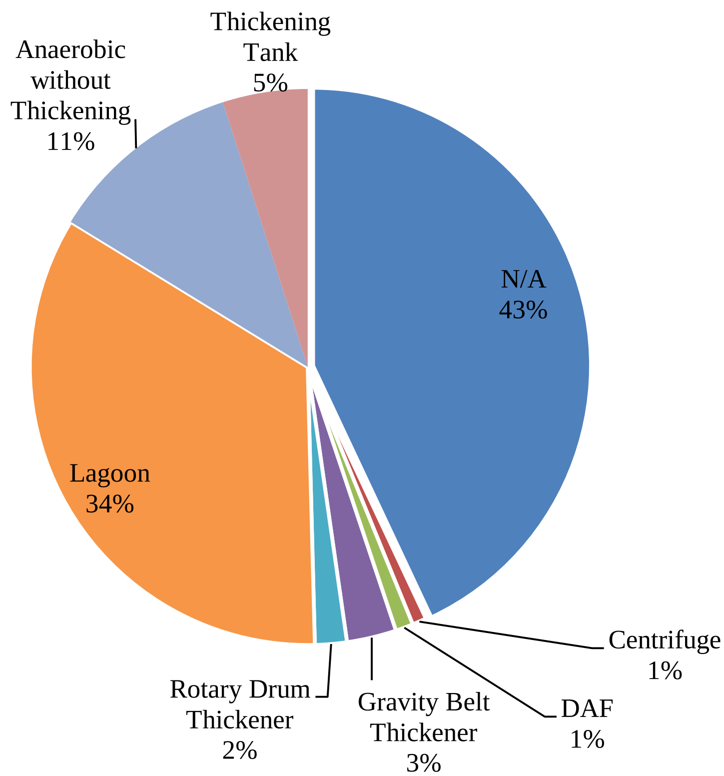

Figure 2-1. Summary of sludge thickening technologies

Figure 2-2 presents a summary of the implementation of thickening technologies as a function of WWTP DHC. From Figure 2-2 it can be seen that thickening is employed relatively infrequently in small and medium size WWTPs. Most of the existing thickening processes have been implemented at plants DHC values more than 10,000 m^3/day. WWTPs that were designed to treat less than 10,000 m^3/day most commonly implemented thickening tanks. It should be noted that the data available in the MOECC database did not give insight into thickening practices that may occur within tankage that is not designated as having a thickening function. For instance, there is ample anecdotal evidence that plants often co-thicken waste activated sludges in primary settlers and also decant aerobic digesters for volume reduction of sludges.

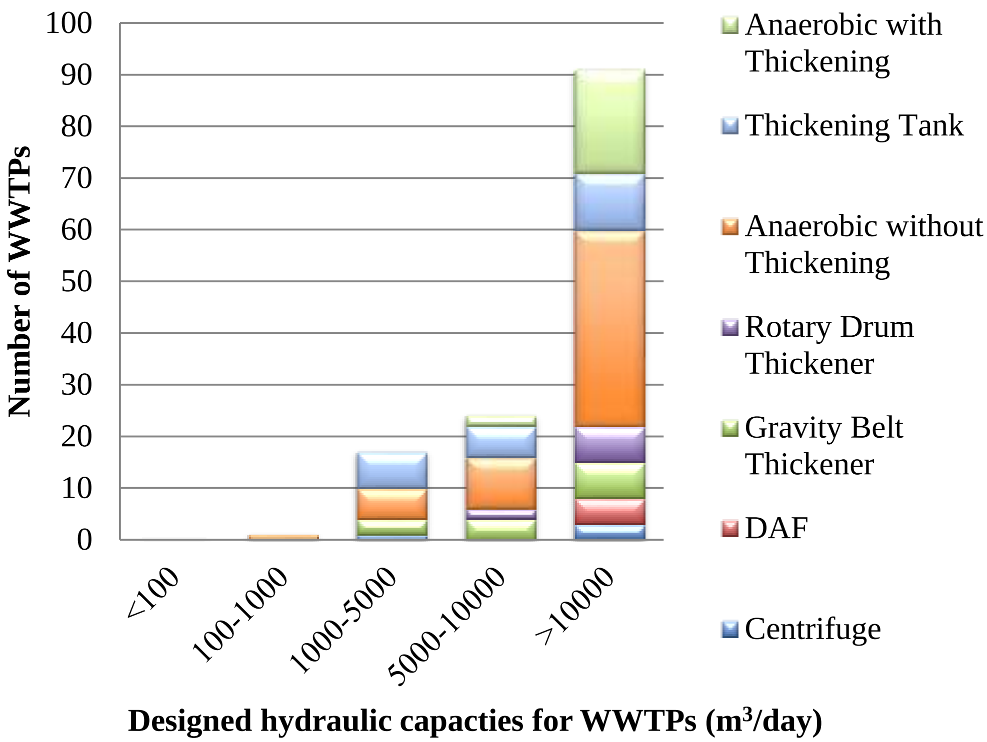

Figure 2-2. Implemented sludge thickening technology vs DHC

Increased use of thickening is an area that may yield significant benefits in Ontario, especially for small and medium size WWTPs. The increased capacity of sludge handling systems and reduced disposition costs that might be achieved through enhanced thickening would be beneficial for plants that:

- receive additional volumes of septage that will require less stabilization but more thickening and dewatering,
- generate increased sludge volumes due to population growth and associated increases in wastewater volume,
- require additional winter storage if biosolids disposition in landfills is banned,
- generate increased sludge volumes due to stricter wastewater permit requirements.

2.2.2 Stabilization processes

Figure 2-3 summaries the technologies that have been implemented for sludge stabilization in the province. Unlike the use of thickening processes, stabilization is commonly implemented for sludge processing with 77% of the surveyed WWTPs reporting installed stabilization technologies. A total of 110 WWTPs didn't report use of a stabilization process. However a majority of these plants employ lagoons to treat wastewater. The high level of implementation of stabilization processes is due to the fact that it is almost always required for disposition of the biosolids. In the plants that employ stabilization, 52.8 % (111 out 210) of them use aerobic digestion whereas 36.7% (77 out of 210) employ anaerobic digestion. Other technologies such as lime stabilization, ATAD and pelletization were reported but in much smaller numbers.

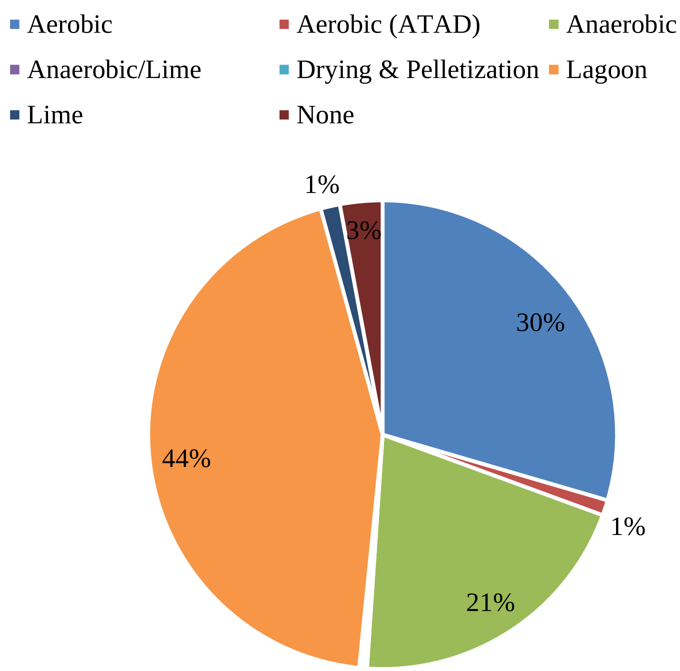

Figure 2-3. Summary of sludge stabilization practices

Figure 2-4 presents the implemented stabilization technologies as a function of DHC of the surveyed WWTPs. From this figure it can be seen that the selection of stabilization technologies is highly influenced by the scale of the WWTPs. Specifically, the implementation of anaerobic stabilization is the most common practice for plants that have larger DHC. As shown in Figure 2-4, for plants with capacities less than 100 m^3/day, anaerobic stabilization is not employed at all. As the DHC increases, the fraction implementing anaerobic digestion increases and in plants with DHC greater than 10,000 m^3/day anaerobic digestion is employed in 67.4% (56 out of 83 plants) of the facilities whereas aerobic digestion is implemented in 7 plants. In contrast, the use of aerobic digestion increases as DHC decreases.

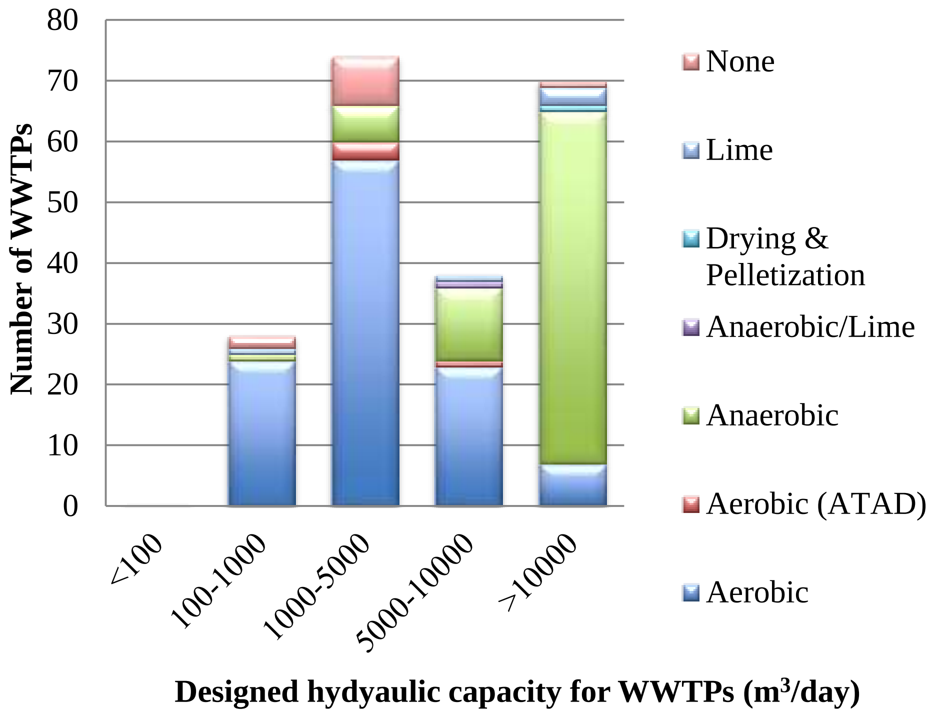

Figure 2-4. Stabilization technology versus DHC

The relatively large number of plants that employ aerobic digestion (notably 7 medium size WWTPs) may represent an opportunity for implementation of stabilization technologies that consume less energy than aerobic digestion or, like anaerobic digestion, generate biogas as an alternative fuel source. As energy consumption and greenhouse gas reduction become increasingly strong drivers in the future, the switch from energy intensive stabilization to energy producing stabilization processes should become more viable (Bogner et al. 2008; Majumder et al. 2014). Historically, smaller WWTPs have implemented aerobic digestion because of operational simplicity and the increased capital costs of anaerobic digestion processes. Changes in the energy/GHG driver should encourage smaller WWTPs to consider anaerobic stabilization technologies (Mata-Alvarez et al. 2000; Cakir & Stenstrom 2005).

2.2.3 Dewatering processes

Figure 2-5 summarizes the dewatering technologies that have been implemented in the province. It can be seen that 65 WWTPs (~13 of all plants) reported use of dewatering. and most dewatering is implemented in plants whose DHC values are greater than 10,000 m^3/day (Figure 2-6). Belt filter presses and centrifuges are the most commonly reported technologies (69% and 22.4% of the total dewatering implementations respectively). A total of 16 plants with a DHC less than 10,000 m^3/day, reported the use of dewatering technologies; most of which are centrifuges. The use of other dewatering technologies such Geotubes, plate and frame presses, membrane filters and drying beds was reported at 1-2 facilities in Ontario. Overall dewatering is not employed at a large number of WWTPs Ontario and its use is primarily at large WWTPs. Plants with DHC less than 1000 m^3/day, did not report use of dewatering.

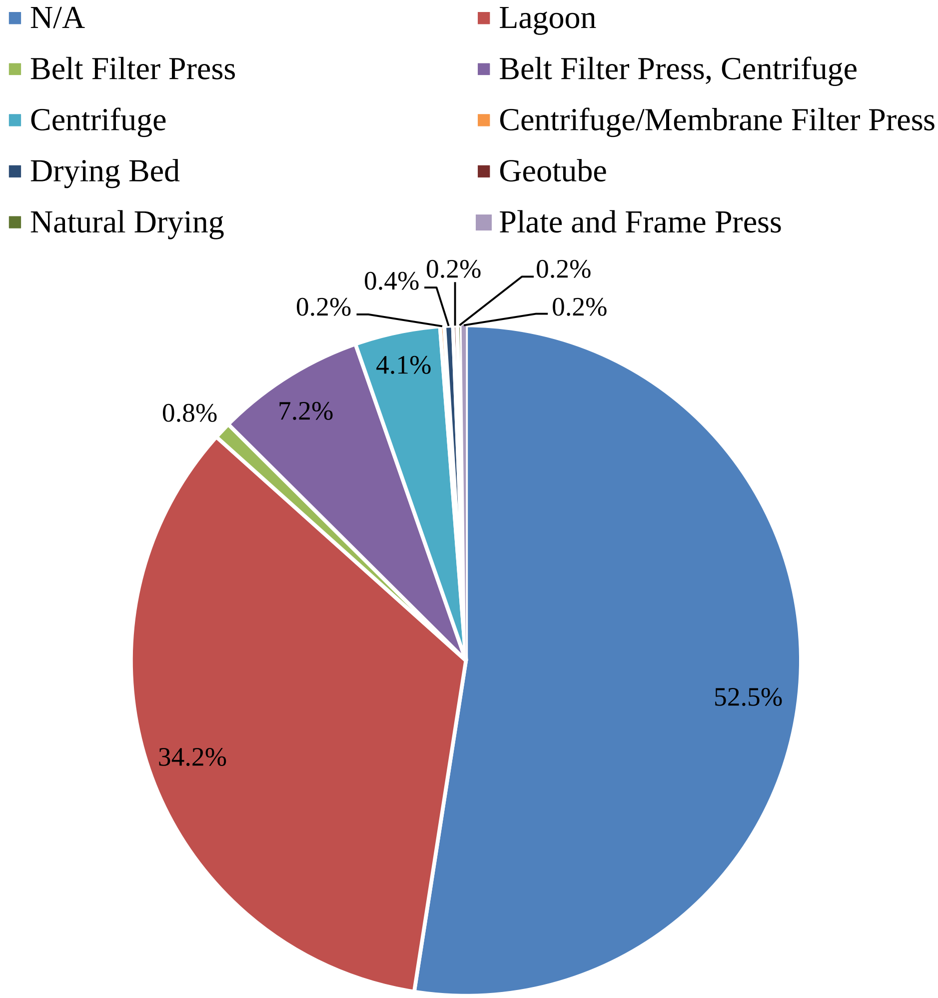

Figure 2-5. Summary of sludge dewatering practices

The increased use of dewatering may be a key strategy for a number of WWTPs to address the drivers that are anticipated to impact sludge handling and biosolids management in the future. The newly invoked federal Wastewater Systems Effluent Regulations (2012) require WWTPs to meet national effluent quality standards that are achievable through secondary wastewater treatment process. This new regulation will mostly affect smaller communities and coastal communities. In these WWTPs it can be expected that there will be increased production of sludges that will challenge existing sludge processing, biosolids storage and disposition capacities. Further, other potential regulatory changes that lead to increased septage handling at WWTPs will also result in increased sludge production; primarily at smaller rural WWTPs. The implementation of innovative dewatering technologies that are developed for smaller WWTPs could be beneficial in this context.

In some locations, changes in land use practices that reduce the availability of agricultural land suitable for biosolids disposition in close proximity to WWTPs will likely drive increased use of dewatering to minimize the volumes of biosolids that are trucked. Larger urban WWTPs will also likely see increased use of downstream processing technologies such as pelletization and incineration that require drier biosolids cakes. Both of these drivers will likely encourage the development of dewatering technologies that are capable of producing a drier product than is current being generated. Technologies capable of producing higher solids product with reduced energy and chemical requirements would be favorably received in the market.

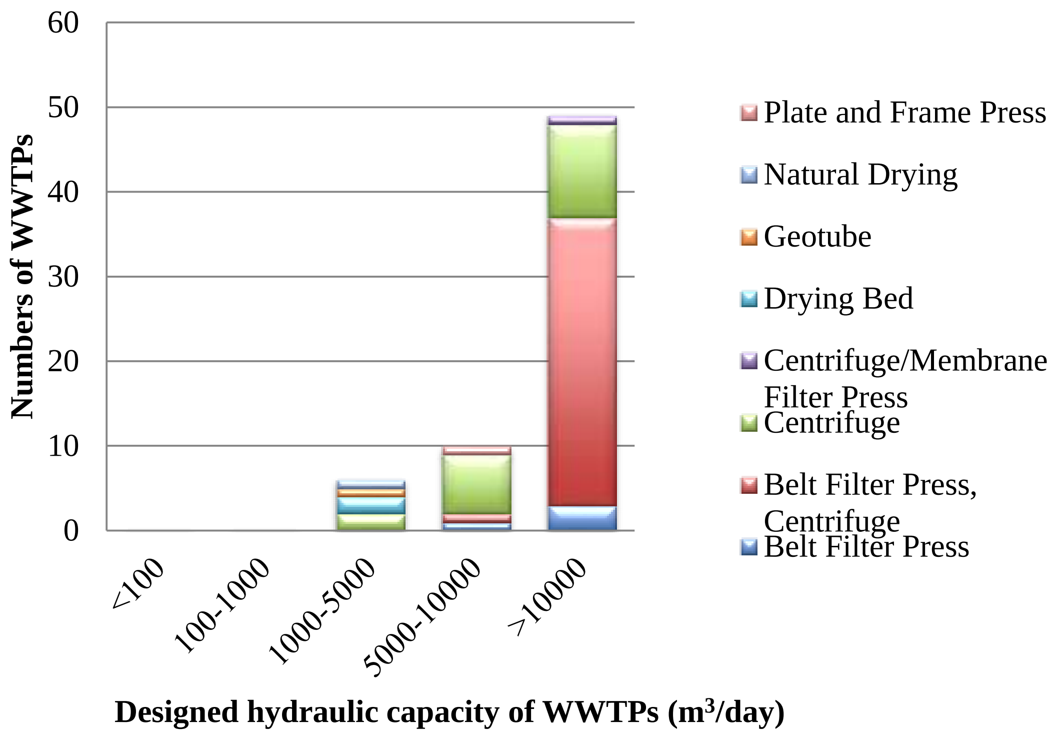

Figure 2-6. Sludge Dewatering technologies vs DHC

2.2.4 Disposition Practices

Figure 2-7 summarizes the disposition practices that were reported for treated biosolids from WWTPs in Ontario. From Figure 2-7 it can be observed that a large number of sub-categories of disposition were reported (i.e. incineration, incineration mix, agricultural, agricultural/drying bed, agricultural/incineration, agricultural/incineration/off site, agricultural/ landfill, landfill drying, off site, pelletizer). It should be noted that the data provided appeared to be mostly self-reported by various stakeholders. Based on the individual preferences of the respondents the use of terminologies/operations were not always consistent. This resulted in some uncertainty about the information collected in this study.

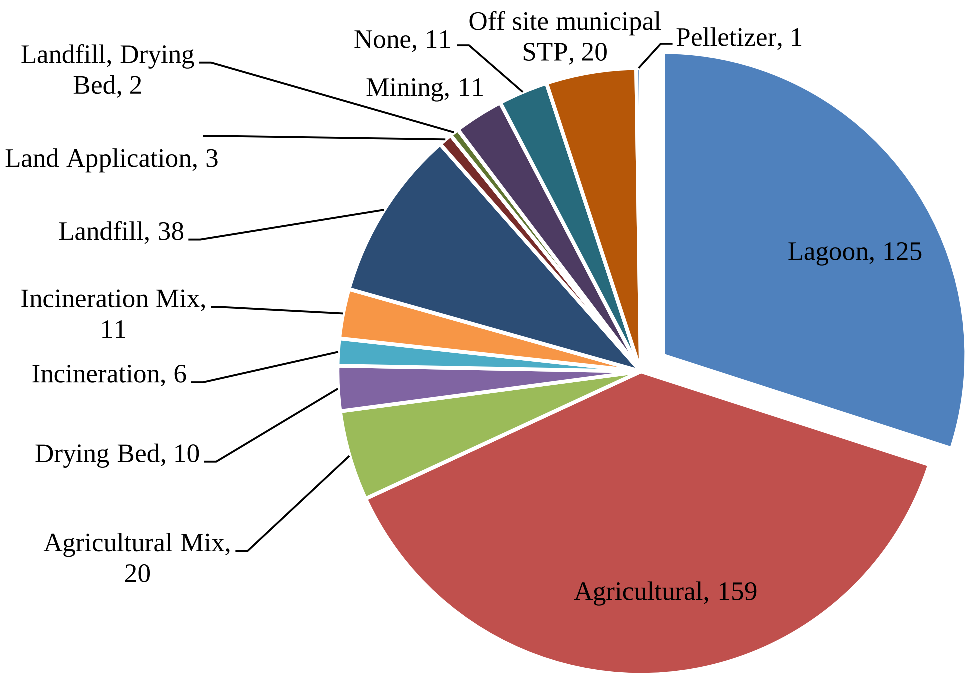

Figure 2-7. Summary of reported disposition practices in terms of the number of facilities

As shown in Figure 2-7, a majority of the treated biosolids are employed for agricultural use and this is followed by landfilling and incineration. There appeared to be no relationship between the DHC of the WWTPs and the disposition practices (Figure 2-8) as the distribution of practices was broad for plants of all DHC ranges. There are 38 WWTPs using landfill as the final destination for their sludge disposition. It should be noted that some of the reported pathways of sludge disposition did not describe the final destination of the treated biosolids. For example, plants that use lagoons for sludge storage will eventually dispose the biosolids to either landfill or agricultural land. However, this information was not available. These were however, small in number and did not greatly influence the conclusions that were derived from the data.

The observed diversity of disposition practices likely has several underlying drivers. The disposition of biosolids can be affected by variability in weather, availability of storage capacity, farmland site availability and the quality of the biosolids. Individual WWTPs may employ more than one disposition practice depending on the conditions and their impact on the feasibility of some pathways. For example, landfilling might be employed when storage capacity is full and land application is not possible. Some WWTPs don't directly discharge biosolids but rather transport the sludges to different location for further treatment. Further, some plants produce small quantities of sludge (i.e. lagoons) and hence disposition occurs only sporadically.

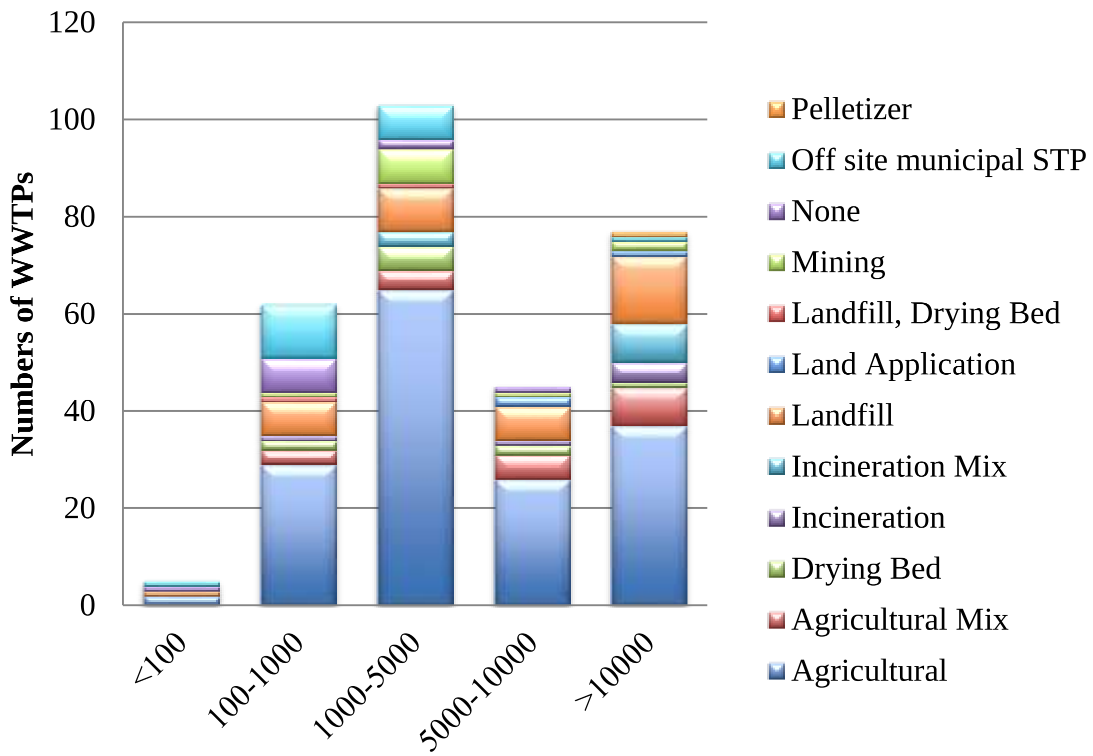

Figure 2-8. Reported sludge disposition practices vs DHC

2.3 Analysis of Biosolids quantities and quality

In this section, the quantity (annual production) and quality (i.e. solids content, pathogens and metals) of the produced biosolids that were reported in Ontario over the period 2014-2016 are summarized and analyzed. The data used in this analysis was provided by a variety of sources including OCWA and individual municipalities that were contacted directly for this project.

2.3.1 Quantity of biosolids

Figure 2-9 describes the distribution of annual liquid (m^3/year) sludge production in Ontario in 2014 -2016 for plants that do not dewater the biosolids product. To facilitate the analysis, the annual liquid biosolids production was categorized into volumetric-based groups. The number of plants that had biosolids production within the range of the individual categories were enumerated and plotted. In general, there were no significant changes in biosolid production in the surveyed plants during the three year period. The largest number of the reporting WWTPs produced between 1,000 to 5,000 m^3/year of liquid biosolids, followed by those that produced less than 1,000 m^3/year and those producing between 10,000~100,000 m^3/year. In general, the number of plants producing biosolids within a given range decreased as the magnitude of the range increased. It was found that over the reporting period there was an increase in the number of plants producing less than 1,000 m^3/year whereas a decrease in the number of plants which produced between 1,000 to 5,000 m^3/year of liquid biosolid was observed. Only a few WWTPs produced more than 100,000 m^3/yr of liquid biosolids. This trend was consistent with the previously described increased implementation of dewatering at larger WWTPs.

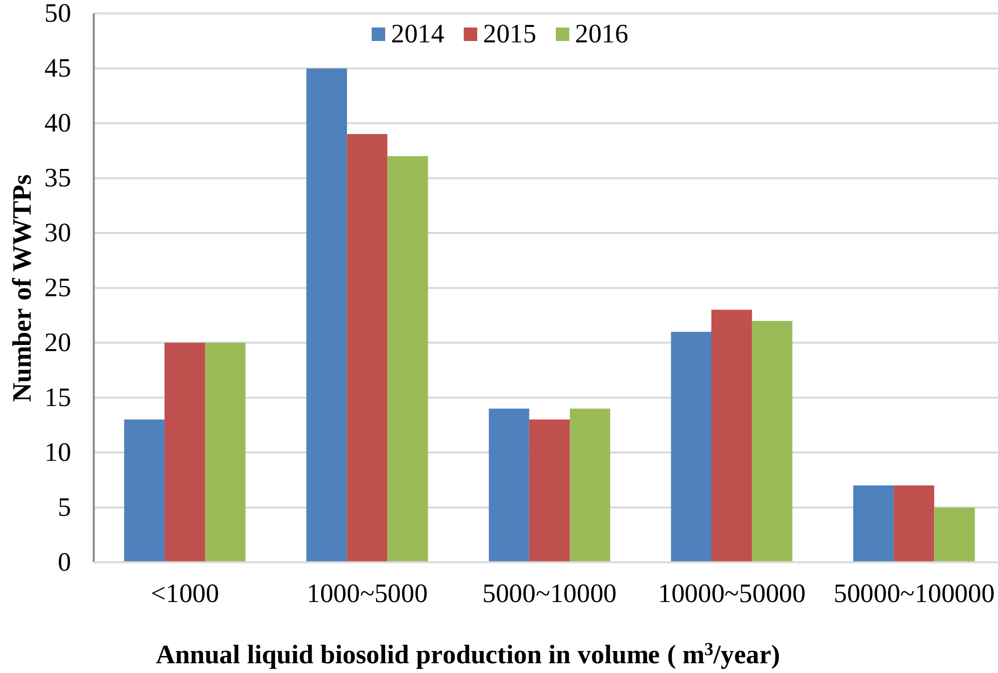

Figure 2-9. Distribution of liquid biosolids production in Ontario

Figure 2-10 describes the distribution of dewatered biosolids production in Ontario. The plants producing dewatered biosolids was categorized by the wet mass of biosolids produced as shown in Figure 2-10. There were no significant changes of dewatered biosolids production for the surveyed plants during the past reporting period. Unlike the liquid biosolids production, the dewatered biosolids production was more focused in WWTPs that produced large quantities of biosolids. A small but increasing (with time) number of plants produced less than 1,000 tonnes/year of dewatered biosolids. WWTPs that produced between 1,000~5,000 tonnes/tear of dewatered biosolids represented the highest number of plants while those that produced between 10,000~100,000 tons/year were second highest. One plant produced more than 100,000 tons per year of dewatered biosolids.

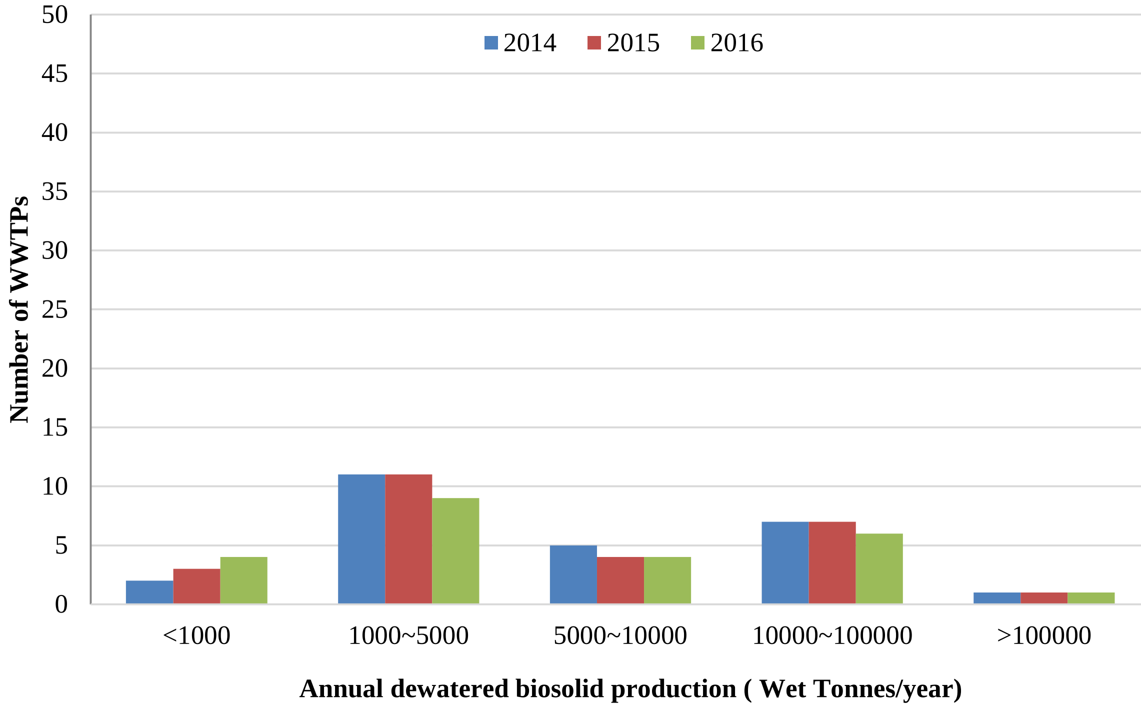

Figure 2-10. Distribution of dewatered biosolids production in Ontario

As might be expected, the patterns of production of liquid and dewatered biosolids production generally align with the implementation of dewatering technologies. As previously described, larger WWTPs have tended to implement dewatering technologies to a greater extent and this has led to production of large quantities of dewatered biosolids. It can be expected that innovations in sludge processing technologies will focus either on large plants that produce dewatered biosolids (improved dewatering technologies) or smaller plants that produce liquid biosolids (technologies designed for small WWTPs conditions). Further, the previously described drivers that influence dewatering technology implementation will lead to greater quantities of dewatered cake production in the future.

2.3.1.1 Solids content

The solids content of produced biosolids is an important quality parameter as the use of technologies that produce products with higher solids content can reduce downstream processing and haulage costs (Burton *et al.*, 2014). In this section, the solids contents (%)

of produced biosolids as provided by a variety of sources are summarized. The solids content of biosolids including liquid and dewatered biosolids are presented as a function of DHC (Figure 2-11). From Figure 2-11 it can be seen that liquid sludge had solids concentrations in the range of 1-4% over the range of DHC from 100 to 100,000 m^3/day. There were a few plants that produced liquid biosolids that had solids concentrations greater than 5% and this corresponded to those that have implemented thickening processes.

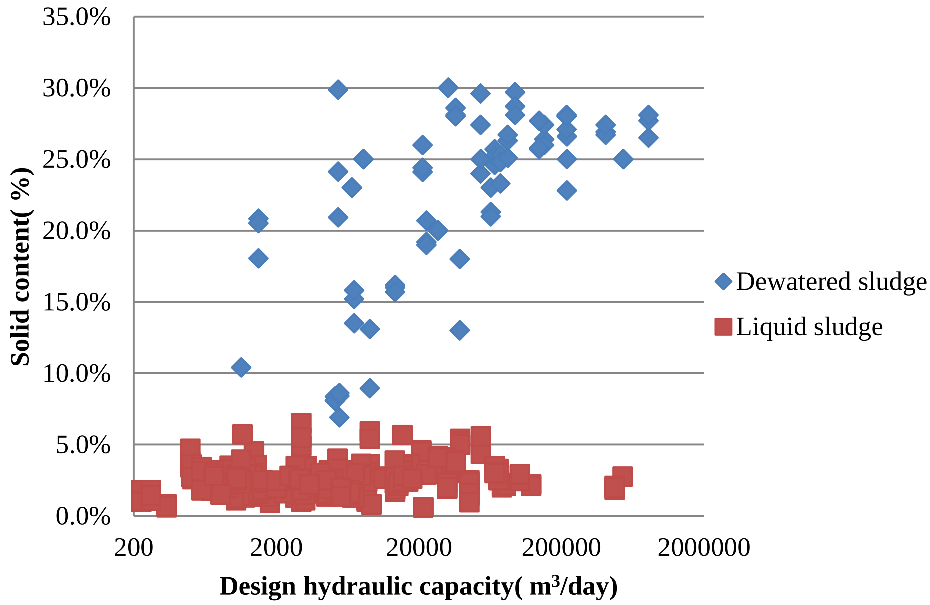

Figure 2-11. Solids concentrations in biosolids vs design hydraulic capacity

The reported solids concentrations of dewatered biosolids were typically between 20% and 30% that is the upper limit of most conventional dewatering technologies (Figure 2-11). The solids content of dewatered biosolids was found to generally increase with the scale of the WWTP as indicated by DHC. The WWTPs producing dewatered solids with solids concentrations at the lower end of the range could likely benefit from the implementation of improved dewatering equipment/strategies. Further, the development/implementation of dewatering technologies that can provide cost effective dewatering for small and medium size WWTPs would allow them to address drivers such as:

- reductions in agricultural land availability for biosolids that require increased haulage distances and cost,
- bans on landfilling and increases in biosolids production from population growth, or increased stringency of discharge regulations that require additional storage capacity at WWTPs.

2.3.2 Pathogen indicator concentrations

In this section, the presence of *E.coli.*, that is employed as a pathogen indicator, in produced biosolids is discussed. It should be noted that different formats (i.e. geometric mean, arithmetic mean, dry weight based and wet weight based values) and various measurement frequencies (i.e. bi-weekly or monthly) were reported by the WWTPs. In principal, the concentrations of *E.coli* should be reported as a geometric mean of dry weight based values when the solids content is greater than 1% and wet weight based values when the solids content is smaller than 1% (NASM, 2002, Ontario Compost Quality Standards, 2012). While the variety of data types reported prevented a perfectly precise characterization of biosolids quality on this parameter, it is believed that the trends in quality are representative and meaningful.

Figure 2-12 presents the distribution of reporting plants on the basis of *E.coli.* concentrations in the produced biosolids. From Figure 2.12 it can be seen that the distribution of WWTPs did not change significantly during the reporting period. The reported concentrations of *E.coli* in the biosolids for a majority of the plants were less than 500,000 CFU/gram. Only 1-3 plants reported *E.coli* concentrations that exceeded the NASM requirement for agricultural land application (2,000,000 CFU/gram). Hence it was concluded that pathogen content is not a major concern for most WWTPs in Ontario for current disposition practices. However, some drivers (reduced availability of agricultural land, increased urban populations) may lead to conditions where reduced pathogen concentrations (i.e. US EPA Class A) are desirable to diversify the disposition options. These conditions may lead to opportunities for implementation of technologies that can disinfect biosolids.

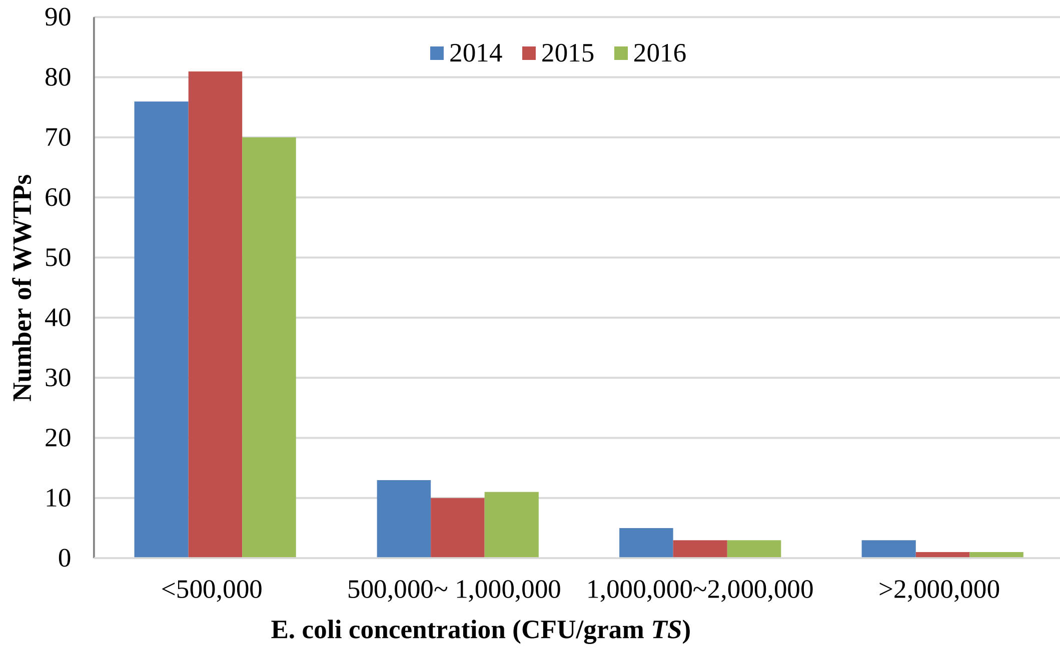

Figure 2-12. Distribution of WWTPs by biosolids *E.coli* concentrations

2.3.3 Metals concentrations

The quality of produced biosolids with respect to regulated metal concentrations over the period 2014-2016 are summarized and analyzed in this section. Two analyses were conducted to quantify the trends in regulated metal concentrations in biosolids. Initially, plants were categorized by metal concentrations on the basis of values required to meet specific regulatory criteria (i.e. Compost A/AA, B or NASM). Subsequently, the measured concentrations of individual metals were plotted as a function of the annual biosolids production (m^3/year for liquid biosolids and tonnes/year for dewatered biosolids) in order to evaluate any relationships between the quantity of biosolids generated and biosolids quality. While conducting these analyses it was observed that amongst the 11 regulated metals, three general patterns were prevalent. Specifically, they were categorized as non-concern metals (Arsenic, Cadmium, Cobalt, Chromium and Lead), medium concern metals (Mercury, Nickel and Zinc) and highest concern metals (Copper, Selenium and Molybdenum), respectively. In the following section, the distributions of representative metals for each category are discussed in detail.

2.3.3.1 Non-concern metals

The metals in this category were found to have concentrations that met the requirements of highest quality product (i.e. Category A/AA compost). Arsenic, cadmium, cobalt, chromium and lead were found to consistently fall in this category. Figure 2-13 describes the overall distribution of arsenic concentration on the basis of regulatory categories, as a representative metal in this category. From Figure 2-13 it can be seen that the biosolids quality with respect to this parameter was consistent with time as there were no significant changes in the number of occurrences of arsenic concentrations over the three year period. The arsenic concentrations from most of the surveyed plants (~ 96.3%) were in the range of Category A/AA compost (<13mg/kg). Only a small number of plants (~3.5%) fell into the range of Category B Compost (<75 mg/kg in dry weight) and all plants met the NASM requirement for arsenic.

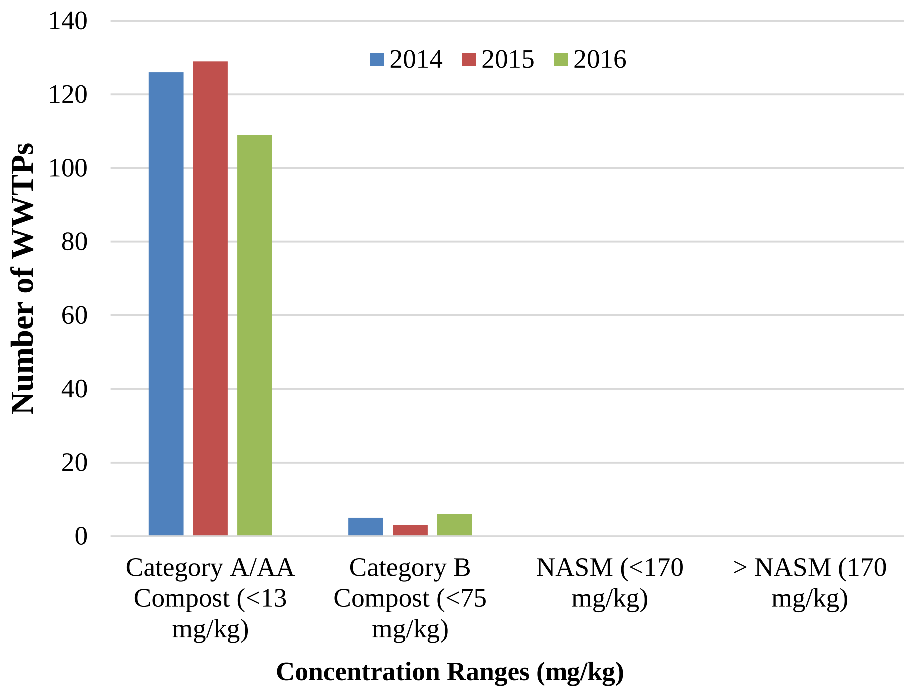

Figure 2-13. Distribution of Arsenic concentrations by regulatory category

Figure 2-14 presents the relationship between arsenic concentration and corresponding annual liquid biosolids production. From this figure it can be seen that a majority of arsenic concentrations were below 10 mg/kg and there was no significant relationship between arsenic concentrations and quantity of liquid biosolids produced (i.e. WWTP size). The biosolids with elevated arsenic concentrations tended to be produced in plants with intermediate quantities of biosolids production (10^3~10^4 m^3/year).

Figure 2-15 presents the relationship between arsenic concentration and corresponding annual dewatered biosolid production. Form figure 2-15 it be observed that dewatered biosolids had lower concentrations of arsenic as compared to liquid biosolids. A majority of arsenic concentrations in the dewatered biosolids were below 6 mg/kg and there was no significant relationship between arsenic concentrations and quantity of dewatered biosolids produced. The trends in the other metals that exhibited similar patterns/behaviors as arsenic (cadmium, cobalt, chromium and lead) are presented in Appendix A.

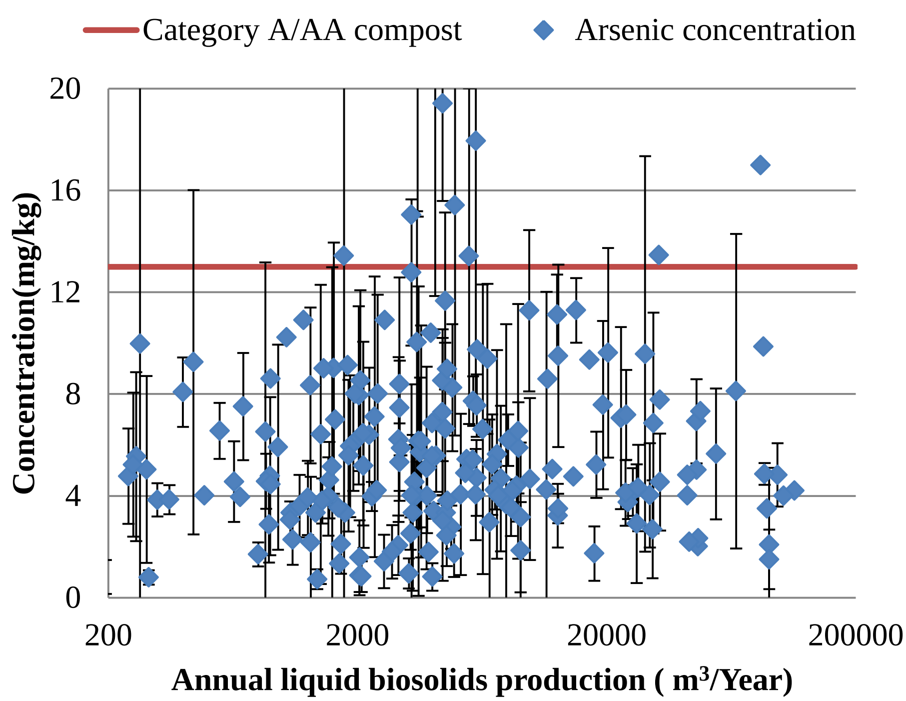

Figure 2-14. Arsenic concentrations vs annual liquid biosolids production

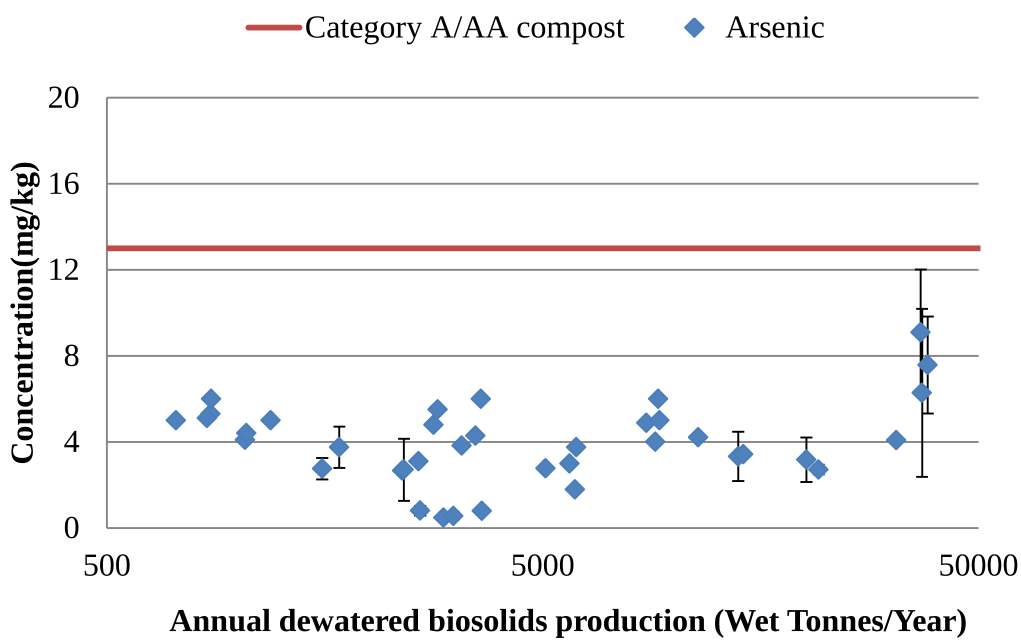

Figure 2-15. Arsenic concentrations vs annual dewatered biosolids production

2.3.3.2 Medium-concern metals

Metals that fell in this category generally met the requirements of the highest quality product (i.e. Category A/AA compost) however, there were more cases where the biosolids quality met intermediate quality product requirements (i.e. Category B compost). Mercury, nickel and zinc were found to fall in this category and trends in mercury concentrations will be presented as a representative metal in this category. Figure 2-16 describes the overall distribution of mercury concentration on the basis of regulatory categories (Category A/AA compost, Category B Compost, NASM). From Figure 2-16 it can be seen that the biosolids quality with respect to this parameter was consistent with time as there were no significant changes in the number of occurrences of mercury concentrations over the three year period. Most reported mercury concentrations (42%) were in the range concentrations required for Category A/AA composts. However the number of values that were within the range of concentrations associated with Category B compost (26.5%) increased significantly. There were a few reported concentrations that exceeded the regulated value for NASM.

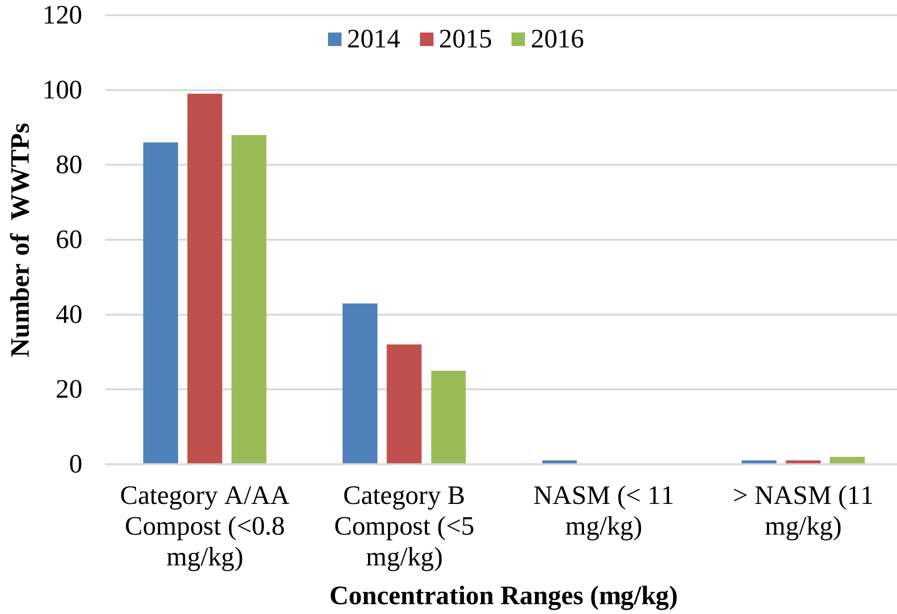

Figure 2-16. Distribution of mercury concentrations by regulatory category

Figure 2-17 illustrates the relationship between mercury concentration and corresponding annual production of liquid biosolids. Figure 2-17 indicates that WWTPs with mercury concentrations in the range of Category B compost or NASM requirements had intermediate biosolid production values (10^3~10^4 m^3/year). In addition, mercury concentrations in biosolids from medium size WWTPs tended to have higher variability as compared to those from the small or large plants. The trends in the other metals that exhibited similar patterns/behavior as mercury (nickel and zinc) can be found in the Appendix A.

Figure 2-18 illustrates the relationship between mercury concentration and the corresponding annual production of dewatered biosolids. From Figure 2-18 it can be observed that the concentrations of mercury in dewatered biosolids were generally lower than the liquid biosolids and had smaller variability. A majority of mercury concentrations in dewatered biosolids were less than 1.5 mg/kg. Further there was no significant relationship between mercury concentrations and the quantity of dewatered biosolids produced.

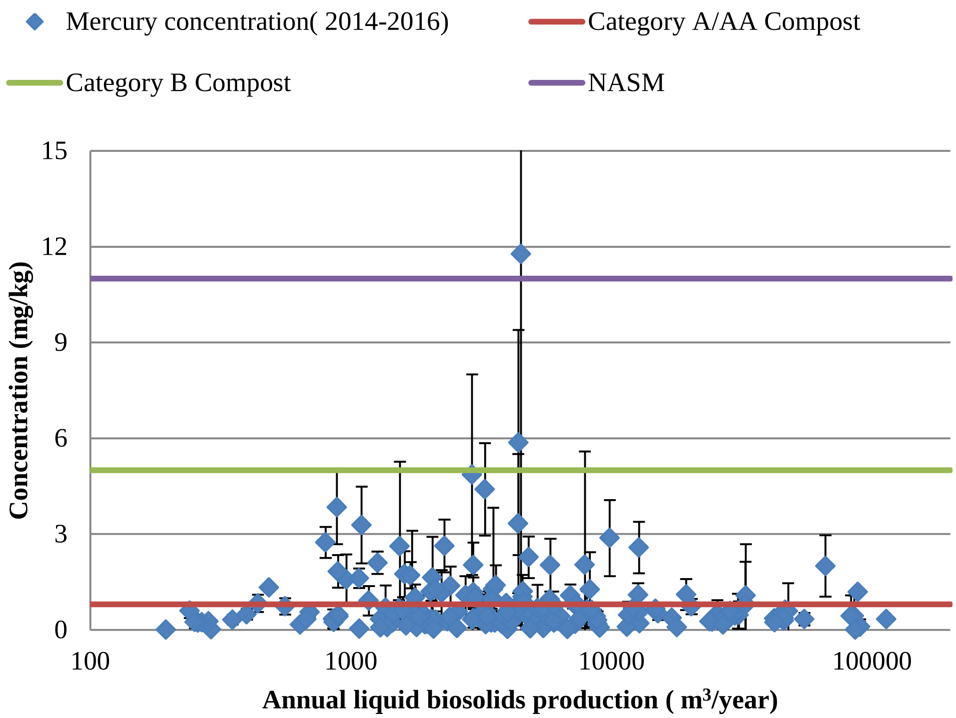

Figure 2-17. Mercury concentrations vs annual liquid biosolids production

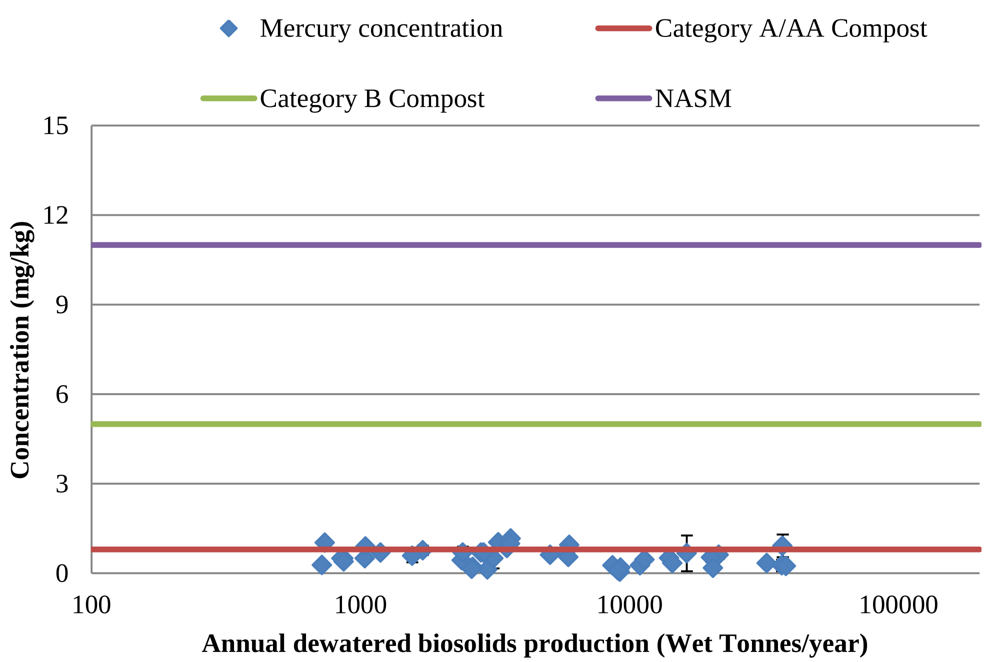

Figure 2-18. Mercury concentrations vs annual dewatered biosolids production

2.3.3.3 *Highest-concern metals*

Metals in this category (copper, selenium and molybdenum) typically were present at concentrations that met the requirements of Category B compost. There were however, more cases where the reported biosolids quality only met or, in some cases, exceeded NASM requirements for biosolids disposition. Figure 2-19 describes the overall distribution of reported copper concentrations as categorized by regulatory quality (Category A compost, Category AA compost Category B Compost, NASM) and is representative of the other two metals. From Figure 2-19 it can be seen that the quality of the biosolids with respect to this parameter were constant with time as there were no significant changes in the number of occurrences of copper in the categories over the reporting period. Further it can be seen that most of the copper concentrations were in the range of Category B compost (~40%) and Category AA compost (~ 39%). A smaller portion of the reported concentrations were in the range of Category A compost (9.3%). An increased number of reported concentrations only satisfied the NASM requirements (12%) and additional values exceeded the NASM requirement for copper.

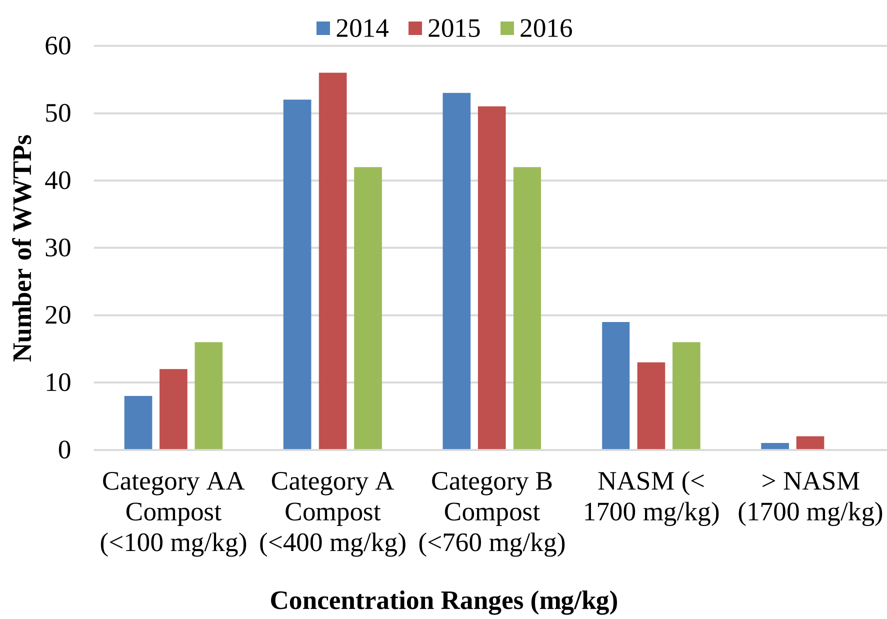

Figure 2-19. Distribution of copper concentrations by regulatory category

Figure 2-20 illustrates the relationship between copper concentration and corresponding annual production of liquid biosolids. From Figure 2-20 it can be seen that, there was no obvious trend in concentrations as a function of annual liquid biosolids production. WWTPs that had copper concentration in the range of Category B compost and NASM, spanned the range of annual biosolids production.

Figure 2-21 illustrates the relationship between copper concentration and corresponding annual production of dewatered biosolids. The reported concentrations of copper in dewatered biosolids had smaller absolute values and variability as compared to those in the liquid biosolids. Almost all the concentrations of copper in the dewatered biosolids were less than 760 mg/kg (the regulated level for Category B). There was no significant relationship between copper concentrations and the quantity of dewatered biosolids produced. The trends in the other metals that exhibited similar patterns/behaviors as copper (selenium and molybdenum) can be found in Appendix A.

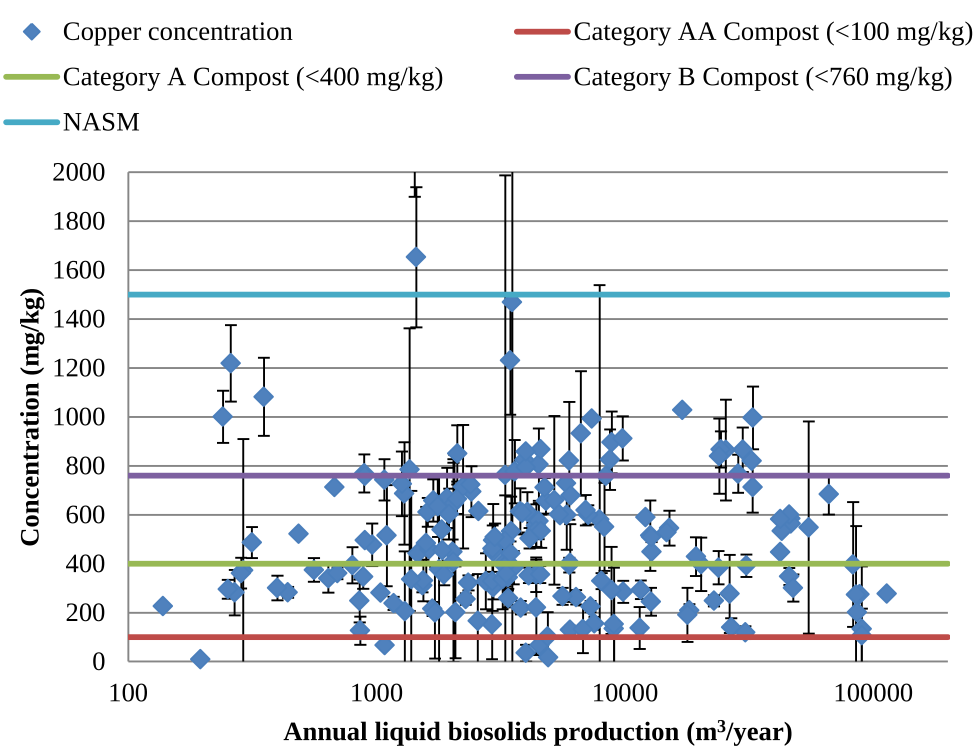

Figure 2-20.Copper concentrations vs annual liquid biosolids production

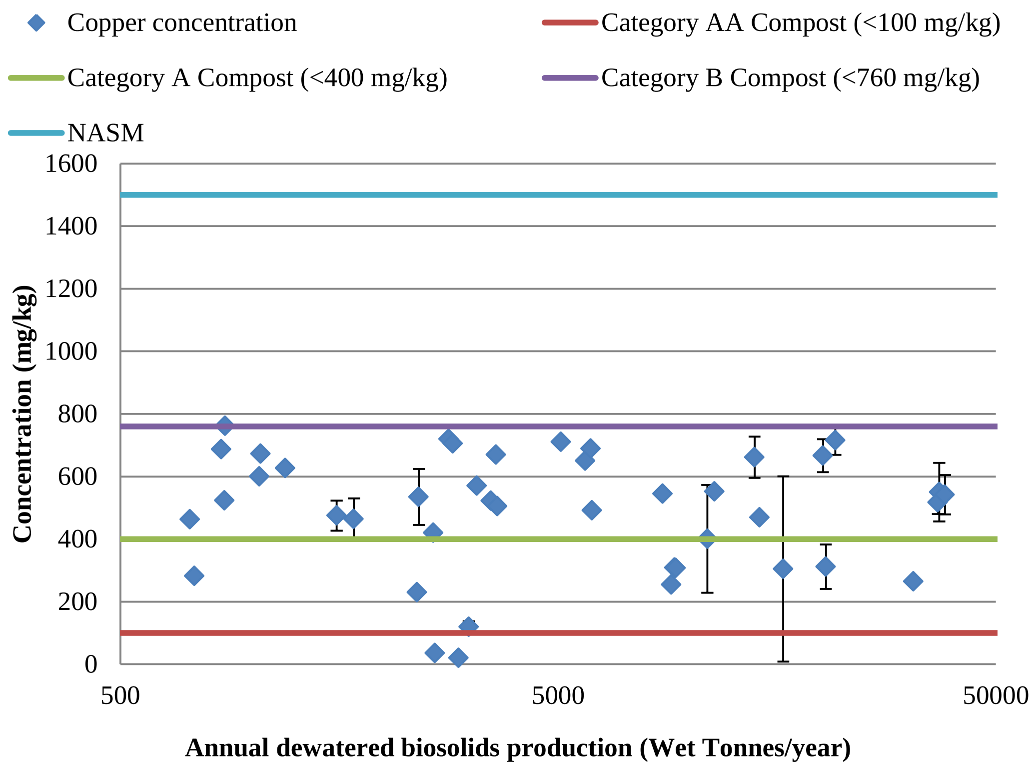

Figure 2-21.Copper concentrations vs annual dewatered biosolids production

When viewed collectively, the metals concentration data reveal that the biosolids produced in the province are well suited for disposition practices associated with Class B composts and NASM application on agricultural land. Metal concentrations in dewatered biosolids mostly meet the requirement of Category B compost with much smaller variability. The biosolids with elevated metal concentrations tended to be produced in non-dewatered plants with intermediate quantities of biosolids production (10^3~10^4 m^3/year). A smaller fraction of the biosolids are suitable for Class A compost applications and the limiting metals are primarily copper, selenium and molybdenum. Drivers that tend to limit agricultural land application in the future will result in greater challenges associated with disposition of the lower grade biosolids. The development of technologies and/or practices that can mitigate the presence of the limiting metals would allow for a greater diversification of disposition practices and would allow plants to prepare for the impacts of drivers that reduce current disposition pathways (i.e. agricultural land application).

3 Review of innovative technologies for sludge treatment

This section presents the results of an exercise that collected and evaluated information on innovative technologies for sludge processing. Particular emphasis was placed on identifying technologies with potential for implementation in Ontario in 5 years. Two data collection activities were conducted and are described in the following section. A keyword search of peer-reviewed journal articles was employed to identify innovative technologies that have been reported during the last 10 years. In addition, innovative commercialized technologies that have been marketed at full and pilot scale were identified. In this regard particular emphasis was placed on those that have been mainly developed in Canada or are being marketed by a Canadian based company. Section 3.1 details the methodologies and classification criteria used for peer reviewed publications and commercial technologies for innovative sludge treatment process. Section 3.2 summarizes and classifies the identified innovative technologies for sludge handling based on geographic location of development, scale of development and the functionality of the processes. Section 3.3 document the detailed assessment of sludge treatment technologies while Section 3.4 summarizes conclusions that were derived.

3.1 Data gathering methodology and classification criteria

3.1.1 Keyword search of peer reviewed publications

This section details the methodology used in collecting literature on innovative technologies, as well as the classification criteria used to sort these reports. A series of keyword searches (Table 3-1) were completed using Scopus, a citation database for peer-reviewed literature. Relevant papers were deemed to be those that addressed innovative sludge processing technologies. Innovation in this context was defined to consist of technologies that extend beyond those described in established texts (Burton *et al.* 2014).

Table 3-1. Keyword searches for literature review

Keywords	**No. of Papers**
Biosolids “and” disinfection	1
Biosolids “and” stabilization	3
Municipal “and” sludge “and” digestion	28
Municipal “and” sludge “and” disinfection	2
Municipal “and” sludge “and” incineration	13
Municipal “and” sludge “and” processing	5
Sludge “and” dewatering	164
Sludge “and” thermal	17
Sludge “and” thickening	29
Total	**262**

Table 3-1 tabulates the search key words used in this study and the number of publications deemed relevant according to the review’s classification criteria. Duplicated publications and papers that were inaccessible for review were excluded from the list. In total, 262 publications were collected and classified with detailed information. Tracking information for the individual publications (paper title and digital object identifier, DOI) can be found in Appendix B. It should be noted that in some cases multiple publications describing various aspects of a single technology development by one research group were observed. While the multiple reports might be considered as indicative of a single innovative technology, it was not possible to develop a scheme that could be consistently applied for reducing the number of reports to discrete technology developments. Hence, the total number of reports was employed as an indicator of the magnitude of research and development activity rather than as a direct measure of the number of innovative technologies that have been studied.

3.1.2 Commercialized technology

Information on commercialized technologies that focused on innovative sludge treatment was collected in various ways. An analysis of past state-of-science technical reports, collection of conference papers, correspondence with industry contacts, reviews of industry newsletters and publications were all used to generate a master list. Innovative commercial technologies that targeted at least one category of digestion, stabilization, compositing, drying, nutrient recovery, thermal processes and quality improvement were identified and collected. Detailed information describing the identified commercial technologies can be found in Appendix C.

3.1.3 Classification Criteria

The classification criteria employed to sort collected information included geographic location, scale of development and their functionality in sludge handling and processing.

The location of technology development that was identified by the keyword searches was employed as a classification criteria in this report. The location of work was determined from the country of origin of the majority of the authors (who generally all resided at a particular research institution). The location of commercial technologies was designated as the location where the technology was first developed or currently operated. If such information could not be found, the location of the head offices of the company marketing the technology was used for identification.

The scale of the development of the technologies (i.e. bench, pilot, and full scales) was used to sort sludge handling technologies. In general, bench scale studies were reported to be conducted in research facilities focusing on preliminary experiments, testing theories, feasibilities or exploring system configurations for a particular technology before larger scale testing. Many of the technologies in this category could be considered embryonic in nature. Pilot scale testing included projects where a custom reactor was designed and tested, or ones that utilized a side stream influent at a full scale treatment plant to test the technology. The full scale designation was used to describe only those reports of technologies that were implemented at full scale wastewater treatment plants and sludge handling facilities. Full scale implementations included both commercial technologies as well as technologies that were still considered in the development stage. Technologies that have been demonstrated at full scale systems are typically well developed and could be considered for implementation in Ontario/Canada in the near future (i.e. 5 years).

The functionality in sludge handling and processing was an additional category employed to further classify technologies. The primary categories of sludge handling technologies were identified as thickening, stabilization, conditioning, dewatering, drying, thermal reduction, and recovery/alternative use. Additional sub-categories that detailed the differences between treatment technologies were used to differentiate the processes within each primary category.

3.2 Geographic distribution and scale of innovative technology development

3.2.1 Geographic distribution of sludge treatment

An analysis of the 262 collected literature reports revealed publications from 29 countries (Figure 3-1). As shown in Figure 3-1, a total of 106 reports originated in China and these contributed 41% of the total identified publications. Four other countries including Canada, Spain, South Korea and Japan had more than 10 reports each and hence the top five countries generated 63% of the total surveyed publications. Viewed collectively it was concluded that East Asia, Europe and North American are the primary developers of innovative technologies for sludge handling.

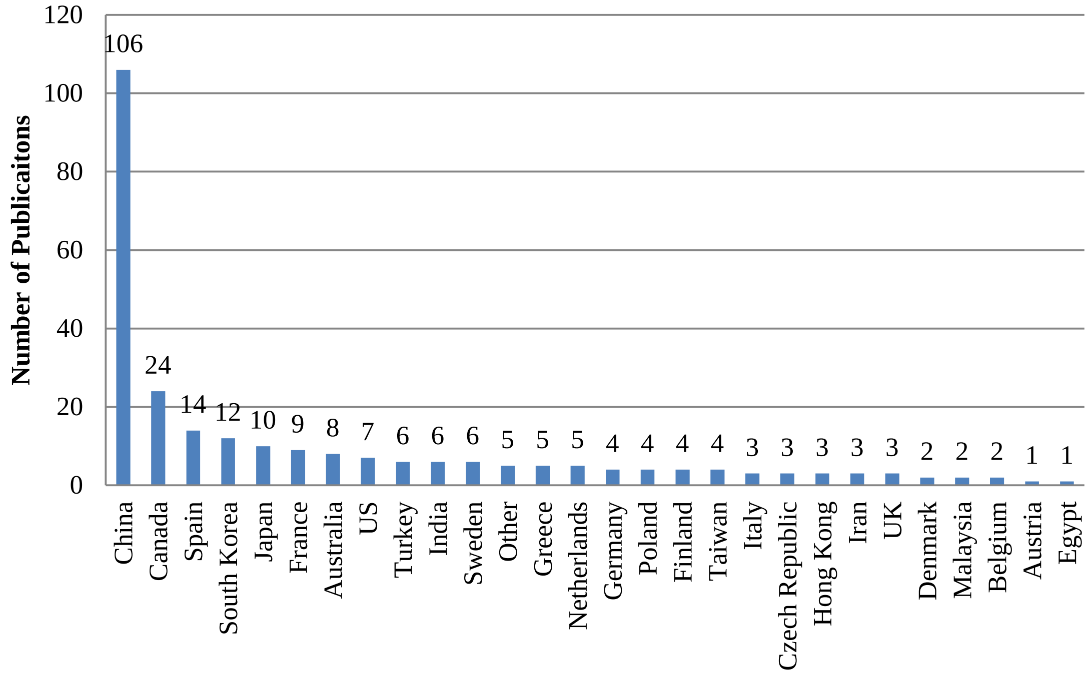

Figure 3-1. Geographic distribution of sludge treatment technology development

3.2.2 Scales of Innovative technology development for sludge treatment

The scale of demonstration of sludge processing technologies was considered as an important indicator of the extent of technology development. Table 3-2 and Figure 3-2 document the development of technologies that have been reported in terms of the scale of demonstration. In general, bench scale studies were most frequently reported whereas pilot and full scale studies had fewer and a similar number of reports between them. Most of the innovative technologies were tested in bench and pilot scale systems but only stabilization, thermal reduction, heat drying, recovery and dewatering were implemented for testing at full scale system. Interestingly, conditioning and thickening had a distinct lack of reports on full scale investigations. The results suggest that some conditioners have not been implemented due to factors like cost or other feasibility issues that limited their use. It is also possible that their full scale implementations were not reported in the peer reviewed literature. Thickening, in general, had minimal reports at all scales. This could be because some of the innovations on thickening were integrated with wastewater treatment process (i.e. co-thickening) which was not been recognized as thickening.

Table 3-2. Scale of implementation of innovative sludge treatment processes (global)

	Thickening	Heat Drying	Thermal Reduction	Recovery	Dewatering	Conditioning	Stabilization
Bench	6	12	13	16	37	68	67
Pilot	1	3	5	2	5	3	18
Full	1	3	6	5	3	3	12
Total	7	18	21	22	45	71	97

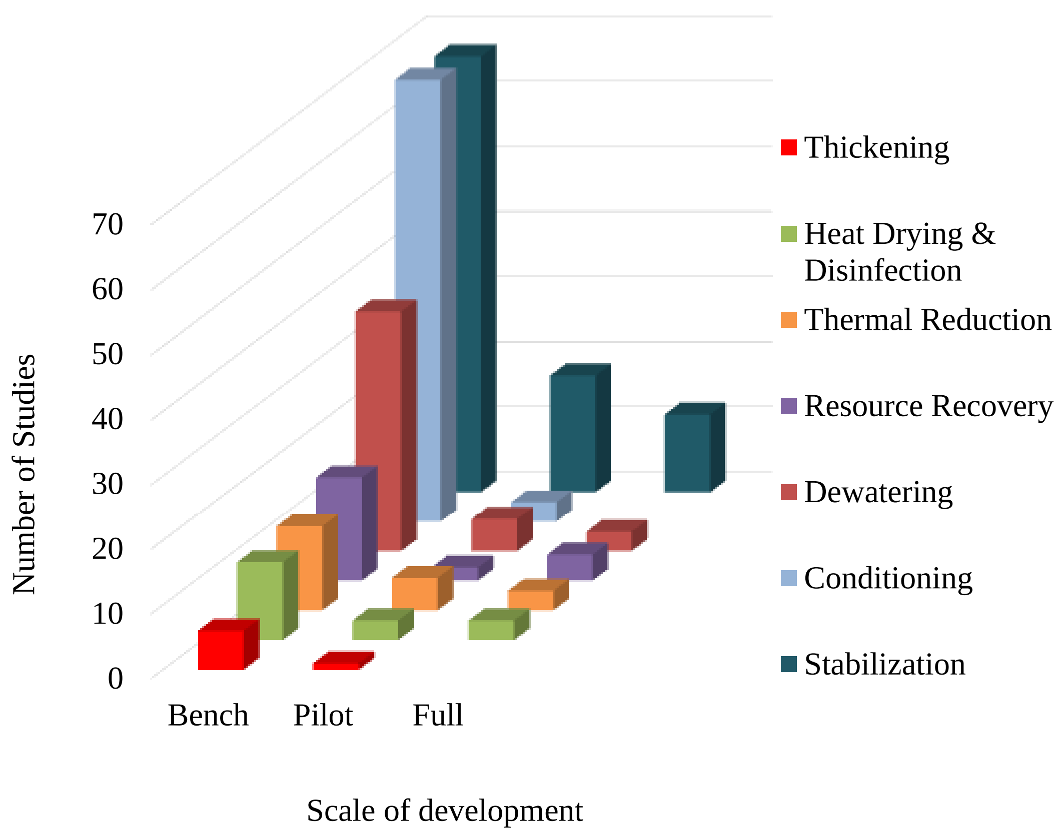

Figure 3-2. Scale of demonstration of reported innovative technologies (global)

The development of innovative sludge treatment technologies in Canada was of particular interest for this study. Hence, reports describing pilot/full testing and commercial technologies developed/operated in Canada were summarized in Figure 3-3. When compared with Table 3-2, there were noticeable differences in the emphasis of technology development as compared to the previously described global trends. Of the 24 Canadian studies, the dominant process development has been in the category of stabilization, with 15 studies being classified in this category. By contrast there were minimal reports in the categories of thickening and heat drying. A majority of the reports describing pilot and full scale implementations have focused on stabilization technologies.

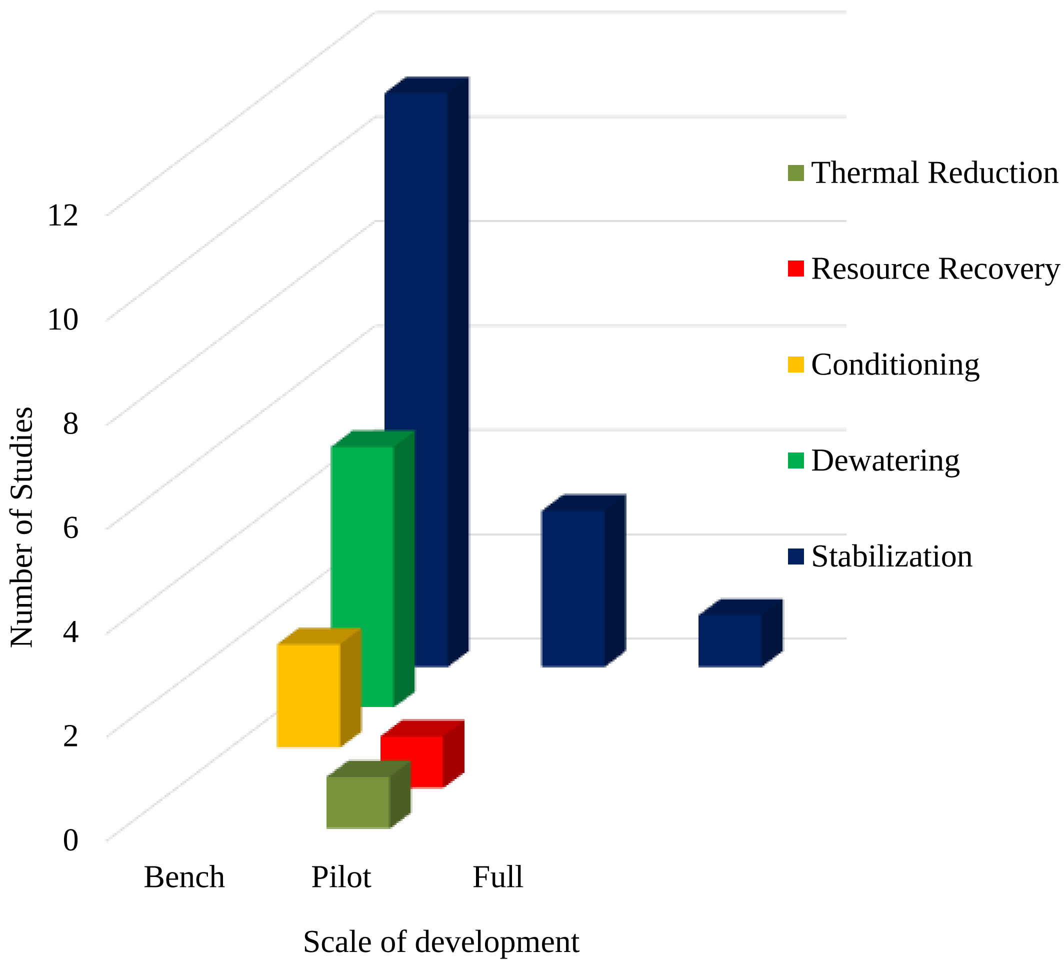

Figure 3-3. Summary of reports on Canadian technology development

3.3 Categorization by functionality

The reports on innovative technologies were summarized by their functionality in sludge processing (Table 3-3) and then were further sub-categorized on the basis of the underlying mechanisms that impact upon sludge properties in the processes. From Table 3-3 it can be seen that in general, most of the recent innovative studies have focused on processes contributing to stabilization, conditioning and dewatering whereas fewer reports have focused on thickening, drying and recovery processes. Reports that focused on innovative stabilization and conditioning technologies represented 34% and 27% of the total number of studies published. Within the category of stabilization, a majority of publications have focused on innovative biological processes whereas chemical-based processes dominated reports on innovation in conditioning. Publications associated with thermal treatment, resource recovery and heat drying processes had similar levels of reporting (6.8~8.4%) in the surveyed literature (Figure 3-4). Reports on innovative thickening processes had relatively few studies (6 reports). The following sections provide a more in depth and quantitative assessment of technologies associated with stabilization, conditioning and dewatering process to give more insight into the types of technologies that were reported in these large classifications.

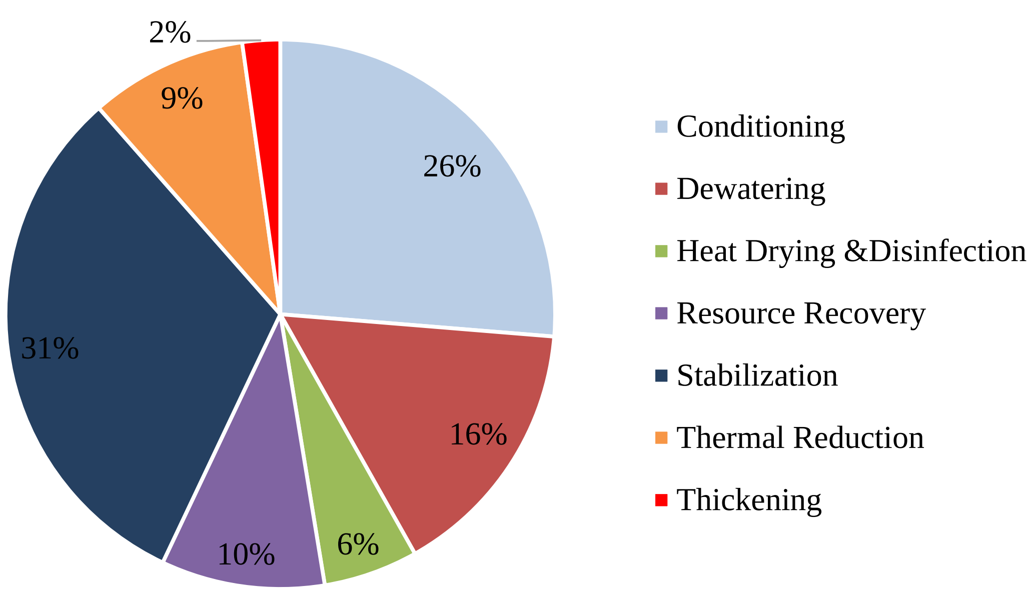

Figure 3-4. Distribution of reports on innovative sludge processing technologies (by functionality)

Table 3-3. Categorization of innovative technologies for sludge treatment processes

Category of technology	No. of Publication	Sub-Category	No. of Reports
Thickening	6	Flotation	4
		Membrane	2
Stabilization	85	Biological	71
		Chemical	7
		Integrated	3
		Other	2
Conditioning	71	Chemical	58
		Integrated	8
		Electrolysis	5
Dewatering	42	Electro-dewatering	23
		Physical	11
		Passive	8
Heat Drying & Disinfection	15	Disinfection	11
		Thermal	4
Thermal Reduction	25	Incineration	8
		SCWO	3
		Mechanical	14
Resource Recovery	26	Nutrients	12
		Materials	6
		Fuels	7
		Bioleaching	1

3.3.1 Innovations in sludge stabilization

Reports of developments in the stabilization category contributed 34% of the total number of reports globally. As stabilization is a relatively broad category of technology it was elected to further sub-categorize the reports in this area (Table 3-4). From Table 3-4 it can be seen that stabilization was divided on the basis of mode of action into biological, chemical, integrated and other subcategories. The largest number of reports within the stabilization category addressed innovation in biological processes. The chemical stabilization technologies typically entailed innovations and improvements in alkaline stabilization. The 'integrated' category addressed research that used combinations with more than one mode of treatment. For example reports in this category addressed technologies like ozone/radio frequency heating, and microwave oxidation combinations. The 'other' category included technologies that did not fit in the previous sub-categories and included technologies like electrochemical oxidation and wet oxidation. These reports described the use of technologies for stabilization rather than dewatering improvements. Reports describing the use of similar technologies for dewatering improvement are discussed in a separate section of the report.

3.3.1.1 Biological stabilization processes

Figure 3-5 delineates the subcategories of innovation in biological treatment processes. From this figure it can be seen that anaerobic digestion processes had the dominant number of biological treatment reports (77%). The anaerobic digestion reports were further classified as those that focused on the use of pre-treatment technologies for enhanced digester performance (68%) and process enhancements (32%), respectively.

Pretreatment technologies are generally intended to improve the waste stream with the specific purpose of improving the anaerobic digestion process (improving biogas yield, lowering retention time, etc.). The reports that described anaerobic digestion pretreatment could be categorized in terms of the mode of action and included chemical, physical, integrated and other classifications (Figure 3-5). The chemical pretreatment category included reports of the use of alkaline, peroxide, iron, photocatalytic, potassium ferrate, and acid pretreatments to improve solids destruction in the subsequent digestion. The physical category included microwave, ultrasound, thermal hydrolysis, thermal, and pressure pretreatments to enhance solids destruction mechanically and some were also reported to achieve a degree of dewatering due to evaporation (excluding ultrasound). The 'integrated' category included reports that described combinations such as the use physical-alkaline, physical-physical, and physical-oxidant technologies. The 'other' category included a limited number of reports of technologies that did not fit the earlier classifications and included the use of biological pretreatment, cation exchange resin, and a comparison of ozone and ultrasound pretreatments.

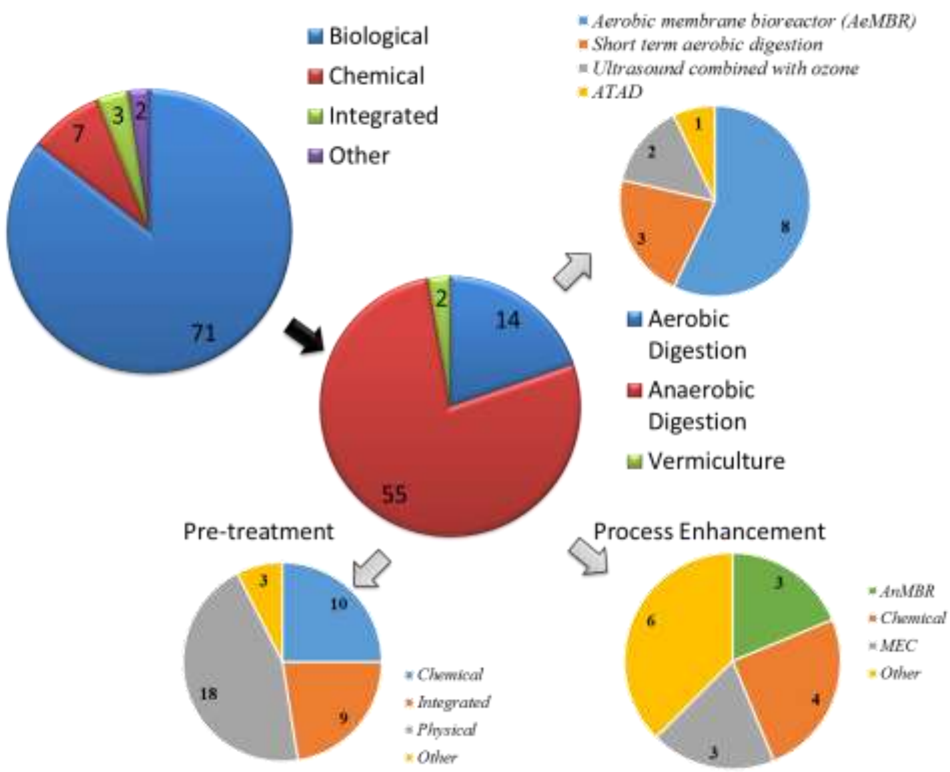

Figure 3-5. Detailed classification of biological processes for sludge stabilization

The use of pretreatments to enhance anaerobic digestion of sludges has clearly been a topic of interest for some time. If successful, these technologies could increase digester throughput and potentially increase the generation of biogas as an alternative energy source. Coincidentally, increased volatile solids destruction could minimize the mass of solids that would need to be handled by downstream processes. Conversely, increased solids destruction in anaerobic digestion could lead to increased loadings of nutrients in recycle streams to the WWTP. This would require additional nutrient handling capacity in the plant and could reduce the nutrient content of digested biosolids that are employed for land application. Implementation of pretreatment technologies could therefore address the following biosolids drivers if the limitations can be addressed:

- Biogas could be an alternative energy source for WWTPs and thereby reduce GHG impacts of biosolids management,
- Increased throughput of digestion that could address increased sludge production resulting from population growth or increased regulations on effluent quality,
- Increased resource recovery if return streams containing nutrients can be processed for recovery,
- Reductions in the mass of produced biosolids could reduce the need for agricultural land and winter storage.

The other major category of reports in the anaerobic digestion category addressed a variety of process enhancements. These technologies might be used instead of traditional anaerobic digesters, or could be incorporated into existing anaerobic digesters to improve performance. Reports in this category described the development of technologies including anaerobic membrane bioreactors (AnMBR), microbial electrochemical cells (MEC), the use of chemical addition and "others".

The anaerobic membrane bioreactor (AnMBR) process combines anaerobic digestion with membranes to maximize the organic loading and biogas production. Notably, Canadian companies (i.e. G.E. Water, ADI systems) have been actively involved in the development of this technology. Pilot scale demonstrations have been conducted and have the potential to be implemented in Ontario in 5 years. The 'microbial electrochemical cell (MEC)' technology is an embryonic technology that utilizes the energy generated by bacteria during anaerobic digestion to directly produce an electrical current. Reports on chemically enhanced anaerobic digestion processes have described the use of alkaline, acid or metal salts for adjusting the pH or other conditions (i.e. ionic strength) to improve performance. A limited number of publications that did not fit the previous classifications described the development of anaerobic fluidized bed reactor (AnFBR), internal circulation anaerobic digester (ICAD), gasification coupling process enhancements. When viewed collectively it can be seen that a variety of strategies/designs for anaerobic digester process enhancements have been reported. In general, there has been little large scale implementation of these technologies. If feasible, the process enhancements could be expected to assist WWTPs in responding to a similar range of drivers as those described previously for anaerobic digestion pretreatment technologies.

3.3.1.2 Other biological stabilization processes

Two minor sub-categories of reports were identified within the biological stabilization category (enhanced aerobic digestion, vermiculture). The aerobic digestion category included reports on process enhancements such as the aerobic membrane bioreactor (AeMBR), short term aerobic digestion, the use of physical and chemical pretreatments, such as ultrasound and ultrasound combined with ozone and ATAD technology (autothermal thermophilic aerobic digestion). The vermiculture sub-category included reports on the use of earthworms as well as aquatic worms for sludge stabilization

The technology developments in these latter categories may be more feasible for smaller WWTPs. Hence, there may be potential for their implementation in the large number of small WWTPs that are in Ontario. The technologies are quite diverse in nature and their potential to assist small WWTPs in responding to sludge handling drivers could be varied. It was however noted that a number of the reports addressed technologies that could achieve increased solids destruction. These may be beneficial for plants that have limited winter storage of biosolids. Further, increased solids destruction would allow small WWTPs to respond to population growth and to potential bans on landfilling of biosolids.

Table 3-4. Summary of innovative stabilization technologies

Category	Sub-Category-I	Sub-Category-II	Sub-Category-III
Biological (71)	Anaerobic Digestion (55)	Pre-treatment (40)	Chemical(10)
			Physical(18)
			Integrated (9)
			Others(3)
		Process Enhancement (15)	AnMBR(4)
			Chemical(4)
			MEC(3)
			Other (4)
	Aerobic Digestion (14)	Aerobic membrane bioreactor (AeMBR)(8)	
		Short term aerobic digestion (3)	
		Ultrasound combined with ozone(2)	
		ATAD (1)	
	Vermiculture(2)	Earthworm (1)	
		Aquatic worm (1)	
Chemical(7)	Lime(2)		
	Quicklime (5)		
Integrated(3)	Ozone/radio frequency heating (1)		
	Microwave oxidation Ozone& radio (2)		
Other(2)	Electrochemical (1)		
	Hydrothermal(1)		

3.3.2 Innovations in sludge conditioning

Reports describing developments in sludge conditioning had the second highest frequency in the literature review results (27% of total reports). A total of 71 reports described the development of conditioning technologies (Table 3-5) for the purpose of enhancing dewatering performance. The reports on conditioning process developments were further sub-categorized by mode of action into chemical, electrolysis, and integrated conditioning technologies. The largest number of reports within the conditioning category addressed chemical conditioners and these were further subcategorized on the basis of whether the chemicals acted as coagulants/flocculants or oxidants.

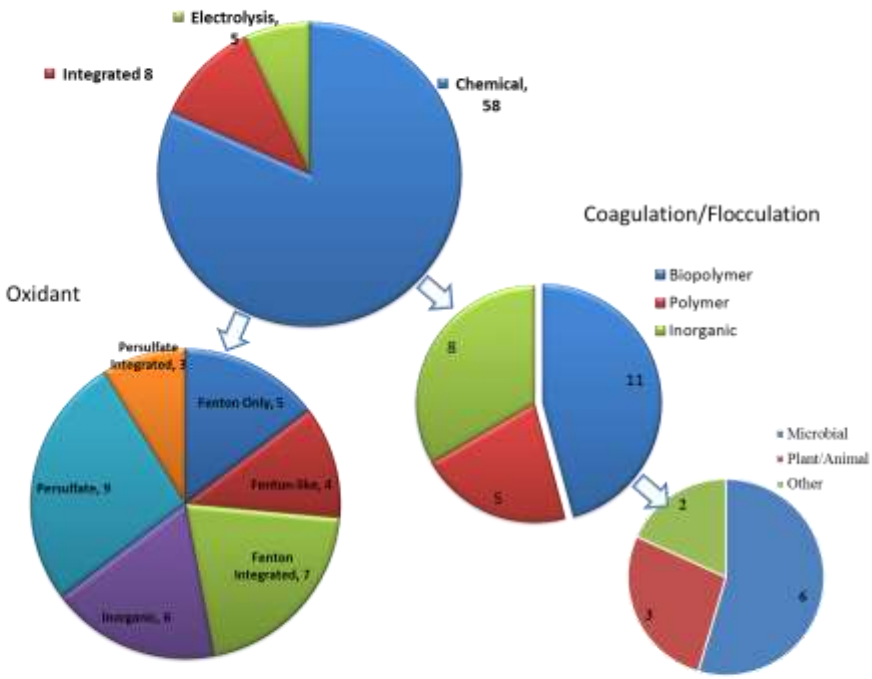

Figure 3-6. Detailed classification of innovative sludge conditioning technologies

Reports of chemical conditioners that enhanced coagulation/flocculation represented 41% of the identified literature on conditioning. Figure 3-6 describes these reports on the basis of whether the chemicals consisted of polymers or inorganic chemicals. Innovations in polymers included the use of microbial/plant based biopolymers and polyacrylamide (PAM) based coagulants. In concept, biopolymers are desirable chemicals due to their low cost, low toxicity and limited environmental footprint. Reports of innovation in inorganic coagulants typically described their integration with other coagulants (i.e. PAM with magnetic field, PAM with inorganic chemical) to enhance conditioning. However, upscaling of the production of these chemicals has not been reported and may be due to challenges/costs associated with synthesis.

Reports of the use of oxidants as chemical conditioners were also prominent in number (47.9%). Technologies based on the use of Fenton, persulfate, and inorganic oxidation were reported most frequently as shown in Figure 3-6. Fenton oxidation which includes Fenton-only, Fenton-like, and integrated Fenton chemistries combines the use of hydrogen peroxide with a ferrous iron catalyst to achieve rapid oxidation of organics. Reports of persulfate based oxidants included the use of peroxydisulfate, peroxymonosulfate or a combination of them with other physical processes (electrolysis and microwaves) for conditioning. Other oxidant studies included the use of calcium peroxide, sodium silicate with ferric chloride, alkaline ferrate, potassium ferrate, and ozone.

Table 3-5. Summary of innovative conditioning technologies

Category	Sub-Category-I	Sub-Category-II
Chemical (58)	Coagulation/ Flocculation (24)	Polymer (16)
		Inorganic (8)
	Oxidant (34)	Fenton related (16)
		Inorganic (6)
		Persulfate related (12)
Integrated (8)		
Electrolysis (5)		

The relatively large number of reports describing innovations in chemical conditioners is closely related to the growing interest in dewatering technologies. Benefits associated with improved conditioners are derived from reduced costs of dewatering, and increased solids content of the dewatered biosolids. Improved chemical conditioners are particularly attractive as they may be implemented with existing dewatering infrastructure and hence the costs of implementation can be modest. The use of improved chemical conditioners could be expected to assist WWTPs in responding to similar biosolids drivers as those described for enhanced dewatering technologies.

A number of reports described the use of electrolysis for conditioning of sludges through the application of a voltage gradient to improve disintegration and dewaterability as well reduce polymer dosage. Additional reports described the integration of chemical, physical and/or electrical treatments for conditioning. As with chemical conditioning the benefits of these additional technologies would be derived through improved dewatering. Technologies that can achieve improved dewatering with reduced chemical addition may be attractive in some facilities. They would however likely incur greater capital costs and hence may be more attractive to plants that don't currently have dewatering technology installed or are undergoing substantial upgrades.

3.3.3 Innovations in sludge dewatering

Reports on dewatering innovations were the third most commonly reported developments and represented 16% of the total number of reports. A total of 42 studies described the development of dewatering technologies (Table 3-6) and they were further sub-categorized into electro-dewatering, physical, and passive technologies. Electro-dewatering (also referred to as electro-osmotic dewatering) dominated the number of reports (23) associated with innovative dewatering technologies. Reports addressed optimization of the process through variations on the use of polyelectrolyte, metallic filter cloth and anodes/cathodes. Seven additional reports described alternative configurations of electro-dewatering technologies that were, in some cases, integrated with other technologies (i.e. bioreactors, ultrasound).

A total of 11 reports described developments in physical dewatering processes that achieved dewatering through active physical processes (other than electrolysis). These included innovations in filtration, thermal, and press dewatering processes. An additional 8 reports described investigations of passive dewatering technologies. These were processes that achieved dewatering through natural processes, rather than mechanical means. These are generally considered to be attractive in some applications due to the fact that they require little energy input. They do however require longer residence times to achieve increased sludge solids contents. Included in this section were drying beds, freeze-thaw, and reed bed/wetland dewatering. These technologies may be of interest to smaller communities that have land available and have limited operator attention.

Innovations in dewatering could represent a significant opportunity for implementation due their potential to respond to a number of the drivers that are expected to impact sludge handling in the future. Currently 13% of the WWTPs in Ontario employ dewatering processes and these are mostly large WWTPs. Improvements in dewatering at these facilities that lead to dewatered biosolids with a higher solids content would:

- reduce the need for winter storage volume that would be needed with the growing urban populations,
- increase the performance of downstream processing such as (i.e. incineration, pelletization) that is more commonly employed at larger WWTPs,
- reduce the costs of haulage of product biosolids to agricultural land.

Table 3-6. Summary of reports of innovative dewatering processes

Category	No. of Publications	Sub-Category-I	No. of Publications
Electro-Dewatering	23	ED General	16
		ED other	7
Passive	8	Drying bed	2
		Freeze-thaw	3
		Wetland	3
Physical	11	Filtration	5
		Press	2
		Thermal	4

The implementation of dewatering at the large number of smaller WWTPs that don't currently employ dewatering is a potential opportunity. However, these facilities typically have limited resources and hence the development of cost effective dewatering technologies that require limited operator attention would allow these WWTPs to respond to the following drivers:

- Increased sludge production due to population growth, changes in septage regulations and stricter discharge requirements leading to the need for increased winter storage,

- Increased biosolids haulage distances due to reductions in the availability of agricultural land,
- Flexibility to respond to fluctuations in weather patterns that constrain land application of biosolids.

3.3.4 Technology innovation on other categories

A smaller number of reports describing developments in thickening, heat drying, thermal and recovery processes (2.3%, 6.8%, 8% and 8% respectively) were identified. The following sections highlight some of these technologies.

3.3.4.1 Thickening

A total of 6 reports described the development of thickening technologies for sludge handling (Table 3-7) and were sub-categorized into flotation and membrane thickening. Electro-flotation (a combination of electrolysis and flotation) was described in three reports that addressed thickening of return and waste activated sludges. The use of membrane thickening with either ultrafiltration or microfiltration membranes as an alternative to standard thickening practices was investigated in two different studies.

Table 3-7. Summary of reports of innovative thickening technology

Category	No. of Publication
Flotation Thickening	4
Membrane Thickening	2

3.3.4.2 Disinfection and drying

A total of 15 reports that address further enhancement of biosolids quality through disinfection or drying were identified (Table 3-8). The production of disinfected biosolids may assist WWTPs in addressing the driver related to reductions in agricultural land availability. Disinfection of biosolids will allow for a greater range of disposition alternatives. Enhanced drying of sludges will reduce the volume of sludges in downstream handling and will enhance thermal reduction technologies due to the increased solids concentrations. Hence, implementation of innovative drying technologies may assist WWTPs address the following biosolids drivers:

- Energy/greenhouse gases: Increased efficiency of thermal reduction processes through enhanced drying could increase energy recovery from biosolids.
- Reductions in agricultural land: Drying will reduce haulage costs and diversify end products that both can offset this driver.
- Resource recovery: Drying of biosolids can be a necessary pretreatment for some resource recovery technologies (i.e. pyrolysis-based processes). Hence, enhancements in dewatering will enhance the feasibility of these technologies.

Table 3-8. Summary of reports on innovative disinfection and drying technologies

Category	No. of Publications	Sub-Category-I	No. of Publications
Drying	4	Direct drying	3
		Hydrothermal	1
Disinfection	11	Bio-drying	5
		Electron Beam	2
		Other	4

3.3.4.3 Thermal Reduction

A total of 22 reports described the development of thermal reduction technologies (Table 3-9). These technologies are typically employed as the final step in destruction of sludges and generally produce ash, water, and gases as by-products and may require energy input to achieve these results. Thermal reduction reports were sub-categorized into incineration and mechanical processes. Technologies involving co-incineration and fluidized bed incineration were described in nine reports that reflected new processes and innovations on established processes that use combustion to achieve solids reduction. A total of 14 reports on mechanical thermal reduction technologies were identified. These technologies differ from incineration processes in that combustion does not occur in the reduction process.

Thermal reduction technologies will likely only be implemented at large wastewater treatment plants. In this context the implementation of these technologies may assist WWTPs to respond to the following biosolids drivers:

- Thermal reduction may represent an alternative energy source. However the ability to recover the energy will depend upon the ability of upstream dewatering to produce high solids cake.
- Increased quantities of sludges as a result of increasing urban populations.
- Reductions in agricultural land availability.
- Resource recovery from mechanical thermal processes that produce oils, synthetic gases and biochars. Conversely, thermal processes create challenges for recovery of nutrients like phosphorus.

Table 3-9. Summary of innovative thermal reduction technologies

Category	No. of Publications	Sub-Category-I	No. of Publications
Incineration	8	Co-incineration	6
		Fluid bed Incineration	2
Mechanical	14	Carbonization	5
		Gasification	4
		Pyrolysis	5
SCWO	3		

3.3.4.4 Resource Recovery Processes

A total of 22 reports described the development of technologies that generate products for recovery or are suitable for alternative uses other than agricultural land application (Table 3-10). The reports were sub-categorized by technologies that produce nutrients, building materials, and fuels, respectively. Nutrients that were recovered included phosphorus, nitrogen and humic substances that can act as fertilizer improvements. Reports on production of building materials as a form of beneficial re-use included generation of aggregates, ceramics, bricks, tiles, and cement. Reports on innovations in generation of fuels included production of biodiesel, bio-hydrogen and lipids. The ‘biogas improvement' process specifically aims to enhance the removal of harmful impurities in biogas (i.e. sulfide) or prohibit their initial formation during the stabilization process.

Table 3-10. Summary of innovative resource recovery technologies

Category	No. of Publications
Fuels	4
Materials	6
Nutrients	12
Biogas Improvement	3
Bioleaching of heavy metals	1

Increased resource recovery at WWTPs has been recognized as a driver that will influence sludge handling technologies in the future. To date, phosphorous has been the most commonly recognized nutrient for recovery due to the limited reserves of mineral phosphorous. However, only a modest number of full scale implementations of phosphorous recovery have been demonstrated in the province. In addition, there has been negligible implementation at any scale of most other alternative recovery technologies. It can be expected that the demand for in-plant recovery technologies will increase as the availability of agricultural land for nutrient recovery declines. Technologies that recover fuels from sludges may also become attractive as the focus on energy neutrality and GHG reduction increase.

3.4 Commercial technologies

In total, 39 innovative commercial sludge processing technologies from various companies were documented in this study (Tables 3.11 to 3.14). Detailed information regarding geographic identification, technical innovation, scale of development and existing industry implementation are presented in Appendix C.

Technologies and/or companies that focus on innovation in sludge stabilization were found to represent 44% of the commercial reports. Table 3-11 summarizes 17 technologies/companies that were identified in this category. It can be seen that 16 of the companies have integrated anaerobic digestion process with other technologies (i.e. thermal hydrolysis, MBR technology, electrolysis electron beam or ultrasound) to enhance the performance of sludge handling. Most of these companies are located in North America and Europe, and 77% of the technologies have been demonstrated at full scale. It is clear that the market for development of anaerobic digestion technologies is highly developed. Further, Canadian-based companies are actively marketing innovative technologies in this category.

From Table 3-11 it can be seen that relatively few innovative technologies based on aerobic stabilization were identified. The limited innovation in this sector is in contrast with the large number of small and mediums sized WWTPs in Ontario that employ this type of technology. The apparent gap in this portion of the market may represent an opportunity for new technologies. Technology innovation in this area may assist small and medium scale WWTPs to address the following biosolids drivers:

- Energy/greenhouse gases: Aerobic stabilization processes are typically energy intensive. Aerobic technologies that can stabilize sludges with reduced energy requirements would assist these WWTPs to reduce energy consumption.
- Changing populations: Small "destination" communities that are experiencing population growth would benefit from technologies that can increase aerobic digester capacity.
- Changes in septage regulations: Septage reception at smaller rural WWTPs will increase loadings on sludge stabilization. Technologies that can stabilize sludges with a high septage fraction would be of benefit to these facilities.

Table 3-11. Commercial stabilization technologies

Technology	Process	Technical Innovation	Location	Scale
OVIVO - Pre-Thickened Aerobic Digestion	AD	Pre-thickened	Canada/Germany	Full
Lysotherm Thermal Pressure Hydrolysis	ANAD	Thermal Hydrolysis	Netherlands	Full
(Trojan) USP PRI-DE® Digester Enhancement	ANAD	Biogas Improvement	Canada	Full
GE AnMBR Technology	ANAD	AnMBR	Canada	Full
GE Monsal Advanced Digestion Technology (ADT)	ANAD	General	Canada	Full
OVIVO BioAlgaNyx Algae Treatment	ANAD	Algae	Canada/Germany	Pilot
Lystek's Low Temperature Alkaline Hydrolysis Process	ANAD	Thermal Hydrolysis	Canada	Full
Cambi THP	ANAD	Hydrothermal	Norway	Full
Biothelys	ANAD	Thermal hydrolysis	International	Full
Anaergia - Omnivore	ANAD	Co-digestion thickening	Canada	Full
BioElectro	AD/ANAD	In-line/ Electrolysis	US	Pilot
Electron Beam Enhanced Anaerobic Digestion	AD/ANAD	Electron Beam	US	Full
Sustec Turbotec	AD/ANAD	Thermal	Netherlands	Full
PONDUS - Thermo-Chemical Hydrolysis Process	AD/ANAD	Thermal Hydrolysis	Germany/US	Full
EXELYS	AD/ANAD	Thermal Hydrolysis	US/China/Denmark	Full

Note: AD: Aerobic Digestion ANAD: Anaerobic Digestion

A number of innovative commercial thermal reduction technologies were identified in this study (Table 3-12). Most of the companies focusing on thermal reduction were identified to be located in the United States and Europe and no Canadian based companies were identified. Thermal reduction technologies are generally quite complex and hence tend to only be employed at large WWTPs. While several municipalities in Ontario currently employ incineration of biosolids, their configurations are generally conventional in nature. The implementation of innovative technologies in the category may assist large WWTPs to address the following biosolids drivers:

- Energy/greenhouse gases: Thermal technologies that can recover energy and/or alternative fuels from biosolids may be of benefit.
- Changing populations: Large WWTPs that are receiving increased wastewater flows due to increased population densities will need to process sludges within space constrained facilities. Advanced thermal reduction technologies may provide a solution in this regard.
- Reductions in agricultural land availability: Haulage distances from large urban WWTPs will likely increase over time. Advanced thermal technologies may provide a viable alternative method of disposition of biosolids
- Increased emphasis on resource recovery: Innovative thermal technologies can generate alternative products of value including fuels and chars that support resource recovery initiatives.

Table 3-12. Commercial thermal reduction technologies

Technology	Process	Innovation	Location	Scale
ZIP-Carb	Mechanical	Hydrothermal	US	Pilot
AquaCritox	Mechanical	Hydrothermal	Ireland	Pilot
Genifuel	Mechanical	Gasification	US	Full
Biocon	Drying	Low temperature	International	Full
BFT Biosolids	Drying	Bio-drying	US	Full
Pyrofluid	Incineration	Fluidised-bed	International	Full
Seaborne Technology	Incineration	Integration	Germany	Full
Savron STARx Smoldering	Incineration	Smolder combustion	Scotland/Canada	Full

Table 3-13 summarizes innovative commercial technologies that indicate a contribution to resource recovery. For the purposes of this study the term resource recovery implies recovery of novel products of value that go beyond traditional recovery strategies such as the production of biogas from anaerobic digestion and recovery of nutrients through application of biosolids to agricultural lands. A review of Table 3-13 reveals that phosphorous is the most common resource targeted for recovery by commercial technologies and Canadian companies (Lystek and Ostara) are active in this category. The other technologies identified in Table 3-13 address a variety of products including fertilizer, biochar, sulfur, cellulose, etc.

To date, only a modest number of implementations of innovative resource recovery technologies have been implemented at WWTPs in Ontario. For the purpose of this report resource recovery was identified as a driver for biosolids management in the future. The results suggest that there is considerable potential for technology implementation in this area as municipalities move towards a circular society paradigm.

Table 3-13. Commercial resource recovery technologies

Technology	Recovered product	Location	Scale
BCR Neutralizer/ CleanB /CleanB-AC	Fertilizer	USA	Full
Lystek	Fertilizer	Canada	Full
AirPrex	Phosphorus	Germany/US	Full
WASSTRIP (Ostara)	Phosphorus	Canada	Full
N-E-W Tech	Phosphorus	USA	Pilot
Biodryer	Biochar	USA	Pilot
Recyllose ™	Cellulose	USA	Pilot
Hydrothermal Liquefication Technology	Biocrude	USA	Full

An additional 6 commercial technologies that address a variety of sludge handling goals were identified and categorized as “other” (Table 3-14). These technologies generally represent innovations in conditioning, thickening and dewatering. The individual technologies address a variety of the biosolids drivers, especially those that would benefit from a reduction in the volume of produced biosolids.

Table 3-14. Other innovative commercial technologies

Technology	Process	Innovation	Location	Scale
SLG Advanced Dewatering	Dewatering	Energy reduction	Germany/France/ US	Full
Metso SDO	Dewatering Optimization	Control	Finland	Full
Salsnes Filtration(Trojan)	Wastewater Filtration, Thickening	Press	Canada	Full
Kemicond Technology	Conditioning	Oxidant	US	Full
Ovivo Sonolyzer	Conditioning	Ultrasound	International	Full
Athos	Conditioning	Hydrothermal oxidation	International	Full
SOLIAMIX	Drying	Solar	International	Full

4 Opportunities for innovative technology implementation

In this section, the potential opportunities for implementing innovative technologies for sludge processing and biosolids management in Ontario are discussed. The discussion is presented in the context of the drivers that are anticipated to impact on WWTPs in the near to middle future. The drivers are not completely independent from each other and some are more certain than others. For example, some depend upon regulatory changes that are somewhat uncertain while others such as population change are well documented. However, the extent and type of population change that will occur in the future has some uncertainty. This section provides a high level synthesis of discussions that are presented in the earlier sections of the report.

4.1 Energy/Greenhouse Gases

There is an increased interest in reducing energy consumption and greenhouse gas emissions at wastewater treatments. Innovations that would assist WWTPs to address this driver include:

- Development of anaerobic digestion technologies that are viable in smaller WWTPs. There are a number of commercially available technologies that can provide enhanced anaerobic digestion but they have primarily focused on medium and large scale WWTPs. A number of sludge pretreatment technologies have been developed but there has been limited implementation.
- Advanced thermal reduction technologies that are capable of energy recovery/and or fuels production while allowing recovery of nutrients. Current thermal technologies that are employed in the province may provide some energy recovery but solids destruction appears to be the primary objective for these systems. Innovations in sludge drying could further increase the viability of thermal reduction technologies.
- High efficiency aerobic digestion technologies with reduced energy consumption. There are a large number of aerobic digesters employed at small and medium

sized WWTPs that tend to be energy intensive. Relatively few reports on innovation in aerobic digestion and few innovative commercial aerobic digestion technologies were identified.

4.2 Changing populations

The growth in population of large cities/regions (i.e. Toronto, Ottawa, Halton, Peel, York, Niagara, Waterloo) and in some "destination" smaller communities (i.e. Collingwood) have ramifications for sludge processing and biosolids management including:

- longer distances to haul biosolids to agricultural lands,
- incentives for scale-driven change in technologies,
- incentives for the generation of biosolids products with local use in an urban environment.

Innovations that would assist WWTPs to address this driver include:

- Enhancements in sludge conditioning/thickening and dewatering that increase process efficiency and produce dewatered biosolids of higher solids content. There has been considerable activity in this regard in the research literature (i.e. electro-dewatering) but implementations in Ontario are modest.
- The implementation of advanced thermal reduction technologies increases in viability at large scale (see discussion in Section 4.1).
- The implementation of digestion enhancements that increase capacity (i.e. sludge pretreatment technologies). Thermal hydrolysis technologies have been implemented internationally but there has been little uptake in Canada.
- The implementation of technologies that provide higher quality products (i.e. disinfection) will diversify the disposition opportunities and may increase local usage.

By contrast there are examples of communities with decreasing populations in a number of more remote communities (typically natural resource driven economies). WWTPs in these communities will have fewer resources to operate and maintain sludge handling systems. Innovations that would assist WWTPs to address this driver include:

- Passive technologies that require minimal operator attention.
- Low cost thickening and dewatering technologies that reduce haulage and disposition costs.

4.3 Reductions in Agricultural Land Availability

Over time, the availability of agricultural land, which is currently the major pathway for disposition of biosolids, is declining. The implications for sludge processing and biosolids management include:

- greater haulage distances of biosolids from WWTPs to suitable fields,
- incentives for generation of products that have disposition paths other than agricultural land.

Innovations that would assist WWTPs to address this driver include:

- Enhanced conditioning, thickening and dewatering technologies. For larger WWTPs there would be a benefit in obtaining higher solids content product to reduce haulage. The development of technologies that support smaller WWTPs would increase implementation. There is currently little use of these technologies in small WWTPs.
- The implementation of advanced thermal reduction technologies (see discussion in Section 4.1).
- The implementation of digestion enhancements that increase solids destruction (i.e. sludge pretreatment technologies; see Section 4.1).
- Implementation of technologies capable of producing biosolids of higher quality to support alternative disposition practices (see section 4.2).

4.4 Changes in Septage Disposition

It is anticipated that the regulatory regime will change such that there will be increased handling of septage at wastewater treatment plants. Since most septage is generated in rural communities, this material will mostly be destined for small and medium size WWTPs and hence there will be a corresponding increase in the quantity of sludges processed in small WWTPs. In addition, while septage treatment will increase the mass of sludges treated, their properties will be somewhat different from those of raw sludges as the septage will already be partially stabilized. Hence, the changes in feedstock may drive a change in technologies with less stabilization and more thickening/dewatering. Innovations that would assist WWTPs to address this driver include:

- Development of thickening and dewatering technologies that address septage solids in small WWTPs (see section 4.3).
- Implementation of technologies capable of producing biosolids of higher quality to support alternative disposition practices (see section 4.2).

4.5 Changes in Landfill Regulations

The possibility of banning disposition of biosolids into landfills has been considered. This is currently a relatively common pathway for disposition of biosolids under a variety of operating conditions. The ramifications of this type of regulation on sludge processing and biosolids management include:

- the need for additional winter storage capacity for some facilities,
- emergency dewatering when storage volumes for liquid biosolids are exceeded.

Innovations that would assist WWTPs to address this driver include:

- Development of thickening and dewatering technologies in small and medium size WWTPs that support increased storage (see section 4.3).

4.6 Increased Emphasis on Resource Recovery

In Ontario, the disposition of biosolids onto agricultural land has historically been employed for recovery of nutrients and organics. There is however an interest in the wastewater treatment industry to maximize the recovery of value-added products from wastewater as this pathway diminishes in feasibility. Further, the generation of additional products such as fuels (beyond traditional biogas) and other products that diversify end uses and perhaps have higher value (i.e. bioplastic monomers) are gaining attention. Innovations that would assist WWTPs to address this driver include:

- Further innovation and implementation of technologies capable of recovering phosphorous and nitrogen. Commercial technologies exists in this regard but their implementation to date has been modest.
- Advanced thermal reduction technologies that are capable of energy recovery/and or fuels production while allowing recovery of nutrients. The growth of larger cities may provide the conditions that are supportive of use of these technologies. Enhancements in supporting technologies such as drying would increase the viability of thermal reduction technologies.
- Integration of resource recovery with technologies that achieve increased solids destruction. For example, recovery of nutrients from dewatering return streams downstream of advanced anaerobic digestion processes.

4.7 **Increasingly stringent regulations on wastewater discharges**

The regulations on wastewater discharges have historically increased in stringency over time. Most recently, the federal Wastewater Systems Effluent Regulations (2012) were introduced and require all WWTPs to achieve a secondary level of treatment. The changes in effluent quality can be expected to result in changes in the quantity and quality of generated sludges. Currently, this driver is most relevant to smaller rural WWTPs. Innovations that would assist WWTPs to address this driver include:

- Passive technologies that require minimal operator attention,
- Low cost thickening and dewatering technologies that reduce haulage and disposition costs,
- High efficiency aerobic digestion technologies with reduced energy consumption. Aerobic digesters employed at small and medium sized WWTPs tend to be energy intensive (Section 4.1).

5 Glossary

Biogas: Gas produced by the fermentation of organic matter including, sewage sludge, under anaerobic conditions. Biogas is comprised primarily of methane and carbon dioxide

Biosolids: Solids generated from the treat of sewage sludge with processes such as anaerobic digestion, aerobic digestion, lime stabilization, etc.

Greenhouse Gases: Gases in the atmosphere that contribute to Climate Change. Those gases include but are not limited to, carbon dioxide, methane and nitrous oxides.

Sewage Sludge: Excess solids produced in municipal wastewater treatment plants Innovation.

Thickening: The process used to increase the solids content of sludge by the separation and removal of a portion of the liquid phase.

Conditioning: Sludge conditioning is a process whereby sludge solids are treated with chemicals or various other means to prepare the sludge for dewatering processes to improve dewatering characteristics of the sludge.

Stabilization: A chemical or biological process that stops the natural fermentation of the sludge.

Dewatering: The reduction of floc-bound and capillary water content of sludges

Disposition: Sludge disposition herein refers to the final management route for the treated biosolids and commonly includes either landfill, agricultural land application, etc.

Incineration: A waste treatment process that involves the combustion of organic substances contained in waste materials.

Septage: Partially treated sludge stored in a septic tank.

6 Abbreviations

AD	Aerobic Digestion
ANAD	Anaerobic Digestion
AnMBR	Anaerobic membrane bioreactors
AnFBR	Anaerobic fluidized bed reactor
AeMBR	Aerobic membrane bioreactor
ATAD	Autothermal thermophilic aerobic digestion
DHC	Design hydraulic capacity
DOI	Digital Object Identifier
ED	Electro-Dewatering
GHG	Greenhouse gases
ICAD	Internal circulation anaerobic digester
MOECC	Ontario Ministry of Environment and Climate Change
MEC	Microbial electrochemical cells
MBR	Membrane bioreactor
NASM	Non-Agricultural Source Materials
OCWA	Ontario Clean Water agency
PAM	Polyacrylamide
SCWO	Supercritical Water Oxidation
SOWC	Southern Ontario Water Consortium
USEPA	United States Environmental Protection Agency
WWTP	Wastewater treatment plant

7 Reference

Bogner J., Pipatti R., Hashimoto S., Diaz C., Mareckova K., Diaz L., Kjeldsen P., Monni S., Faaij A. and Gao Q. (2008). Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). *Waste Manage Res.* **26**(1), 11-32.

Burton F. L., Stensel H. D. and Tchobanoglous G. (2014). Wastewater engineering: treatment and Resource recovery. McGraw-Hill.

Cakir F., Stenstrom M. (2005). Greenhouse gas production: a comparison between aerobic and anaerobic wastewater treatment technology. *Water Res.* **39**(17), 4197-4203.

Global Biosolids Market - By Application, Class, Form, and Regions - Market Trends and Demand Forecasts (2016-2022), March. 2017. https://www.researchandmarkets.com//research/cmxg62/global_biosolids

Kelessidis A., Stasinakis A. S. (2012). Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. *Waste Manage.* **32**(6), 1186-1195.

Karlsson, G. (2007). Kemicond – Kemira sludge conditioning technology. Available at www.ril.fi/Resource.phx/jaosto/jaosto-vesi/vyseminaari.htx.i1163.ppt.

Müller, J. A., Günther, L., Dockhorn, T., Dichtl, N., Phan, L. C., Urban, I& Bayerle, N. (2007). Nutrient recycling from sewage sludge using the Seaborne process. In Conference, Proceedings on Moving Forward Wastewater Biosolids Sustainability: Technical, Managerial, and Public Synergy (pp. 629-633). GMSC.

Majumder R., Livesley S. J., Gregory D. and Arndt S. K. (2014). Biosolid stockpiles are a significant point source for greenhouse gas emissions. *J Environ Manage.* **143**, 34-43.

Mata-Alvarez J., Mace S. and Llabres P. (2000). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresour Technol.* **74**(1), 3-16.

Ontario Ministry of the Environment and Climate Change. (2012). Ontario Compost Quality Standards. https://www.ontario.ca/page/ontario-compost-quality-standards

Ontario Ministry of the Environment and Climate Change. (2002). Non-Agricultural Source Materials (NASM), http://www.omafra.gov.on.ca/english/nm/nasm.html

Wastewater Systems Effluent Regulations (SOR/2012-139), http://laws.justice.gc.ca/eng/regulations/SOR-2012-139/page-1.html

Appendix A:

Additional information for Metal concentrations

Information on concentrations of individual metals in the category of non-concern metals (cadmium, cobalt, chromium and lead), medium-concern metal (nickel and zinc) and high-concern metals (selenium and molybdenum) are presented in this section, as a function of the annual biosolids production (m^3/year for liquid solid and tonnes/year for dewatered biosolid) respectively.

A.1 Non-concern metals

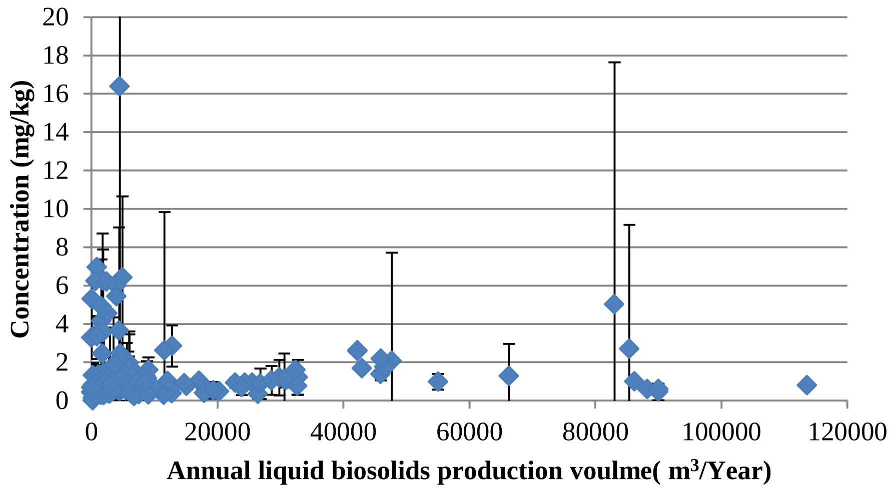

Figure A- 1. Cadmium concentrations vs annual liquid biosolids production

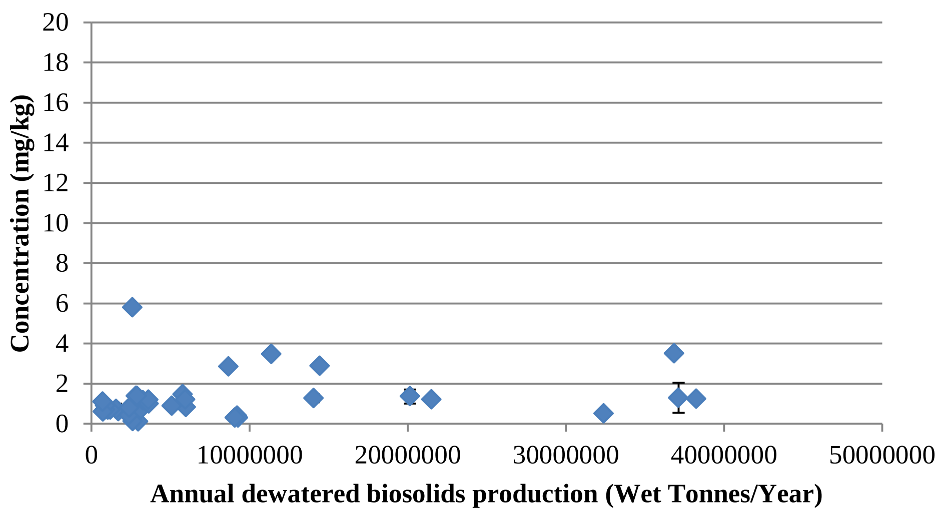

Figure A- 2. Cadmium concentrations vs annual dewatered biosolids production

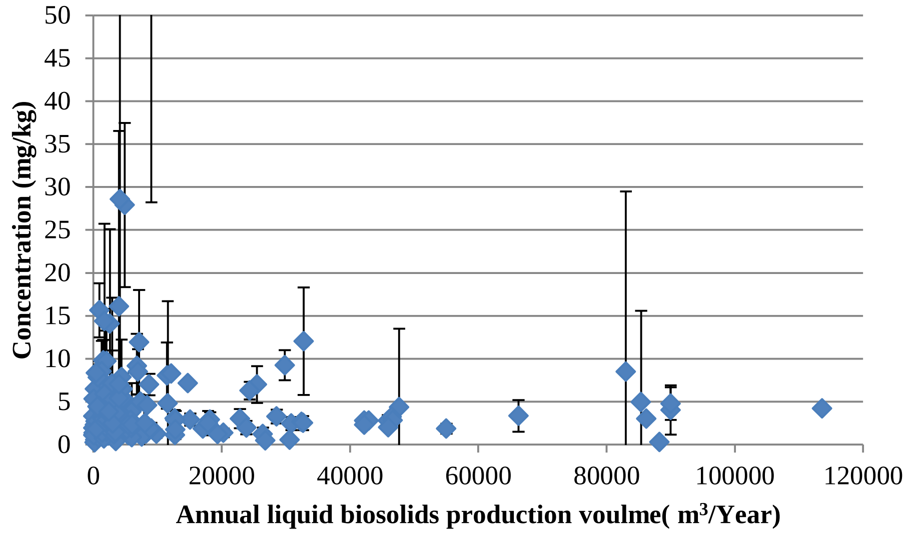

Figure A- 3. Cobalt concentrations vs annual liquid biosolids production

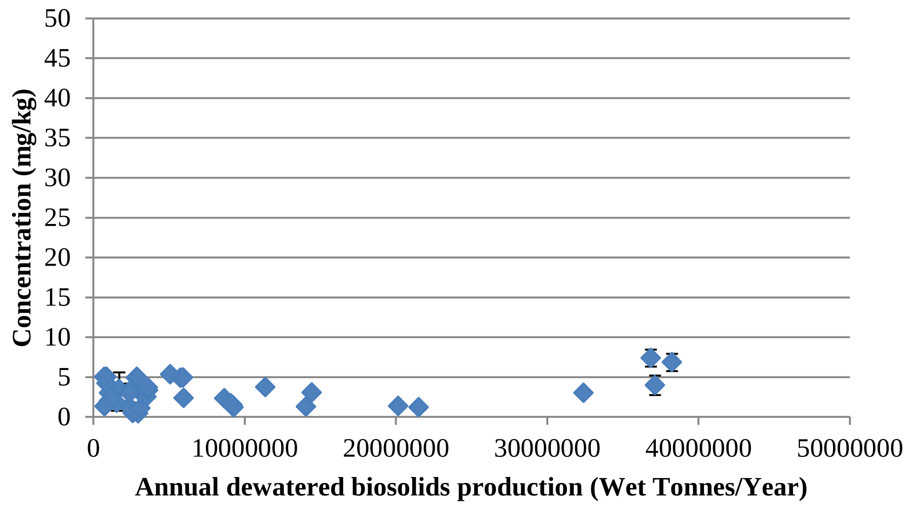

Figure A- 4. Cobalt concentrations vs annual dewatered biosolids production

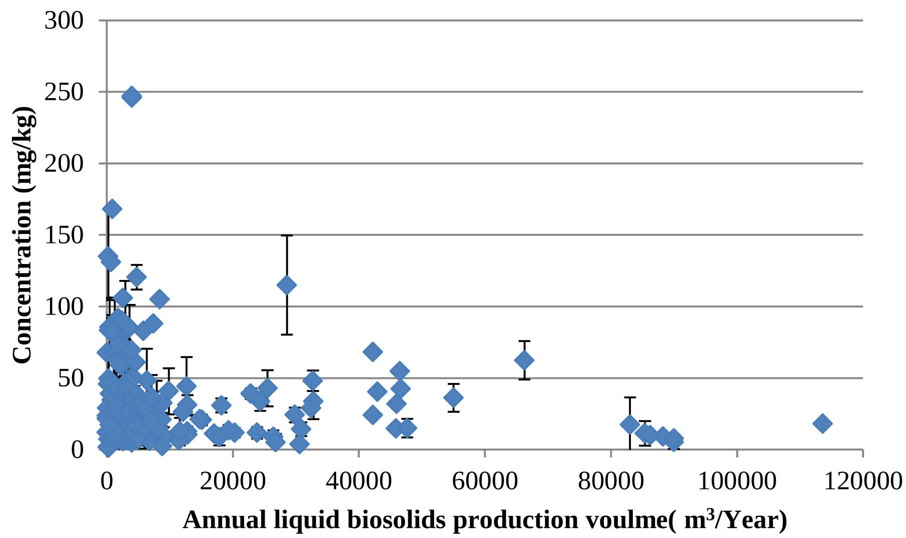

Figure A- 5. Chromium concentrations vs annual liquid biosolids production

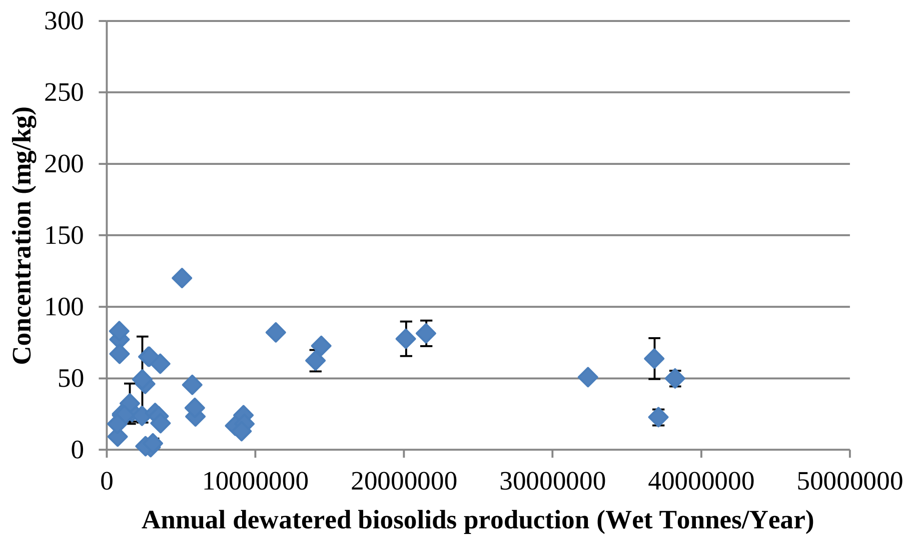

Figure A- 6. Chromium concentrations vs annual dewatered biosolids production

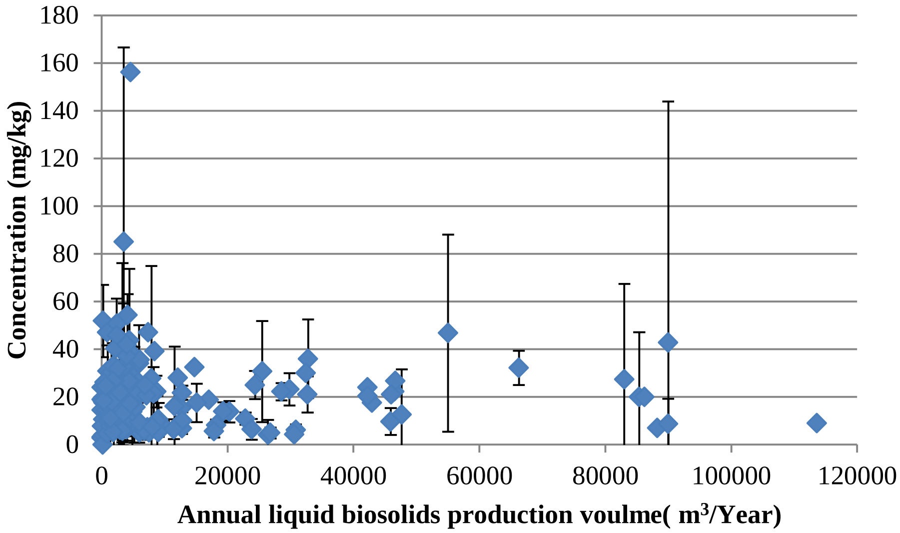

Figure A- 7. Lead concentrations vs annual liquid biosolids production

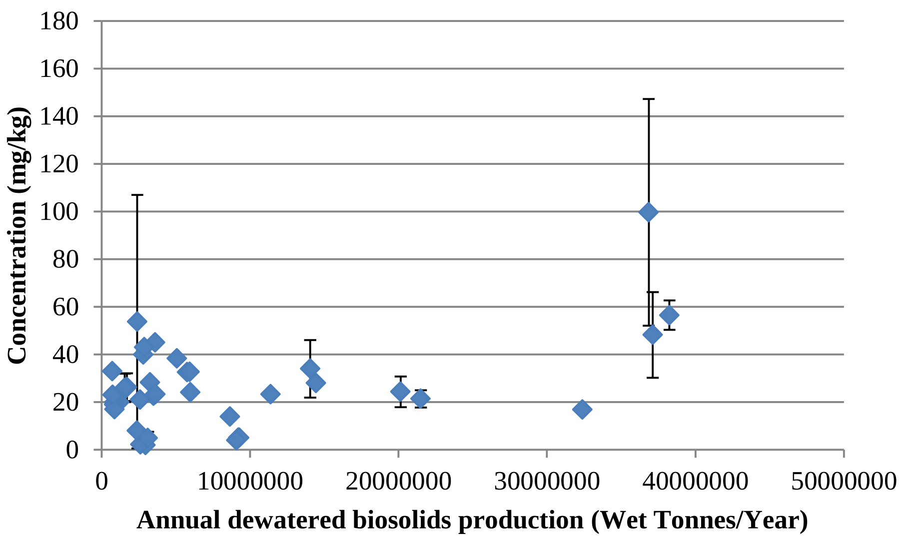

Figure A- 8. Lead concentrations vs annual dewatered biosolids production

A.2 Medium-concern metals

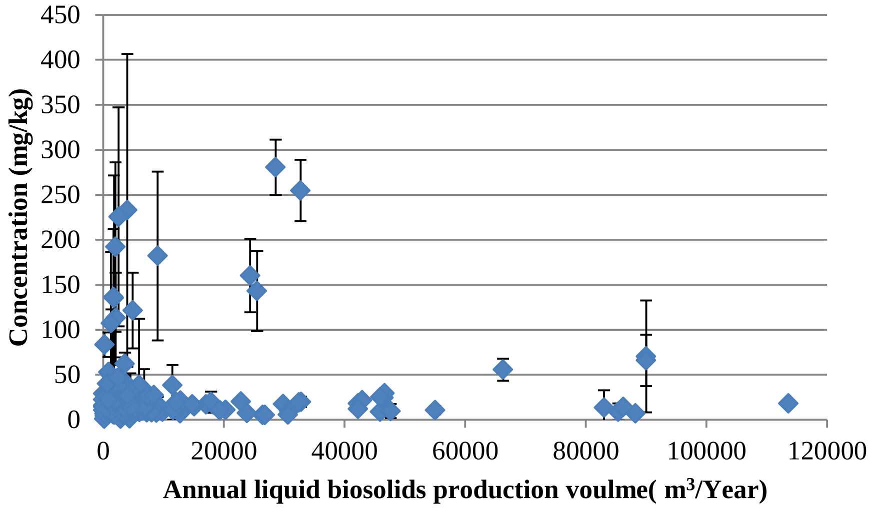

Figure A- 9. Nickel concentrations vs annual liquid biosolids production

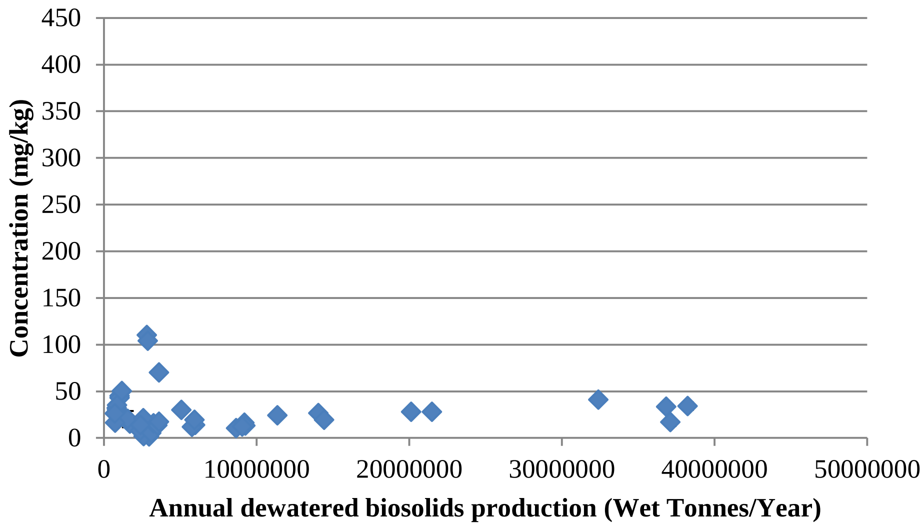

Figure A- 10. Nickel concentrations vs annual dewatered biosolids production

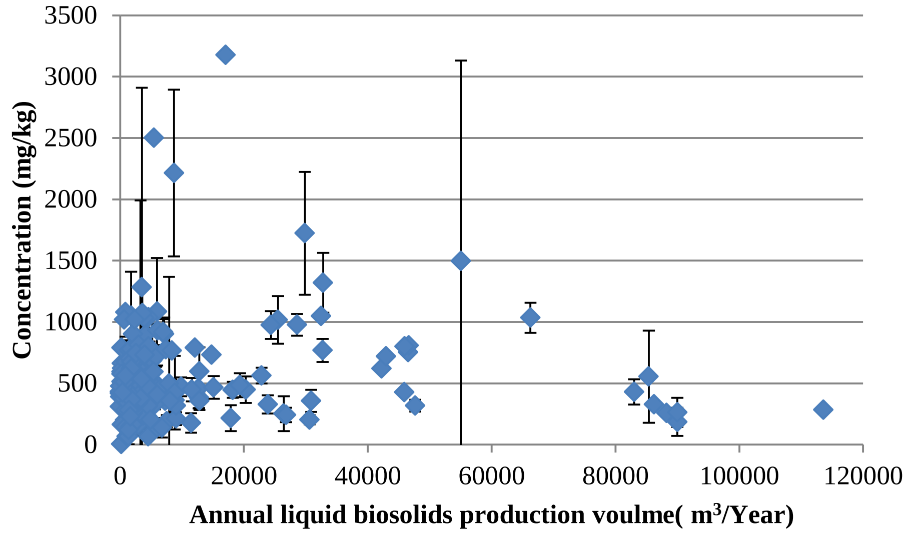

Figure A- 11. Zinc concentrations vs annual liquid biosolids production

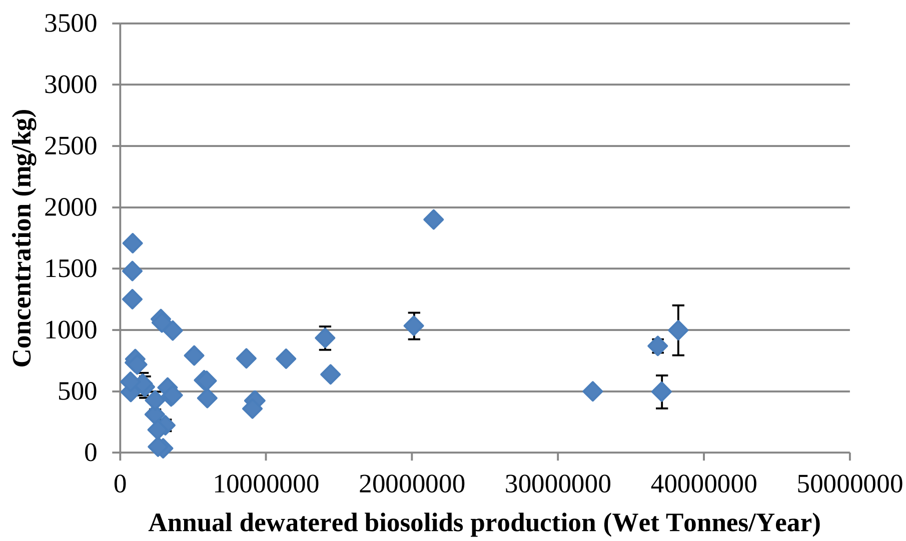

Figure A- 12. Zinc concentrations vs annual dewatered biosolids production

A.3 High-concern metals

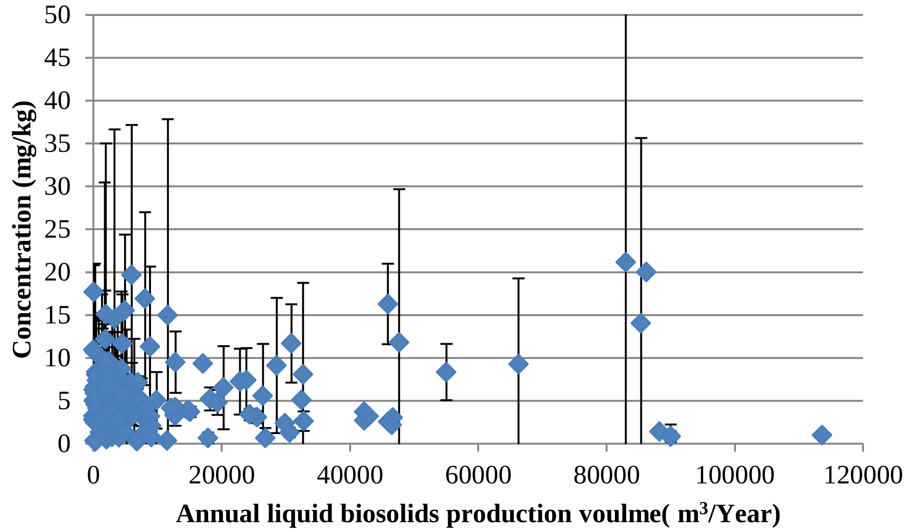

Figure A- 13. Selenium concentrations vs annual liquid biosolids production

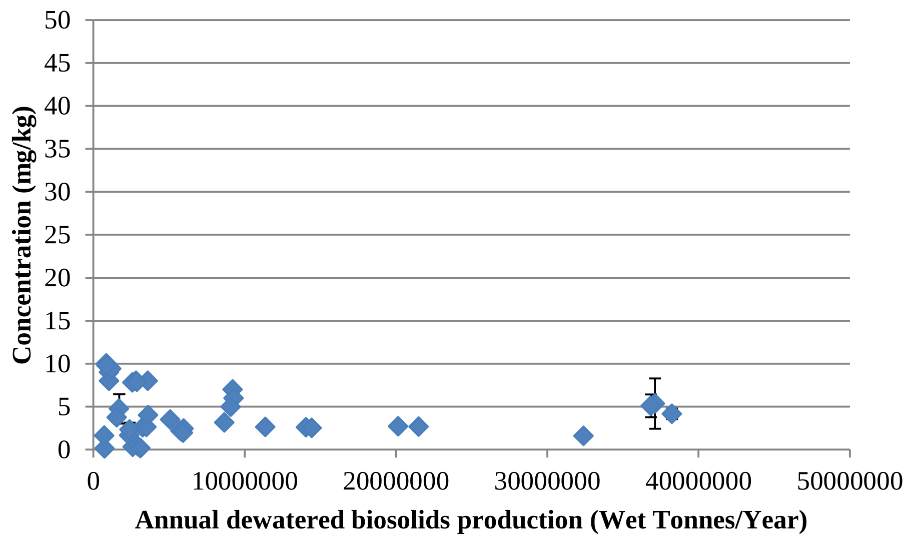

Figure A- 14. Selenium concentrations vs annual dewatered biosolids production

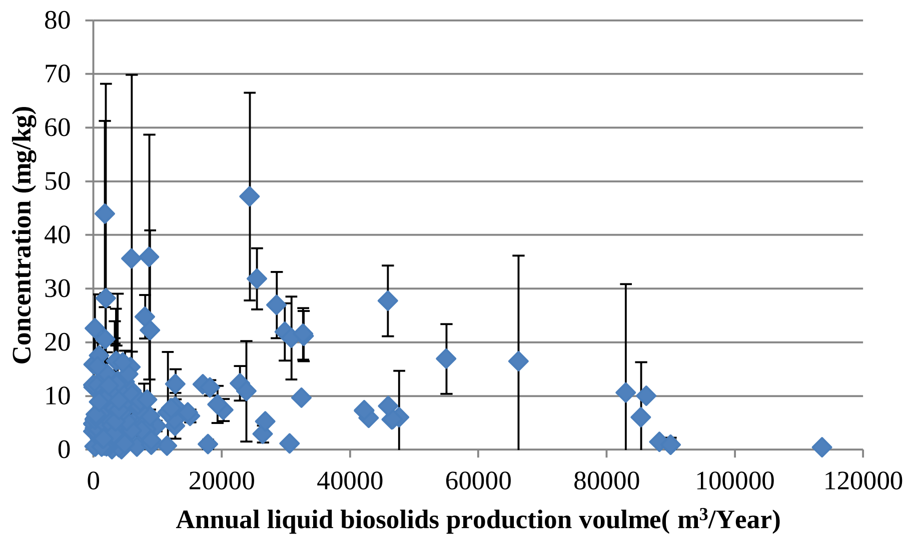

Figure A- 15. Molybdenum concentrations vs annual liquid biosolids production

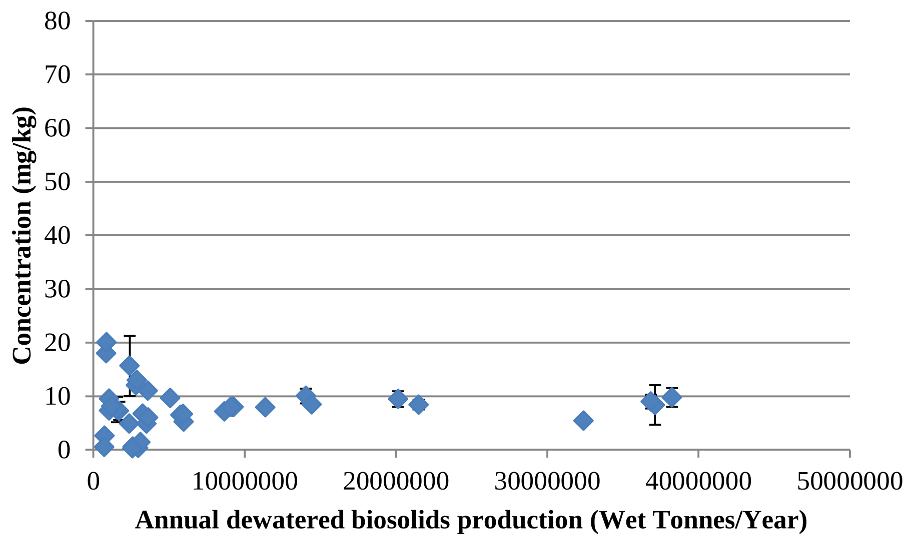

Figure A- 16. Molybdenum concentrations vs annual dewatered biosolids production

Appendix B:

DOI list for peer-reviewed literature

Table B- 1. DOI List of literature for sludge conditioning

Title	DOI
Stimulation of anaerobic digestion of thickened sewage sludge by iron-rich sludge produced by the fenton method	10.1263/jbb.106.107
The study of Na2SiO3 as conditioner used to deep dewater the urban sewage dewatered sludge by filter press	10.1016/j.seppur.2016.11.004
Development of montmorillonite-supported nano CaO2 for enhanced dewatering of waste-activated sludge by synergistic effects of filtration aid and peroxidation	10.1016/j.cej.2016.08.096
Enhanced sludge dewatering and drying comparison of two linear polyelectrolytes co-conditioning with polyaluminum chloride	10.1080/19443994.2016.1178602
Enhancing the sludge dewaterability by electrolysis/electrocoagulation combined with zero-valent iron activated persulfate process	10.1016/j.cej.2016.06.041
Biosynthesised magnetic iron nanoparticles for sludge dewatering via Fenton process	10.1007/s11356-016-7351-4
Enhancement of waste activated sludge dewaterability using calcium peroxide pre-oxidation and chemical re-flocculation	10.1016/j.watres.2016.07.018
Enhanced dewatering of excess activated sludge through decomposing its extracellular polymeric substances by a Fe@Fe2O3-based composite conditioner	10.1016/j.biortech.2016.06.139
Disintegration of Waste Activated Sludge by Thermally-Activated Persulfates for Enhanced Dewaterability	10.1021/acs.est.6b00019
Impact of microwave treatment on dewaterability of sludge during Fenton oxidation	10.1080/19443994.2015.1065765
Dewatering and removal of metals from urban anaerobically digested sludge by Fentonâ€™s oxidation	10.1080/09593330.2016.1199598
Effect of inorganic coagulant addition under hydrothermal treatment on the dewatering performance of excess sludge with various dewatering conditions	10.1007/s10163-016-0522-z
The impact of peroxydisulphate and peroxymonosulphate on disintegration and settleability of activated sludge	10.1080/09593330.2015.1112434
Roles of iron species and pH optimization on sewage sludge conditioning with Fenton's reagent and lime	10.1016/j.watres.2016.03.016
A novel approach for simultaneous improvement of dewaterability, post-digestion liquor properties and toluene removal from anaerobically digested sludge	10.1016/j.cej.2016.01.103
Enhanced dewaterability of waste activated sludge by Fe(II)-activated peroxymonosulfate oxidation	10.1016/j.biortech.2016.01.088
Microwave-acid pretreatment: A potential process for enhancing sludge dewaterability	10.1016/j.watres.2015.12.012
Improvement of settleability and dewaterability of sludge by newly prepared alkaline ferrate solution	10.1016/j.cej.2015.11.037

Changes of physicochemical properties of sewage sludge during ozonation treatment: Correlation to sludge dewaterability	10.1016/j.cej.2016.04.151
Beneficial effects of treating waste secondary sludge with thermally activated persulfate	10.1002/jctb.5108
A Fenton-like process for the enhanced activated sludge dewatering	10.1016/j.cej.2015.03.034
Optimisation of extraction and sludge dewatering efficiencies of bio-flocculants extracted from Abelmoschus esculentus (okra)	10.1016/j.jenvman.2015.04.028
The characteristics of sludge from enhanced coagulation processes using PAC/PDMDAAC composite coagulants in treatment of micro-polluted raw water	10.1016/j.seppur.2015.04.015
Bioflocculant from pre-treated sludge and its applications in sludge dewatering and swine wastewater pretreatment	10.1016/j.biortech.2015.07.113
A rapid Fenton treatment technique for sewage sludge dewatering	10.1016/j.cej.2015.02.001
Synthesis, characterization, and secondary sludge dewatering performance of a novel combined silicon-aluminum-iron-starch flocculant	10.1016/j.jhazmat.2014.12.005
Optimizing chemical conditioning for odour removal of undigested sewage sludge in drying processes	10.1016/j.jenvman.2014.11.012
Effects of different sludge disintegration methods on sludge moisture distribution and dewatering performance	10.1016/j.jes.2014.06.040
Dual-conditioning of sludge using chitosan and metal cations	10.2166/wpt.2015.047
Chitosan use in chemical conditioning for dewatering municipal-activated sludge	10.2166/wst.2014.532
Feasibility of bioleaching combined with Fenton oxidation to improve sewage sludge dewaterability	10.1016/j.jes.2014.05.039
Enhanced dewaterability of waste-activated sludge by combined cationic polyacrylamide and magnetic field pretreatment	10.1080/09593330.2014.952341
Ultrasound, thermal and alkali treatments affect extracellular polymeric substances (EPSs) and improve waste activated sludge dewatering	10.1016/j.procbio.2015.01.001
Enhanced dewaterability of sewage sludge with zero-valent iron-activated persulfate oxidation system	10.2166/wst.2015.206
Coagulant and polyelectrolyte application performance testing in sonicated sewage sludge dewatering	10.1080/19443994.2014.989632
Ferric biogenic flocculant produced by Acidithiobacillus ferrooxidans enable rapid dewaterability of municipal sewage sludge: A comparison with commercial cationic polymer	10.1016/j.ibiod.2014.09.001
Improving dewaterability of waste activated sludge by combined conditioning with zero-valent iron and hydrogen peroxide	10.1016/j.biortech.2014.10.009
Impact of ultrasonic treatment on dewaterability of sludge during Fenton oxidation	10.1007/s10661-014-3988-y

A novel acrylamide-free flocculant and its application for sludge dewatering	10.1016/j.watres.2014.03.047
Enhanced dewatering characteristics of waste activated sludge with Fenton pretreatment: Effectiveness and statistical optimization	10.1007/s11783-013-0530-3
Characterization and evaluation of dewatering properties of PADB, a highly efficient cationic flocculant	10.1021/ie403635y
Effective water content reduction in sewage wastewater sludge using magnetic nanoparticles	10.1016/j.biortech.2013.12.003
Optimized production of a novel bioflocculant M-C11 by Klebsiella sp. and its application in sludge dewatering	10.1016/j.jes.2014.08.007
Enhanced dewaterability of anaerobically digested sewage sludge using Acidithiobacillus ferrooxidans culture as sludge conditioner	10.1016/j.biortech.2014.06.057
Study on dewaterability of municipal sludge conditioning by physical conditioners with ultrasonic and magnetic field application	10.1080/19443994.2013.821038
Combined effects of Fenton peroxidation and CaO conditioning on sewage sludge thermal drying	10.1016/j.chemosphere.2014.09.038
Microwave-assisted chemical oxidation of biological waste sludge: Simultaneous micropollutant degradation and sludge solubilization	10.1016/j.biortech.2013.07.043
Dewaterability of sewage sludge by ultrasonic, thermal and chemical treatments	10.1016/j.cej.2013.06.046
Addition of polyaluminiumchloride (PACl) to waste activated sludge to mitigate the negative effects of its sticky phase in dewatering-drying operations	10.1016/j.watres.2013.04.012
Influence of nanoparticles on the polymer-conditioned dewatering of wastewater sludges	10.2166/wst.2013.097
Synthesis, characterization and application of a novel starch-based flocculant with high flocculation and dewatering properties	10.1016/j.watres.2013.01.050
Innovative combination of electrolysis and Fe(II)-activated persulfate oxidation for improving the dewaterability of waste activated sludge	10.1016/j.biortech.2013.03.007
Performance evaluation of a bipolar electrolysis/electrocoagulation (EL/EC) reactor to enhance the sludge dewaterability	10.1016/j.chemosphere.2012.09.069
Effect of potassium ferrate (K 2FeO 4) on sludge dewaterability under different pH conditions	10.1016/j.cej.2012.09.013
Synergetic pretreatment of waste activated sludge by Fe(II)-activated persulfate oxidation under mild temperature for enhanced dewaterability	10.1016/j.biortech.2012.08.039
Bacterial polymer production using pre-treated sludge as raw material and its flocculation and dewatering potential	10.1016/j.biortech.2012.06.075
An integrated approach to optimize the conditioning chemicals for enhanced sludge conditioning in a pilot-scale sludge dewatering process	10.1016/j.biortech.2012.06.093
Biochemical diversity of the bacterial strains and their biopolymer producing capabilities in wastewater sludge	10.1016/j.biortech.2012.06.103

Novel insights into enhanced dewaterability of waste activated sludge by Fe(II)-activated persulfate oxidation	10.1016/j.biortech.2012.05.115
Enhancing sewage sludge dewaterability by bioleaching approach with comparison to other physical and chemical conditioning methods	10.1016/S1001-0742(11)60958-3
Enhanced dewaterability of sewage sludge in the presence of Fe(II)-activated persulfate oxidation	10.1016/j.biortech.2012.01.170
Conditioning of sewage sludge by Fenton's reagent combined with skeleton builders	10.1016/j.chemosphere.2012.02.084
Improvement of activated sludge dewaterability by mild thermal treatment in CaCl 2 solution	10.1016/j.watres.2011.11.014
Effects of Fenton Pre-Treatment on Waste Activated Sludge Properties	10.1002/clen.201000199
New sludge pretreatment method to improve dewaterability of waste activated sludge	10.1016/j.biortech.2011.02.076
Enhancement of waste activated sludge dewaterability by electro-chemical pretreatment	10.1016/j.jhazmat.2010.12.106
Dewaterability characteristics of sludge conditioned with surfactants pretreatment by electrolysis	10.1016/j.biortech.2010.10.065
Conditioning of sewage sludge with electrolysis: Effectiveness and optimizing study to improve dewaterability	10.1016/j.biortech.2009.12.147
Enhanced dewatering of waste sludge with microbial flocculant TJ-F1 as a novel conditioner	10.1016/j.watres.2010.02.033
Effect of cations on simultaneous enhancement of dewaterability and settleability of activated sludge under mild thermal treatment	10.1080/19443994.2015.1090918

Table B- 2. DOI List of literature for sludge thickening

Title	DOI
Continuous thickening of activated sludge by electro-flotation	10.1016/j.seppur.2013.01.022
Investigation of the sludge thickening potential of waste activated sludge using membranes	10/5004/dwt.2012.2450
Continuous clarification and thickening of activated sludge by electrolytic bubbles under control of scale deposition	10.1016/j.biortech.2009.11.075
Enhancing filterability of flat-sheet membrane by addition of cationic polymer for sludge thickening system	10.5004/dwt.2010.1692
Feasibility of electroflotation to separate solids and liquid in an activated sludge process	10.1080/09593330903313802
Application of the flotation process to thicken the sludge from a DAF plant	10.2166/wst.2006.220

Table B- 3. DOI List of literature on stabilization processes

Title	DOI
Disinfection and solubilization of sewage sludge using the microwave enhanced advanced oxidation process	10.1016/j.jhazmat.2010.05.134
Vermistabilization of sewage sludge (biosolids) by earthworms: Converting a potential biohazard destined for landfill disposal into a pathogen-free, nutritive and safe biofertilizer for farms	10.1177/0734242X09342147
Enriching functional microbes with electrode to accelerate the decomposition of complex substrates during anaerobic digestion of municipal sludge	10.1016/j.bej.2016.03.002
Enhanced decomposition of waste activated sludge via anodic oxidation for methane production and bioenergy recovery	10.1016/j.ibiod.2015.10.020
Enhanced digestion of waste activated sludge using microbial electrolysis cells at ambient temperature	10.1016/j.watres.2015.05.045
Low pH anaerobic digestion of waste activated sludge for enhanced phosphorous release	10.1016/j.watres.2015.05.062
Improvement of anaerobic digestion of waste-activated sludge by using H2O2 oxidation, electrolysis, electro-oxidation and thermo-alkaline pretreatments	10.1007/s11356-015-4677-2
Anaerobic bioleaching of metals from waste activated sludge	10.1016/j.scitotenv.2014.12.073
Effects of metal salt addition on odor and process stability during the anaerobic digestion of municipal waste sludge	10.1016/j.wasman.2015.07.050
High pressure homogenization and two-phased anaerobic digestion for enhanced biogas conversion from municipal waste sludge	10.1016/j.watres.2014.08.045
Anaerobic digestion of municipal wastewater sludges using anaerobic fluidized bed bioreactor	10.1016/j.biortech.2014.09.081
Improvement of methane production from waste activated sludge by on-site photocatalytic pretreatment in a photocatalytic anaerobic fermenter	10.1016/j.biortech.2013.12.041
Solubilization of municipal sewage waste activated sludge by novel lytic bacterial strains	10.1007/s11356-013-2228-2
Effect of microwave pre-treatment of thickened waste activated sludge on biogas production from co-digestion of organic fraction of municipal solid waste, thickened waste activated sludge and municipal sludge	10.1177/0734242X14554641
Enhancing aerobic digestion potential of municipal waste-activated sludge through removal of extracellular polymeric substance	10.1007/s11356-013-1976-3
Sono-biostimulation of aerobic digestion: A novel approach for sludge minimization	10.1002/jctb.4202
A modified anaerobic digestion process with chemical sludge pre-treatment and its modelling	10.2166/wst.2014.164

Anaerobic digestion and gasification coupling for wastewater sludge treatment and recovery	10.1177/0734242X14538308
Improving the amenability of municipal waste activated sludge for biological pretreatment by phase-separated sludge disintegration method	10.1016/j.biortech.2014.07.065
The effect of direct addition of iron(III) on anaerobic digestion efficiency and odor causing compounds	10.2166/wst.2013.507
Biological pretreatment of non-flocculated sludge augments the biogas production in the anaerobic digestion of the pretreated waste activated sludge	10.1080/09593330.2013.810294
Microwave and thermal pretreatment as methods for increasing the biogas potential of secondary sludge from municipal wastewater treatment plants	10.1016/j.biortech.2013.02.001
The influence of the energy absorbed from microwave pretreatment on biogas production from secondary wastewater sludge	10.1016/j.biortech.2011.09.052
Electrochemical Oxidation technique for sludge stabilization and treatment.	10.1061/(ASCE)EE.1943-7870.0000538
Hydrothermal degradation of organic matter in municipal sludge using non-catalytic wet oxidation	10.1016/j.cej.2014.09.063
Effect of microwave irradiation on the disintegration and acidogenesis of municipal secondary sludge	10.1016/j.cej.2009.06.032
Alkaline and acid thermal hydrolysis of biological excess sludge in sequencing batch reactor	10.1080/19443994.2015.1137788
Enhancing anaerobic digestion of waste activated sludge by the combined use of NaOH and Mg(OH)2: Performance evaluation and mechanism study	10.1016/j.biortech.2016.08.043
Preliminary investigation on the effect of earthworm and vegetation for sludge treatment in sludge treatment reed beds system	10.1007/s11356-016-6399-5
Effects of thermal-alkaline pretreatment on solubilisation and high-solid anaerobic digestion of dewatered activated sludge	10.15376/biores.11.1.1280-1295
Effects of stabilization and sludge properties in a combined process of anaerobic digestion and thermophilic aerobic digestion	10.1080/09593330.2015.1049212
Effect of Combined Microwave-Ultrasonic Pretreatment of Real Mixed Sludge on the Enhancement of Anaerobic Digester Performance	10.1007/s11270-015-2586-0
Effects of potassium ferrate oxidation on sludge disintegration, dewaterability and anaerobic biodegradation	10.1016/j.ibiod.2015.01.002
Microwave oxidation treatment of sewage sludge	10.1080/10934529.2015.1019811
Influence of NaOH and thermal pretreatment on dewatered activated sludge solubilisation and subsequent anaerobic digestion: Focused on high-solid state	10.1016/j.biortech.2015.02.050
Optimizing chemical conditioning for odour removal of undigested sewage sludge in drying processes	10.1016/j.jenvman.2014.11.012

Experimental study on municipal sludge dewatering capacity by using quicklime and slag	10.1080/19443994.2014.889607
Evaluation of a pretreatment method using cation exchange resin to enhance the sludge solubilization and disintegration for improving the efficiency of anaerobic digestion	10.1080/19443994.2014.965222
Radiofrequency-oxidation treatment of sewage sludge	10.1016/j.chemosphere.2015.07.053
Combined electrical-alkali pretreatment to increase the anaerobic hydrolysis rate of waste activated sludge during anaerobic digestion	10.1016/j.apenergy.2014.04.062
Hybrid conditioning before anaerobic digestion for the improvement of sewage sludge dewatering	10.1080/19443994.2014.884685
Thermal hydrolysis of waste activated sludge at Hengelo Wastewater Treatment Plant, the Netherlands	10.2166/wst.2014.107
Study on dewaterability of municipal sludge conditioning by physical conditioners with ultrasonic and magnetic field application	10.1080/19443994.2013.821038
Combined effects of Fenton peroxidation and CaO conditioning on sewage sludge thermal drying	10.1016/j.chemosphere.2014.09.038
Effects of thermal pre-treatment on anaerobic co-digestion of municipal biowastes at high organic loading rate	10.1016/j.chemosphere.2013.12.007
Stabilisation of dewatered domestic sewage sludge by lime addition as raw material for the cement industry: Understanding process and reactor performance	10.1016/j.cej.2013.07.104
Application of low-strength ultrasonication to the continuous anaerobic digestion processes: UASBr and dry digester	10.1016/j.biortech.2013.03.116
Alkaline post-treatment for improved sludge anaerobic digestion	10.1016/j.biortech.2013.04.093
Effect of ultrasonic, microwave and combined microwave-ultrasonic pretreatment of municipal sludge on anaerobic digester performance	10.1007/s11270-013-1559-4
Effect of microwave pretreatment in presence of NaOH on mesophilic anaerobic digestion of thickened waste activated sludge	10.1016/j.biortech.2012.09.057
Enhanced anaerobic digestion and sludge dewaterability by alkaline pretreatment and its mechanism	10.1016/S1001-0742(11)61031-0
Enhancing sewage sludge dewaterability by bioleaching approach with comparison to other physical and chemical conditioning methods	10.1016/S1001-0742(11)60958-3
Advanced thermal hydrolysis: Optimization of a novel thermochemical process to aid sewage sludge treatment	10.1021/es204203y
Comparison between ozone and ultrasound disintegration on sludge anaerobic digestion	10.1016/j.jenvman.2010.07.030
Techno-economic evaluation of ultrasound and thermal pretreatments for enhanced anaerobic digestion of municipal waste activated sludge	10.1016/j.wasman.2011.10.007
Advanced Thermal Hydrolysis of secondary sewage sludge: A novel process combining thermal hydrolysis and hydrogen peroxide addition	10.1016/j.resconrec.2011.03.008

Effect of thermal pretreatment on the physical and chemical properties of municipal biomass waste	10.1016/j.wasman.2011.09.027
Effect of ultrasonic pretreatment on anaerobic digestion and its sludge dewaterability	10.1016/S1001-0742(10)60618-3
Enhancement of the conventional anaerobic digestion of sludge: Comparison of four different strategies	10.2166/wst.2011.593
Evaluation of continuous mesophilic, thermophilic and temperature phased anaerobic digestion of microwaved activated sludge	10.1016/j.watres.2011.02.032
The effect of acid pretreatment on the anaerobic digestion and dewatering of waste activated sludge	10.1016/j.biortech.2010.12.043
Application of acidic thermal treatment for one- and two-stage anaerobic digestion of sewage sludge	10.2166/wst.2010.490
Disintegration of biological sludge: Effect of ozone oxidation and ultrasonic treatment on aerobic digestibility	10.1016/j.biortech.2010.06.019
Full-stream and part-stream ultrasound treatment effect on sludge anaerobic digestion	10.2166/wst.2010.893
New insight into sludge digestion mechanism for simultaneous sludge thickening and reduction using flat-sheet membrane-coupled aerobic digesters	10.1016/j.cej.2016.10.014
Performance of anaerobic membrane bioreactor during digestion and thickening of aerobic membrane bioreactor excess sludge	10.1016/j.biortech.2016.06.124
Inline thickener-MBR as a compact, energy efficient organic carbon removal and sludge production devise for municipal wastewater treatment	10.1016/j.cep.2015.11.010
Pilot-scale study of sludge pretreatment by microwave and sludge reduction based on lysis-cryptic growth	10.1016/j.biortech.2015.04.046
Alkaline treatment of high-solids sludge and its application to anaerobic digestion	10.2166/wst.2014.469
Effects of ultrasonic disintegration of excess sludge obtained in disintegrators of different constructions	10.1080/09593330.2015.1024759
Enhanced anaerobic digestion of waste activated sludge of low organic content in a novel digester	10.2166/wst.2015.296
Effect of short-time aerobic digestion on bioflocculation of extracellular polymeric substances from waste activated sludge	10.1007/s11356-013-1887-3
Biological treatment and thickening with a hollow fibre membrane bioreactor	10.1016/j.watres.2014.03.063
Efficiency of a pilot-scale integrated sludge thickening and digestion reactor in treating low-organic excess sludge	10.1080/09593330.2011.630423
Laboratory-scale ultrasound pre-treated digestion of sludge: Heat and energy balance	10.1016/j.biortech.2011.05.025
Temporal variations of membrane foulants in the process of using flat-sheet membrane for simultaneous thickening and digestion of waste activated sludge	10.1016/j.biortech.2011.04.042

Various operating conditions affecting the performance of aerobic digestion coupled with membrane filtration	10/5004/dwt.2011.2890
A pilot study of anaerobic membrane digesters for concurrent thickening and digestion of waste activated sludge (WAS)	10.2166/wst.2010.028
Aquatic worms eat sludge: Mass balances and processing of worm faeces	10.1016/j.jhazmat.2009.12.079
Identification of sustainable flux in the process of using flat-sheet membrane for simultaneous thickening and digestion of waste activated sludge	10.1016/j.jhazmat.2008.06.020
Floc destruction and its impact on dewatering properties in the process of using flat-sheet membrane for simultaneous thickening and digestion of waste activated sludge	10.1016/j.biortech.2008.10.026
Membrane fouling mechanisms in the process of using flat-sheet membrane for simultaneous thickening and digestion of activated sludge	10.1016/j.seppur.2008.07.013
Synergetic pretreatment of sewage sludge by microwave irradiation in presence of H2O2 for enhanced anaerobic digestion	10.1016/j.watres.2008.08.010
Application of flat-sheet membrane to thickening and digestion of waste activated sludge (WAS)	10.1016/j.jhazmat.2007.10.057

Table B- 4. DOI List of literature for thermal reduction processes

Title	DOI
Ultra high temperature gasification of municipal wastewater primary biosolids in a rotary kiln reactor for the production of synthesis gas	10.1016/j.jenvman.2016.02.043
Pyrolysis of activated sludge: Energy analysis and its technical feasibility	10.1016/j.biortech.2014.09.134
Carbonization of heavy metal impregnated sewage sludge oriented towards potential co-disposal	10.1016/j.jhazmat.2016.09.010
Fuel design in co-combustion of demolition wood chips and municipal sewage sludge	10.1016/j.fuproc.2015.08.037
Chemical speciation, mobility and phyto-accessibility of heavy metals in fly ash and slag from combustion of pelletized municipal sewage sludge	10.1016/j.scitotenv.2015.07.126
Integrated drying and incineration of wet sewage sludge in combined bubbling and circulating fluidized bed units	10.1016/j.wasman.2014.08.018
Environmental effects of sewage sludge carbonization and other treatment alternatives	10.3390/en6020871
Review of biosolids management options and co-incineration of a biosolid-derived fuel	10.1016/j.wasman.2011.06.008
Preparation of adsorbents from sewage sludge by steam activation for industrial emission treatment	10.1205/psep.05161
Biosolids - A fuel or a waste? An integrated appraisal of five co-combustion scenarios with policy analysis	10.1021/es052181g
Environmental and economic assessment of sewage sludge handling options	10.1016/j.resconrec.2003.10.006
Effect of the Heating Rate on the Thermochemical Behavior and Biofuel Properties of Sewage Sludge Pyrolysis	10.1021/acs.energyfuels.5b02232
Hydrogen-rich gas production by steam gasification of hydrochar derived from sewage sludge	10.1016/j.ijhydene.2015.12.188
Comparative assessment of municipal sewage sludge incineration, gasification and pyrolysis for a sustainable sludge-to-energy management in Greece	10.1016/j.wasman.2013.11.003
Characterization of nitrogen transformation during microwave-induced pyrolysis of sewage sludge	10.1016/j.jaap.2013.11.021
Using liquid waste streams as the moisture source during the hydrothermal carbonization of municipal solid wastes	10.1016/j.wasman.2014.06.024
Atmospheric emission characterization of a novel sludge drying and co-combustion system	10.1016/S1001-0742(12)60272-1
Nitrogen conversion in relation to NH3 and HCN during microwave pyrolysis of sewage sludge	10.1021/es304248j

Electrodialytic treatment for metal removal from sewage sludge ash from fluidized bed combustion	10.1016/j.jhazmat.2009.11.150
Influence of the reactant carbon-hydrogen-oxygen composition on the key products of the direct gasification of dewatered sewage sludge in supercritical water	10.1016/j.biortech.2016.02.070
Techno-economic analysis of wastewater sludge gasification: A decentralized urban perspective	10.1016/j.biortech.2014.03.040
Partial oxidative gasification of municipal sludge in subcritical and supercritical water	10.1080/09593330.2011.618933

Table B- 5. DOI List of literature for dewatering process

Title	DOI
Individual and Combined Effects of Freeze-Thaw and Ferrate(VI) Oxidation for the Treatment and Dewatering of Wastewater Sludges	10.1007/s11270-016-3039-0
Drying characteristics of electro-osmosis dewatered sludge	10.1080/09593330.2016.1175511
Influence of process operating parameters on dryness level and energy saving during wastewater sludge electro-dewatering	10.1016/j.watres.2016.07.016
Electro-dewatering of activated sludge: Electrical resistance analysis	10.1016/j.watres.2016.05.033
Electrokinetic dewatering of sewage sludge with fixed and moving electrodes: Attenuation mechanism and improvement approach	10.1061/(ASCE)EE.1943-7870.0001016
Migration and distribution of water and organic matter for activated sludge during coupling magnetic conditioning-horizontal electro-dewatering (CM-HED)	10.1016/j.watres.2015.10.001
Characterization of the structure and interaction of sludge biosolids during the conditioning-electro-dewatering process	10.1016/j.colsurfa.2015.07.056
Electro-conditioning of activated sludge in a membrane electro-bioreactor for improved dewatering and reduced membrane fouling	10.1016/j.memsci.2015.07.051
Dewaterability of five sewage sludges in Guangzhou conditioned with Fenton's reagent/lime and pilot-scale experiments using ultrahigh pressure filtration system	10.1016/j.watres.2015.07.041
Electro-dewatering of wastewater sludge: An investigation of the relationship between filtrate flow rate and electric current	10.1016/j.watres.2015.04.006
Application of forward osmosis (FO) under ultrasonication on sludge thickening of waste activated sludge	10.2166/wst.2015.341
Evaluation of solar sludge drying alternatives by costs and area requirements	10.1016/j.watres.2015.04.043
Impact of joule heating and ph on biosolids electro-dewatering	10.1021/es5048254
Highly efficient forward osmosis based on porous membranes-Applications and implications	10.1021/es504164w

Hydrothermal treatment coupled with mechanical expression at increased temperature for excess sludge dewatering: The dewatering performance and the characteristics of products	10.1016/j.watres.2014.10.016
Hydrothermal treatment coupled with mechanical expression at increased temperature for excess sludge dewatering: Influence of operating conditions and the process energetics	10.1016/j.watres.2014.07.020
Dynamic changes in the characteristics and components of activated sludge and filtrate during the pressurized electro-osmotic dewatering process	10.1016/j.seppur.2014.07.019
The role of temperature and CaCl2 in activated sludge dewatering under hydrothermal treatment	10.1016/j.watres.2013.11.034
A Study for Development of Real-Scale Thermal Filter Press Dewatering (TFPD)	10.1080/07373937.2013.807283
Electro-Dewatering of Anaerobically Digested and Activated Sludges: An Energy Aspect Analysis	10.1080/07373937.2014.884133
Evaluation of Suitable Material Properties of Sludge for Electroosmotic Dewatering	10.1080/07373937.2012.760581
Application of forward osmosis on dewatering of high nutrient sludge	10.1016/j.biortech.2013.01.028
Can sludge dewatering reactivate microorganisms in mesophilically digested anaerobic sludge? Case of belt filter versus centrifuge	10.1016/j.watres.2012.10.028
Study on the effect and mechanism of hydrothermal pretreatment of dewatered sewage sludge cake for dewaterability	10.1080/10962247.2013.788458
Characteristics of WWTP sludge after drying in greenhouse for agricultural purposes	10.2166/wst.2012.326
Pressurised electro-osmotic dewatering of activated and anaerobically digested sludges: Electrical variables analysis	10.1016/j.watres.2012.05.053
Inactivation mechanisms of bacterial pathogen indicators during electro-dewatering of activated sludge biosolids	10.1016/j.watres.2012.05.009
Influence of electric field application by reducing area of electrode compared with cross-sectional area of sludge bed on electro-osmotic dewatering process	10.1252/jcej.11we137
Effect of Polyelectrolyte Conditioning and Voltages on Fractionation of Macro and Trace Metals due to Sludge Electro-Dewatering	10.1080/01496395.2011.640377
Influence of Filter Cell Configuration and Process Parameters on the Electro-Osmotic Dewatering of Sewage Sludge	10.1080/01496395.2011.616567
Effect of various design and operation parameters on performance of pilot-scale Sludge Drying Reed Beds	10.1016/j.ecoleng.2011.10.003
Stability and maturity of thickened wastewater sludge treated in pilot-scale sludge treatment wetlands	10.1016/j.watres.2011.09.036
Conditioning of wastewater sludge using freezing and thawing: Role of curing	10.1016/j.watres.2011.08.064
Modeling cake filtration under coupled hydraulic, electric and osmotic effects	10.1016/j.memsci.2011.05.038

Dewatering mechanisms in pilot-scale Sludge Drying Reed Beds: Effect of design and operational parameters	10.1016/j.cej.2011.05.111
Electro-dewatering of wastewater sludge: Influence of the operating conditions and their interactions effects	10.1016/j.watres.2011.02.029
Freezing as a combined wastewater sludge pretreatment and conditioning method	10.1016/j.desal.2010.10.014
Influence of salt, pH and polyelectrolyte on the pressure electro-dewatering of sewage sludge	10.1016/j.watres.2011.01.001
Effect of freeze/thaw conditions, polyelectrolyte addition, and sludge loading on sludge electro-dewatering process	10.1016/j.cej.2010.08.028
Electroosmotic flows in sludge at dewatering	10.1080/07373937.2010.506172
Influence of filter cloth on the cathode on the electroosmotic dewatering of activated sludge	10.1016/S1004-9541(10)60259-5
Feasibility of applying forward osmosis to the simultaneous thickening, digestion, and direct dewatering of waste activated sludge	10.1016/j.biortech.2011.12.064

Table B- 6. DOI List of selected literature for heat drying and disinfection process

Title	DOI
Stabilization of sewage sludge by using various by-products: Effects on soil properties, biomass production, and bioavailability of copper and zinc	10.1007/s11270-014-2014-x
Electron beam inactivation of selected microbial pathogens and indicator organisms in aerobically and anaerobically digested sewage sludge	10.1016/j.biortech.2013.07.034
Usage of UV to rid WW of legionella strains.	10.2166/wst.2016.258
Possible solutions for sludge dewatering in China	10.1007/s11783-010-0001-z
Environmental assessment of supercritical water oxidation and other sewage sludge handling options	10.1177/0734242X05054324
Effect of electron beam irradiation on bacterial and Ascaris ova loads and volatile organic compounds in municipal sewage sludge	10.1016/j.radphyschem.2015.02.013
Environmental assessment of supercritical water oxidation of sewage sludge	10.1016/j.resconrec.2003.12.002
Evaluation on the air-borne ultrasound-assisted hot air convection thin-layer drying performance of municipal sewage sludge	10.1016/j.ultsonch.2016.06.036
Structure modification and extracellular polymeric substances conversion during sewage sludge biodrying process	10.1016/j.biortech.2016.05.102
Urea for sanitization of anaerobically digested dewatered sewage sludge	10.1089/ees.2013.0230
A novel approach for improving the drying behavior of sludge by the appropriate foaming pretreatment	10.1016/j.watres.2014.10.036
The thin-layer drying characteristics of sewage sludge by the appropriate foaming pretreatment	10.2166/wst.2014.093
The biodrying concept: An innovative technology creating energy from sewage sludge	10.1016/j.biortech.2013.07.138
Influence of forced air volume on water evaporation during sewage sludge bio-drying	10.1016/j.watres.2013.03.048
Sludge Bio-drying Process at Low Ambient Temperature: Effect of Bulking Agent Particle Size and Controlled Temperature	10.1080/07373937.2012.665113
Partial oxidative gasification of municipal sludge in subcritical and supercritical water	10.1080/09593330.2011.618933
Anaerobic storage as a pretreatment for enhanced biodegradability of dewatered sewage sludge	10.1016/j.biortech.2010.08.036
Effect of air-flow rate and turning frequency on bio-drying of dewatered sludge	10.1016/j.watres.2010.07.002

Table B- 7. DOI List of literature for resource recovery processes

Title	DOI
Direct liquid-liquid extraction of lipid from municipal sewage sludge for biodiesel production	10.1016/j.fuproc.2014.07.041
Thermochemical treatment of sewage sludge ashes for phosphorus recovery	10.1016/j.wasman.2008.09.011
Full-Scale Highly-Loaded Wastewater Treatment Processes (A-Stage) to Increase Energy Production from Wastewater: Performance and Design Guidelines	10.1089/ees.2016.0022
Valorization of sludge from a wastewater treatment plant by glass-ceramic production	10.1016/j.ceramint.2016.10.083
Sewage sludge ash characteristics and potential for use in bricks, tiles and glass ceramics	10.2166/wst.2016.040
Utilization of sewage sludge in the manufacture of lightweight aggregate	10.1007/s10661-015-5010-8
Speciation Dynamics of Phosphorus during (Hydro)Thermal Treatments of Sewage Sludge	10.1021/acs.est.5b04140
Environmental and technical assessments of the potential utilization of sewage sludge ashes (SSAs) as secondary raw materials in construction	10.1016/j.wasman.2013.01.004
Sludge valorization from wastewater treatment plant to its application on the ceramic industry	10.1016/j.jenvman.2011.06.016
Effects of thermally dried and composted sewage sludges on the fertility of residual soils from limestone quarries	10.1016/j.apsoil.2011.05.001
Sewage sludge ash to phosphorus fertiliser (II): Influences of ash and granulate type on heavy metal removal	10.1016/j.wasman.2010.03.037
Recovering humic substances from the dewatering effluent of thermally treated sludge and its performance as an organic fertilizer	10.1007/s11783-015-0827-5
Application of ultra-sonication, acid precipitation and membrane filtration for co-recovery of protein and humic acid from sewage sludge	10.1007/s11783-014-0763-9
Potential of phosphorus recovery from sewage sludge and manure ash by thermochemical treatment	10.1016/j.wasman.2016.01.020
Long-term performance of side-stream deammonification in a continuous flow granular-activated sludge process for nitrogen removal from high ammonium wastewater	10.2166/wst.2015.096
Start-up of a full-scale deammonification SBR-treating effluent from digested sludge dewatering	10.2166/wst.2014.421
Extracting humic acids from digested sludge by alkaline treatment and ultrafiltration	10.1007/s10163-013-0153-6
Biodiesel production from wet municipal sludge: Evaluation of in situ transesterification using xylene as a cosolvent	10.1016/j.biortech.2014.05.001

Effects of dilution ratio and Fe dosing on biohydrogen production from dewatered sludge by hydrothermal pretreatment	10.1080/09593330.2014.931469
Lead glass-ceramics produced from the beneficial use of waterworks sludge	10.1016/j.watres.2012.11.045
Biodiesel from dewatered wastewater sludge: A two-step process for a more advantageous production	10.1016/j.chemosphere.2013.03.046
Optimization of phosphorus removal from reject water of sludge thickening and dewatering process through struvite precipitation	10.1080/19443994.2015.1072059
Using focused pulsed technology to remove siloxane from municipal sewage sludge	10.1061/(ASCE)EE.1943-7870.0000975
Microaerobic control of biogas sulphide content during sewage sludge digestion by using biogas production and hydrogen sulphide concentration	10.1016/j.cej.2014.04.027
Pretreatment of municipal waste activated sludge for volatile sulfur compounds control in anaerobic digestion	10.1016/j.biortech.2010.12.020
Anaerobic bioleaching of metals from waste activated sludge	10.1016/j.scitotenv.2014.12.073

Appendix C:

Commercial technologies for sludge treatment

Company: Ovivowater (International)

Technology: OVIVO - Thickened Aerobic Digestion

General description: The Pre-thickened Aerobic Digestion (PAD) process is a controlled aerobic digestion system designed to handle thickened sludge and to meet the Class B requirements for pathogens and vector attraction. There are 3 different PAD approaches being employed.

1. The Ovivo® M-TAD™ (Mechanically Thickened Aerobic Digestion) process is designed to handle sludge produced by mechanical thickeners such as gravity belt thickeners or rotary drums.

- Lowers cost of anaerobic digester retrofits;
- Minimizes footprint of new construction or expands capacity of existing tanks;
- Enhanced pH and temperature control.

2. Ovivo® Mem-TAD™ (Membrane Thickened Aerobic Digestion) process brings aerobic digestion and flat sheet membrane performance together into one integrated system. The system consists of two or more aerobic digesters operating in conjunction with an anoxic basin and membrane thickener (MBT).

- Sludge quality will meet or exceed Class B standards;
- Capable of thickening up to 5% without any polymer or coagulant.

3. Ovivo's G-TAD™ (Gravity Thickened Aerobic Digestion) consists of two Aerobic Digester basins operating in conjunction with a PreMix basin and a Gravity Thickener

- Produces a stabilized, homogenous Class B sludge;
- Increased solids concentration in gravity thickener;
- Enhanced pH and temperature control.

Stage of development: All three approaches can be found across the U.S. and globally

Source of information: http://www.ovivowater.ca/contact/

Company: Eliquo Water and Energy (Germany)

Technology: Lysotherm® Thermal Pressure Hydrolysis

General description: A high pressure, thermal hydrolysis pre-treatment process for anaerobic digestion of primary or secondary sludge. The process reduces viscosity by a factor of 10, results in a higher biogas yield, and can improve dewatering.

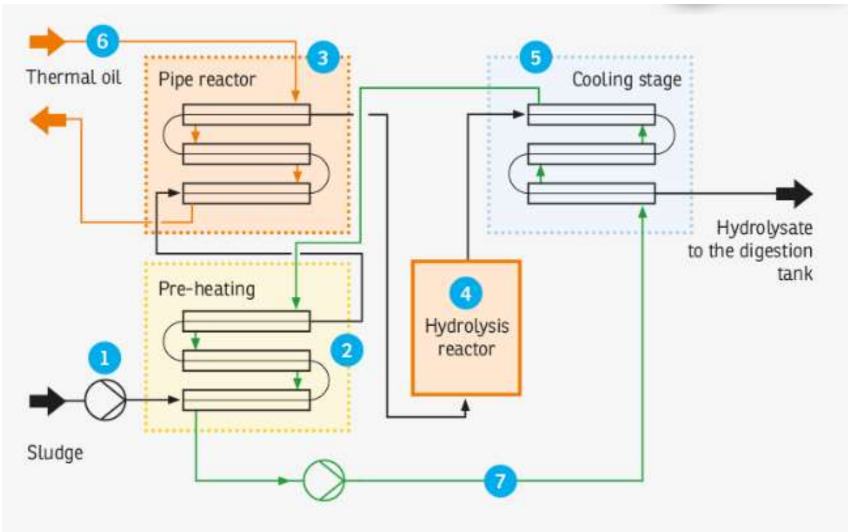

Figure B- 1. Schematic of Lysotherm® treatment process

Key features include:

- Easy installation prior to an anaerobic digester;
- No requirement of existing equipment modification;
- Efficient heat exchange system, without any steam utilities or steam injection;
- Biogas production that can be utilized for the cogeneration of heat and electricity.

Stage of development: The process has been commissioned in a 12000 ton wastewater treatment plant in the Netherlands.

Source of information: http://www.eliquo-we.com/en/lysotherm.html

Company: Trojan (International/Ontario)

Technology: PRI-DE^{TM} Digester Enhancement

General description: When applied to primary settled solids (prior to thickening and digestion), the effect of the PRI technology is two-fold:

- To remove dissolved sulfide that either contributes to immediate biogas H2S levels or provides a sink for Fe added subsequently; and
- To remove total sulfide and so ‘free up' the iron bound as FeS. That ‘freed up' Fe is then available to control H2S production and/or struvite scaling within the digester.

A benefit of controlling struvite scaling is lower biogas H_2S levels. Further, the incidence of H_2S inhibition within the digestion process is reduced. With higher H_2O_2 doses, mercaptan levels may decrease.

Stage of development: Full scale system at Dos Rios, San Antonio

Source of information: http://www.h2o2.com/municipal-applications/wastewater-treatment.aspx?pid=124&name=PRI-DE

Company: GE Water (International/Ontario)

Technology: GE AnMBR Technology

General description: Anaerobic membrane reactor (AnMBR) technology that provides improved effluent quality, reliability, and efficiency using GE's ZeeWeed* 500 reinforced hollow fiber membrane integrated into the AnMBR system.

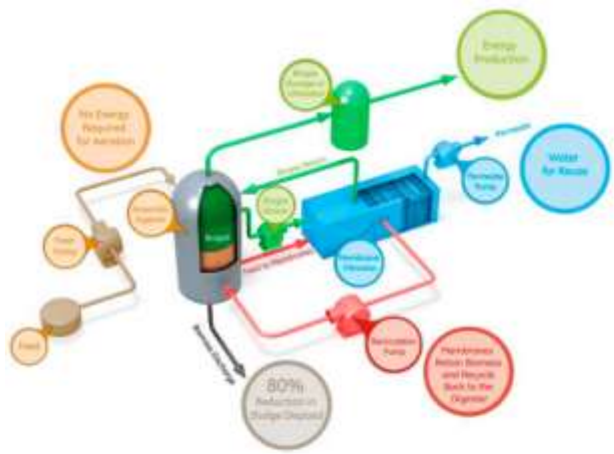

Figure B- 2. Schematic of GE AnMBR

Key features include:

- Methane rich biogas produced can be used as a renewable, storable energy source;
- Superior effluent quality and reliability using GE's ZeeWeed 500 membranes;
- Modular scalable system design, which minimizes onsite construction;
- Retrofit upgrade possibility for existing conventional anaerobic digestion systems;
- No biological oxygen required reducing energy costs for operation;
- 80% reduction in the amount of waste biological sludge;
- High organic loading rates which reduce footprint requirements;
- Process sealed to external environment so odor, VOC, and greenhouse gas emission control is more efficient.

Stage of development: Full and pilot scale systems have been demonstrated globally

Source of information: https://www.gewater.com/products/anaerobic-mbr-technology

Company: GE Water (International/Ontario)

Technology: Monsal Advanced Anaerobic Digestion Technology

General description: The Monsal ADT Hydrolysis Pasteurization Digestion (HPD) Key features include:

- High efficiency anaerobic digestion with over 80% conversion of COD to biogas;
- Low digester retention times;
- Modular and scalable design capable of treating small to large flows;
- Fully integrated design with process control to operate 24/7 in full automatic;
- Production of a nutrient rich, high quality digestate, either liquid or dewatered cake capable of being beneficially utilized;
- Integrated pasteurization process using Monsal 70 system to comply with all local legislative drivers;
- Widest range of feedstocks including source segregated food waste, commercial and industrial wastes and organic slurries.

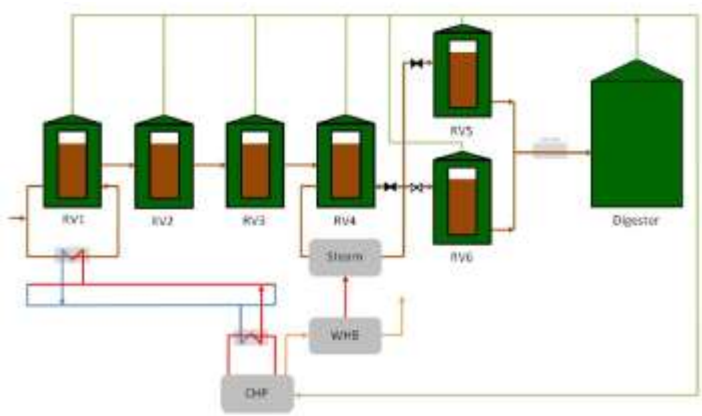

Figure B- 3. Enhanced Enzymic Hydrolysis (Steam Heating) Flowsheet

Stage of development: Full scale demonstration has been reported globally

Source of information: https://www.gewater.com/products/advanced-anaerobic-digestion-systems

Company: Ovivowater (International)

Technology: BioAlgaNyx™ -Anaerobic Digestion Improvement

General description: Utilizes phagotrophic algae that feed by ingesting particles, as opposed to the phototrophic algae, which feed using photosynthesis, that are typically leveraged for treatment solutions. This technology creates an environment low in dissolved oxygen that encourages algae to ingest bacteria and dissolved organics. They store the organic carbon as lipids and, without cell walls, can digest it quickly.

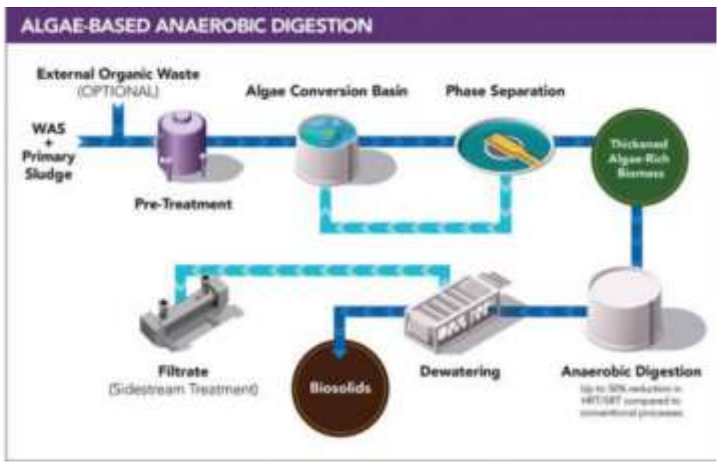

Figure B- 4. Schematic of BioAlgaNyx™ process

Key features include:

- 20 to 30 % increase in volatile solids destruction;
- 50 to 75 % reduction in sludge holding tank volumes;
- Class B biosolids designation or fertilizer.

Stage of development: Pilot scale study with University of Akron

Source of information: https://www.wateronline.com/doc/bioalganyx-bringing-sludge-management-into-the-st-century-0001

Company: Lystek (Ontario, Canada)

Technology: LysteGro LysteMizing™ and LysteCarb™

General description: The Lystek process involves a combination of heat, alkali, and high shear mixing to achieve effective lysis (breakdown) of the biological material in the biosolids. The resultant liquefied material provides a fertilizer product (LysteGro) with applications in agriculture, sod farming, horticulture and more. It can also be used for optimizing (LysteMize) the operation of a wastewater treatment plant.

Figure B- 5. Schematic of Lystek™ process and products

Key features include:

- Recycled Lystek processed biosolids to anaerobic digesters enhances biogas/methane production by 25% or more;
- Reduced biosolids generation requiring offsite disposal by 30% or more;
- The processed biosolids product is a readily available nutrient feedstock that improves organic utilization by the microbial population during the anaerobic digestion process.

Stage of development: Full scale implementation at 9 cities in Canada

Source of information: http://lystek.com/thermal-hydrolysis-technology

Company: CAMBI (Norway)

Technology: CambiTHP™ and Cambi SolidStream™

General description: CambiTHP™ is a high-pressure steam pre-treatment for anaerobic digestion of municipal.

Key features include:

- Increased digester loading and increased biogas production (by factor of 2-3);
- Pathogen-free and stabilized biosolids product with increased cake dewaterability;
- Transport and energy cost reduction;
- End product that can be applied directly to agricultural processes , composted, or dried for use as fertilizer or bio-fuel;
- Elimination of odour problems associated with the treatment of organic materials.

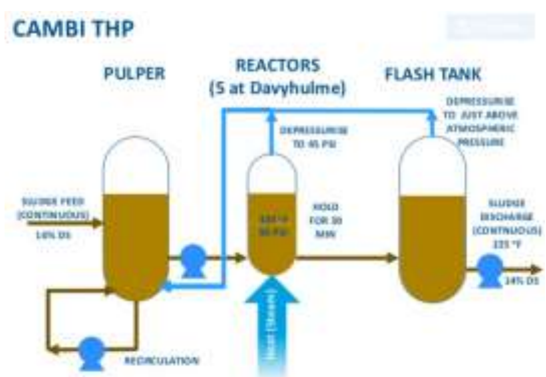

Figure B- 6. Schematic of CAMBI THP™ process

Cambi SolidStream™ is a patented Cambi process for existing and green field plants. After conventional digestion, biosolids (treated sludge) typically dewater to 20-25% dry solids, which means 75-80% of the further costs for transporting and handling are associated with the water. By increasing dewaterability of digested solids to 40-60% dry solids, the water volume and associate costs can be reduced by 75%. In addition, Cambi SolidStream™ results in a Class A, pathogen-free product.

Stage of development: Cambi THP have been installed throughout the world

Source of information: http://www.cambi.com/

Company: Veolia (International)

Technology: Biothelys™

General description: A batch operated, thermal hydrolysis and anaerobic digestion combination technology. Dehydrated sludge first goes through a batch thermal hydrolysis phase during which steam is injected in reactors operating under specific pressure (9 bar) and temperature (165 ℃) conditions for approximately 30 minutes.

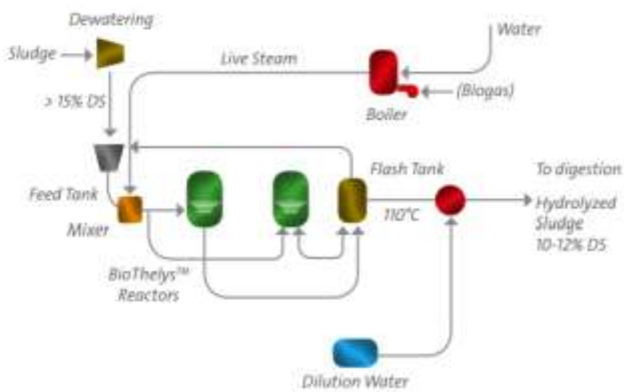

Figure B- 7. Schematic of Biothelys™ treatment process

Key features include:

- 25-35% less dry matter;
- 30-50% more biogas production;
- No odours;
- A pasteurised digestate, for full control over the sanitation hazards and safe agricultural reuse;
- Increased biogas production.

Stage of development: At least 7 full scale implementation globally

Source of information: http://technomaps.veoliawatertechnologies.com/biothelys/en/

Company: Anaergia (Ontario, Canada)

Technology: OMNIVORE™

General description: An anaerobic digester retrofit technology to double the biogas production of a typical digester by co-digesting local organic wastes. The Omnivore can increase the total solids content in a typical digester from 2% to as high as 6% through the proprietary thickening and mixing solutions. The added capacity can be used to digest local organics wastes including food processing waste, source separated organics and contaminated organics such as restaurant waste or cafeteria waste.

Figure B- 8. Schematic of Omnivore™ thickening system

Stage of development: Full scale demonstration have been conducted globally

Source of information: http://www.anaergia.com/services/municipal/waste-water/co-digestion

Company: Electrocell Technologies Inc. (USA)

Technology: Bio-Electric treatment

General description: The treatment system utilizes electrical pulse flows to lyse cells and treat organic liquid wastes. Waste liquid is pumped through engineered tubes, where a shaped electrical pulse flows across the liquid between electrodes. The calibrated electrical charge ruptures the walls of organic cells, destroying pathogens and altering and improving the composition of the liquid waste. The Bio-Electric treatment can:

- Be inserted into existing wastewater treatment infrastructures at a variety of points to improve performance, capacity and efficiency;
- Improve aerobic digestion, anaerobic digestion, nutrient reduction systems, dewatering, and odor management.

Figure B- 9. representative installation Bio-Electric technology

Stage of development: N/A

Source of information:

http://www.electrocell.us/ElectroCell_Technologies_Rev_2/electrocell-wastewater-treatment.html

Company: Texas A&M University and City of Dallas

Technology: Electron Beam Enhanced Anaerobic Digestion (eBEAD)

General description: An ongoing project to evaluate the applicability of high-energy eBeam technology to hydrolyze sewage sludge for enhanced biogas production. Specifically, researchers are examining the influence of eBeam dose and solids content on methane gas production, as well as the chemical and biological properties of sludges processed with the eBeam technology to identify by-products that have high commercial value. The City of Dallas has provided funding to initiate the project and Texas A&M University is providing significant cost-share to support the research.

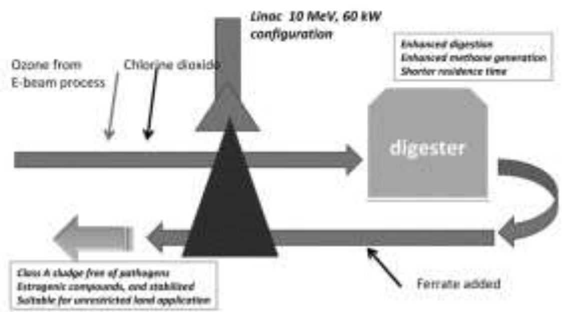

Figure B- 10. Schematic of eBeam technology, from US 20130032547 A1

Preliminary data shows that electron beam (eBeam) technology can result in:

- Increased methane production and sludge dewaterability;
- Reduced sludge viscosity, resulting in increased digester sludge loading rates;
- Reduced sludge residence times;
- Reduced footprint and reduced capital cost-most cost-effective for larger facilities that treat greater than 100 million gallons per day (mgd).

Stage of development: Currently under research stage

Source of information:

http://www.werf.org/i/Get_Involved/TCR/a/n/TCR.aspx?hkey=d4e7b42f-060a-4ea6-a640-d72d57510d49#Biosolids

Company: Sustec (Netherlands, Ontario Canada)

Technology: Turbotec®

General description: A continuous, thermal hydrolysis process that recovers its heat via heat exchangers and mixing/separation of the incoming and hydrolysed material. The process treats organic material (biomass) at a standard pressure of 4-6 bar and a temperature of 140-160 ℃ or up to 180 ℃ which ensures hygienisation of the final biomass cake (Class A). Pre-concentrating of the biomass at just 10-12% TS, minimizes the use of costly chemicals.

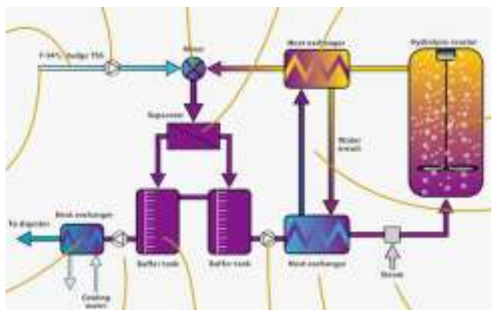

Figure B- 11. Schematic of Turbotec® process

Key features include:

- Up to 35% increase in biogas production;
- Over 30% sludge solids content after dewatering;
- Decreased HRT and increased concentration;
- Low investment and operational costs as compared to batch processes;
- Steam consumption for heating is limited to less than 800 kg/tTS, due to the efficient heat recovery via heat-exchangers and the mixing/separation step.

Stage of development: Turbotec® process has been installed in seven wastewater plants in the Netherlands.

Source of information: http://sustec.nl

Company: CNP Technology Water and Biosolids Corporation (Germany and USA)

Technology: PONDUS® Thermo-Chemical Hydrolysis Process

General description: A thermo-chemical hydrolysis process that leads to increased biogas production, higher dry cake solids, increased digester capacity, and reduced digester foaming. The thickened WAS is first mixed with a small dose of caustic soda (1500 ppm), and then heated in a loop through a high-efficiency heat exchanger. It is then fed into a two stage reactor, and goes through hydrolysis. The sludge is heated with water that comes from a CHP unit. After the hydrolysis process, the sludge leaves the reactor close to a neutral pH level and the remaining thermal energy can be used in the anaerobic digester. The primary sludge and hydrolyzed sludge are then mixed to achieve an ideal mesophilic temperature of the combined sludge and then pumped into the digester.

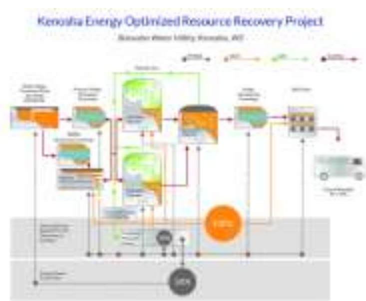

Figure B- 12. Schematic of PONDUS® process

Key features include:

- Increased biogas production by approximately 30%;
- Dryer cake solids and low polymer consumption;
- High digester loading rates and reduction of digester foaming;
- More efficient mixing and pumping due to lower viscosities;
- Optional Class A Biosolids production.

Stage of development: Full scale demonstration at Kenosha Water Utility, USA

Source of information: https://www.cnp-tec.com/pondus/

Company: Veolia (International)

Technology: EXELYS^{TM}

General description: A continuous thermal hydrolysis process that operates at a temperature in excess of 130 ℃ and at pressures greater than 130 psi.

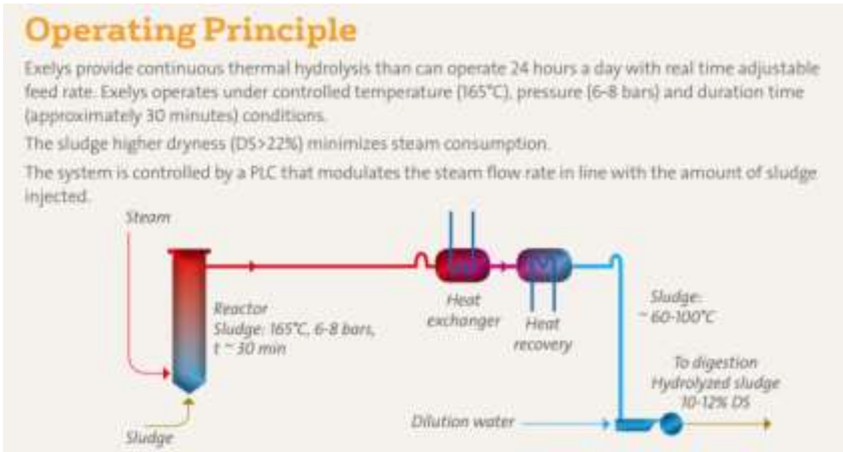

Figure B- 13. Schematic of operating principle for EXELYS^{TM}

Key features include:

- Energy-efficient process for thermal sludge hydrolysis;
- Lowered sludge viscosity resulting in increased existing digester capacity by up to 100%;
- Increased volatile solids reduction up to 65%;
- Improved dewaterability producing 28-40% dry solids content.

Stage of development: Full scale demonstration of the EXELYS process has been tested in Korea (3500 tDs/Year), Demark (5200 tDS/Year), France (9300 tDs/Year and 25000 tDS/Year), and Slovenia (19400 tDS/Year).

Source of information: http://technomaps.veoliawatertechnologies.com/exelys/en/

Company: HydroTORR

Technology: ZIP-Carb^{TM} (Zero Input Process Carbonization)

General description:

A hydrothermal process to convert wet biomass waste to a phosphorus-rich hydrophobic solid product and a nitrogen-rich liquid fertilizer via a modular, scalable, skid-mounted system. Converts wastes into a more environmentally friendly and safer biosolids than current Class A. ZIP-Carb processing uses only heat and pressurized water, accelerating a natural geochemical process for transforming biomass to fossil fuels. The aqueous biomass slurry (e.g., biosolids) is pressurized to 40 bars and rapidly heated to a temperature of 250 ℃ in a continuous flow reactor. Within a short residence time, the reactants in liquid water are converted by hydrothermal carbonization (HTC) process, the basis of ZIP-Carb, through hydrolysis, dehydration, and decarboxylation.

Stage of development:

Bench and pilot scale testing has been conducted at University of Nevada, Reno.

Source of information:

http://www.werf.org/lift/docs/LIFT_Notes_Docs/2016/Technology_Spotlight/Technology_Spotlight_2-18-16.aspx

Company: SCFI-Smarter Environmental Technologies (Ireland)

Technology: AquaCritox®

General description: The process mineralizes wet waste (such as biosolids) and converts it to carbon dioxide, elemental nitrogen, water and a small quantity of nutrient-rich, inert and odourless solid residue.

Key features include:

- Recovery of clean energy that would normally be lost during sludge disposal;
- Reduction of waste volume by up to 97%, and makes it safe for disposal through conventional routes;
- Lower costs and quicker payback;
- Reduced carbon footprint;
- Destruction rate equal to incineration;
- Greater destruction rate than conventional wet air oxidation;
- Odour-free process.

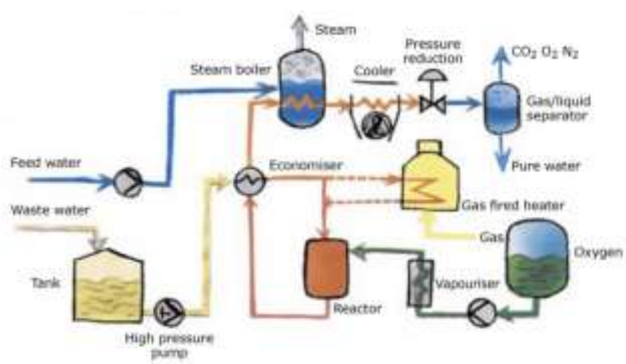

Figure X.

Figure B- 14 Schematic of AquaCritox® process

Stage of development: N/A

Source of information:http://www.scfi.eu/water/the-technology/what-is-aquacritox/

Company: Genifuel (USA)

Technology: Hydrothermal Liquefaction and Catalytic Hydrothermal Gasification

General description: Genifuel's Hydrothermal Processing Systems produce biocrude oil and renewable natural gas (methane). The systems can operate in the mode of Hydrothermal Liquefaction (HTL), Catalytic Hydrothermal Gasification (CHG), or both together.

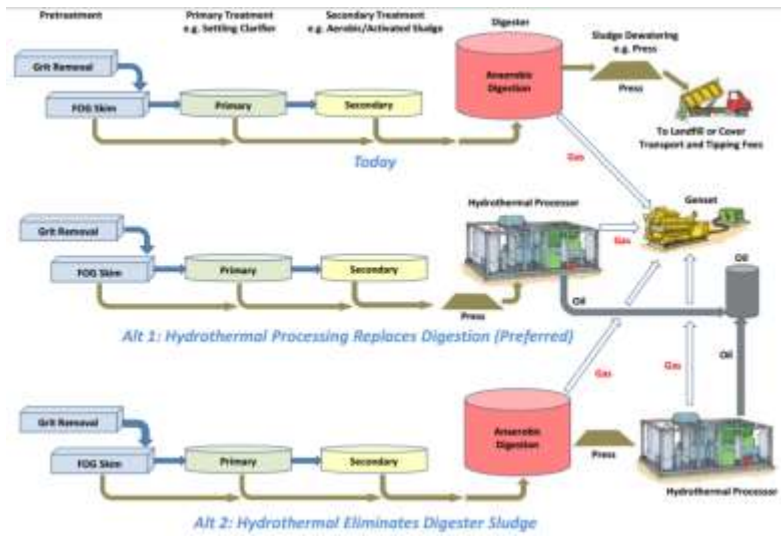

Figure B- 15. WWTPs process flow alternatives showing hydrothermal processing

Key features include:

- Conversion of more than 85% of the feedstock carbon to renewable fuels;
- No net release of carbon dioxide;
- Recovery all the plant nutrients in the feedstock, including nitrogen, phosphorus and potassium;
- Recovery of micro-nutrients that can be used as renewable fertilizer;
- Discharge directly into the environment under existing regulations.

Stage of development: N/A

Source of information: http://www.genifuel.com/process.html

Company: Veolia (International)

Technology: Biocon™ and Biocon ERS low-temperature thermal drying

General description: The BIOCON™ Dryer treats municipal dewatered sludge at low temperature and in complete safety for the operator. The BIOCON™ Dryer consists of two moving belts that allow the sludge to reach levels of dryness of between 65% and 90% by circulating hot drying air through the sludge layer on the belts.

Key features include:

- Reduction of initial sludge quantity to less than 5% (when combined with an energy recovery system);
- Elimination of odours;
- Sludge disinfection (US EPA class A);
- No equipment abrasion;
- No dust (no sludge movement);
- Quiet process;
- Energy recovery;
- Low operating costs.

Stage of development: More than 12 full scale implementations globally

Source of information: http://technomaps.veoliawatertechnologies.com/exelys/en/

Company: BioForceTech (USA)

Technology: Biodryer ™

General description: The BioForceTech plant is composed of multiple BioDryer units coupled with a pyrolysis reactor. This configuration allows a high mass reduction rate; from one ton of initial biosolids (at 20%sc) just 174 lbs of char are obtained. If the biosolids' moisture content is equal or higher than 20%, no external fossil fuel is needed for the drying process. Syngas, water, and char are the by-products of the BioForceTech process. The syngas is a gas that is rich in hydrocarbons and hydrogen, which has a high LHV. The char obtained from biosolids has an average composition of 65% ash, 20% organic carbon, and 15% fixed carbon. BFT has performed several studies to define the recyclability of the char.

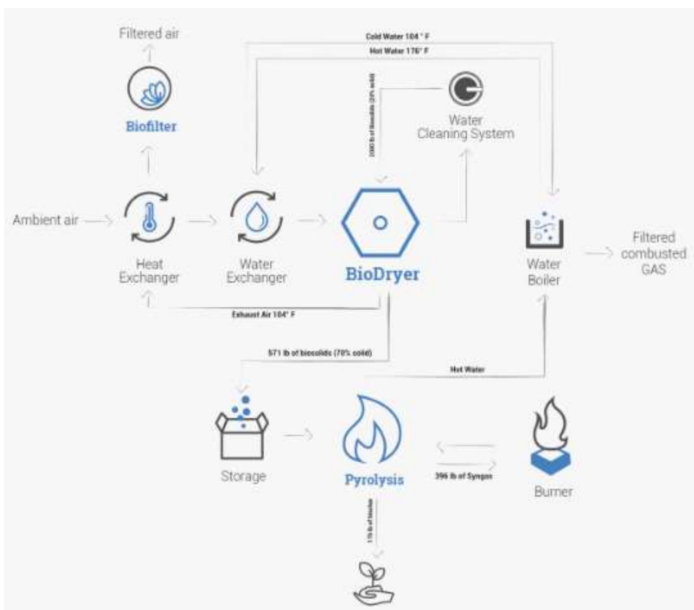

Figure B- 16. Schematic of BioForceTech™ plant treatment process

Stage of development: Full scale demonstration is available in the USA.

Source of information: http://www.bioforcetech.com/biodryer.html

Company: Veolia (International)

Technology: PYROFLUID™ , sludge incineration, energy recovery and ash recycling

General description: A thermal treatment process that oxidizes organic matter contained within sewage sludge. It is a fluidised-bed incinerator (where sand is maintained in suspension by a constant up-flow of air) that operates at approximately 900 ℃ in order to incinerate sludge within a matter of seconds.

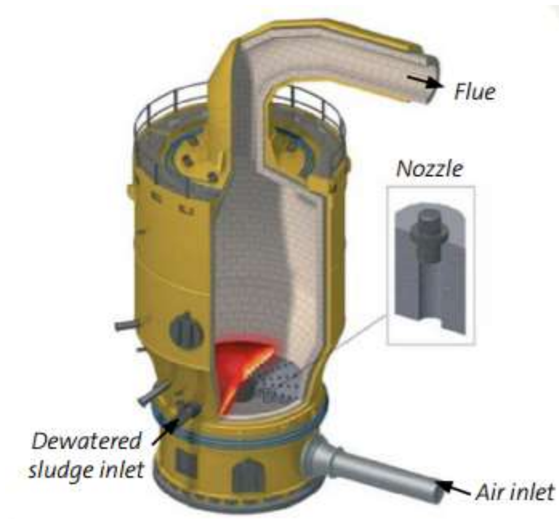

Figure B- 17. Schematic of treatment process for Pyrofluid™

Key features include:

- Total mineralization of sludge;
- 100% reduction of initial sludge quantities combined with mineral by-product recycling (road construction and civil engineering projects);
- Total destruction of pathogens;
- High energy recovery efficiency;
- No odours;
- Low maintenance costs.

Stage of development: Full scale implementation globally

Source of information: http://technomaps.veoliawatertechnologies.com/pyrofluid/en/

Company: Seaborne Environmental Research Laboratory

Technology: Seaborne Technology

General description:

This technology is based on a combination of several processes, including incineration, acid treatment, desulphurization, methane production, heavy metals separation, and struvite precipitation. Advantages include recovery of multiple nutrients with apparently no heavy metals and organic pollutants and H2S-free biogas. The Seaborne technology can basically be described in three steps.

- Metals and nutrients are dissolved by lowering the pH with an acid solution. The organic residual and the soluble compounds are separated using a centrifuge. The organic residual is incinerated.
- Hydrogen sulfide in digester gas is used to precipitate the metals from the centrate. The metals are separated by filtration
- Sodium hydroxide and magnesium oxide are added to the filtrate.

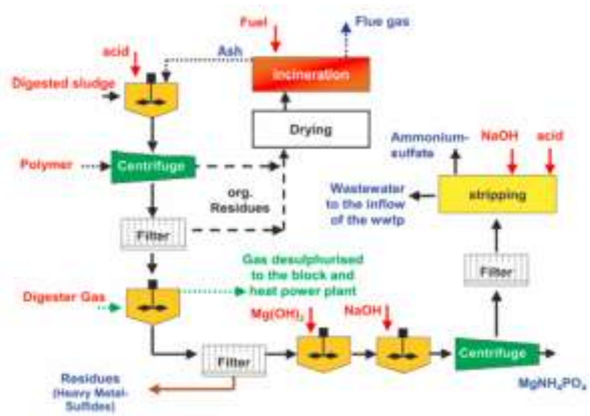

Figure B- 18. Schematic of Seaborne technology(From Müller et al., 2007)

Stage of development:

Full scale test have been conducted at the Gifhorn wastewater treatment in lower Saxony, Germany.

Source of information: Müller et al, 2007

Company: Savron STARx Smoldering Combustion (International/Ontario, Canada)

Technology: STARx

General description: Savron's Ex Situ (STARx) treatment systems use the same patented process as the in situ STAR technology: smoldering combustion. The STARx process uses "off-the-shelf" equipment as the STAR technology (compressors, blowers, vapor treatment), but is carried out in fabricated reactor systems or in engineered soil piles depending on throughput requirements, available footprint, and treatment time requirements.

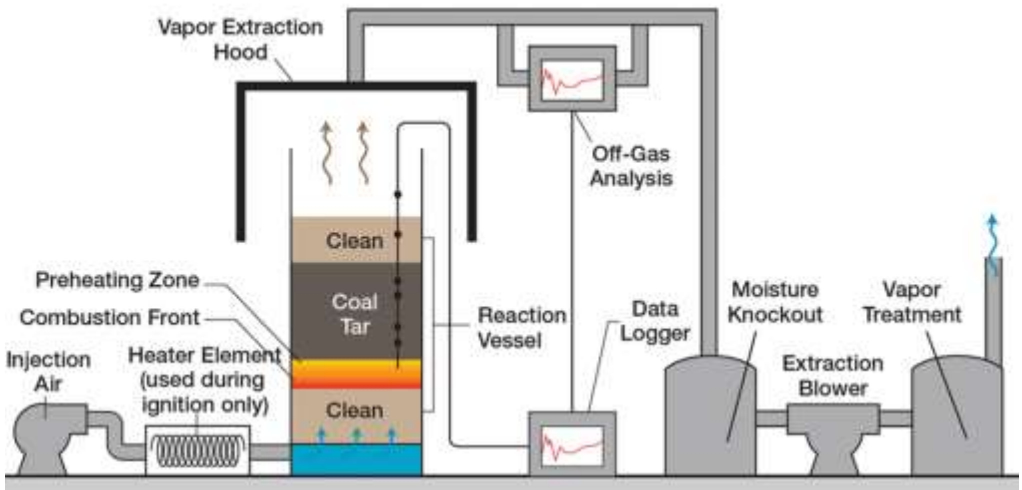

Figure B- 19. Schematic of Ex Situ Treatment process

With waste oils and sludges, the STARx process includes the admixing of a porous matrix (e.g., coarse sand) to facilitate the self-sustained smoldering process. This is a necessary step to transform waste materials that will not burn on their own, to a mixture that will smolder in a self-sustaining (i.e., low energy) process.

Stage of development: Implemented full scale for the treatment of hydrocarbon contaminated soils, and demonstrated feasibility in the treatment of lagoon sludges.

Source of information: http://savronsolutions.com/products

C**ompany**: BCR Environmental (USA/Ontario, Canada)

Technology: BCR Neutralizer, CleanB and CleanB-AC

General description:

BCR Neutralizer treats Waste Activated Sludge (WAS) in a batch process to produce nutrient rich Class A/EQ fertilizer in accordance with USEPA regulations. The CleanB system chemically treats WAS to produce Class B biosolids in less than 10 minutes. CleanB-AC is Class A/EQ composting system for producing completely odor free, nutrient rich compost in approximately 30 days from biosolids to finished product.

Key features include:

- Reduced capital costs and operating costs;
- Reduced energy requirements by 90%;
- Accelerated processing time;
- Elimination of digestion produces a more consistent end product and enhances nutrient retention in the biosolids;
- Enhanced dewatering, resulting in a high quality, higher % solids Class A/EQ product;
- Elimination of odor issues;
- Enhanced regulatory compliance.

Stage of development: BCR Neutralizer is currently operating in 17 facilities in Florida, with the hope to expand and deliver across the U.S. and Canada.

Source of information:

http://bcrenv.com/solutions/neutralizer/process

Company: CNP Technology Water and Biosolids Corporation (Germany and USA)

Technology: AirPrex®

General description: A sludge optimization and phosphorus recovery system that's installed between anaerobic digestion and dewatering. The boundary conditions for struvite precipitation are set by air stripping in the AirPrex® reactor and the addition of a magnesium chemical product. This combination of biological phosphate elimination and the AirPrex® system achieves unrivaled effectiveness in terms of wastewater dewatering efficiency and cost savings.

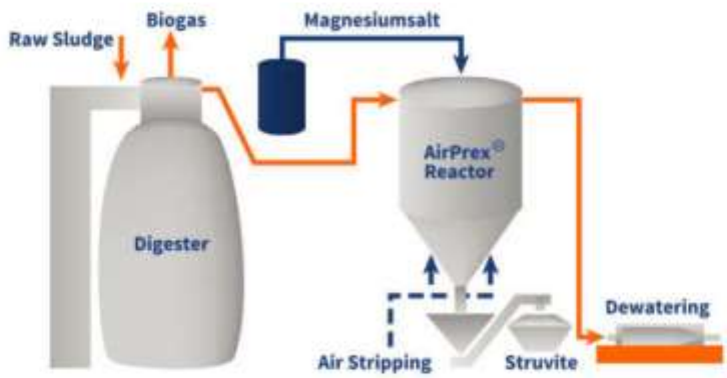

Figure B- 20. Schematic of AirPrex® system

Key features include:

- 90-95% phosphate reduction in the returned/decanted liquor;
- Polymer reduction by up to 30%;
- Disposal cost reduction by up to 20%;
- Maintenance cost reduction by up to 50%;
- Increased revenue from fertilizer by up to 10%.

Stage of development: AirPrex is installed at seven wastewater treatment plants (WWTP) in Europe and China ranging from 10 MGD to 170 MGD.

Source of information: https://www.cnp-tec.com/#solution

Company: OSTARA (Canada)

Technology: WASSTRIP®

General description: The WASSTRIP (Waste Activated Sludge Stripping to Recover Internal Phosphate) process is designed to release nutrients phosphorus, magnesium and potassium (PO_4, Mg, K) from waste activated sludge produced in an enhanced biological phosphorus removal process prior to anaerobic digestion. The WASSTRIP process releases phosphorus and magnesium upstream of the anaerobic digester and sends it directly to the Pearl reactor for recovery, increasing the overall volume of phosphorus and ammonia recovered.

Figure B- 21. Schematic of WASSTRIP®

Key features include:

- Increased P available for recovery;
- 10-20% reduction in sludge production;
- Up to 4% increase in cake solids (corresponding to ~ 20% volume reduction);
- Reduced polymer consumption by 5-20%;
- Reduced total phosphorus in remaining biosolids by nearly 10%;
- Reduced water-soluble phosphorus in biosolids by up to 70%.

Stage of development: WASSTRIP is in operation at Ostara in Tigard, OR; Saskatoon, SK; Madison, WI; and in Buford, GA. Additional facilities are under construction in Hillsboro, OR; Chicago, IL; Winchester, VA; Amersfoort, Holland; and Madrid, Spain.

Source of information: http://ostara.com/nutrient-management-solutions/

Company: University of Idaho

Technology: N-E-W Tech™

General description:

N-E-W Tech™ integrates hydrous ferric oxide reactive filtration in a moving bed sand filter with added ozone and 1-10 grams per gallon of functionalized biochar. N-E-W Tech is a third generation technology built on the reactive filtration platform developed by the University of Idaho. Licensed to Blue Water Technologies, first-generation Blue PRO installations allow limit-of-performance phosphorus removal at wastewater treatment plants with demonstrated scalable success in up to 15 MGD installations. Blue CAT with added ozone for catalytic oxidation, combines with low level P removal with oxidative destruction of trace organic compounds including priority substances. N-E-W Tech advances these capabilities with phosphorus recovery.

Stage of development:

Pilot scale testing has been funded by Idaho Global Entrepreneurial Mission.

Source of information:

http://www.uidaho.edu/research/news/research-reports/2016/environment/wastewater

http://www.werf.org/lift/docs/LIFT_Notes_Docs/2016/Technology_Spotlight/Technology_Spotlight_4-14-16.aspx

Company: Applied Clean Tech

Technology: Recyllose ™

General description: A cellulose recovery from wastewater technology. The sewage recycling system (SRS) pre-treats the wastewater before sludge is formed. The SRS sewage mining technology recycles sewage solids.

Key features include:

- Reduction of sludge formation by up to 50 %;
- Reduction of sewage related health hazards and treatment costs;
- Extraction of cellulose from the sewage solids and recycles it (Recyllose™);
- Treatment plant cost and energy consumption savings;
- Increased treatment plant capacity;
- Reduction of greenhouse gas emissions & carbon footprint.

Stage of development: Successful trial with Dutch Waterschap Aa en Maas (WSAM)

Source of information:

http://www.appliedcleantech.com/index.php

http://www.wateronline.com/doc/applied-cleantech-transforms-wastewater-major-waterboard-in-the-netherlands-0001

Company: Pacific Northwest National Laboratory (PNNL) (USA)

Technology: Hydrothermal Liquefaction Technology (HTL)

General description: Hydrothermal liquefaction technology (HTL) mimics the geological conditions that create crude oil, using high pressure and temperature to achieve in minutes something that naturally takes millions of years. According to the Pacific Northwest National Laboratory (PNNL), this biocrude can then be refined using conventional petroleum refining operations. Sewage sludge was previously seen as a poor source of biofuel because it's too wet. With the process developed by PNNL researchers, sewage does not need to be dried out before it can be transformed into biocrude. Hydrothermal liquefaction breaks down organic matter, such as human waste, into simpler chemical compounds. The material is pressurized to 3,000 PSI and sent into a reactor system operating at about 350C. The heat and pressure cause the cells of the waste material to break down into different fractions – biocrude and an aqueous liquid phase. PNNL estimates that a single person could generate seven to 11 litres of biocrude per year.

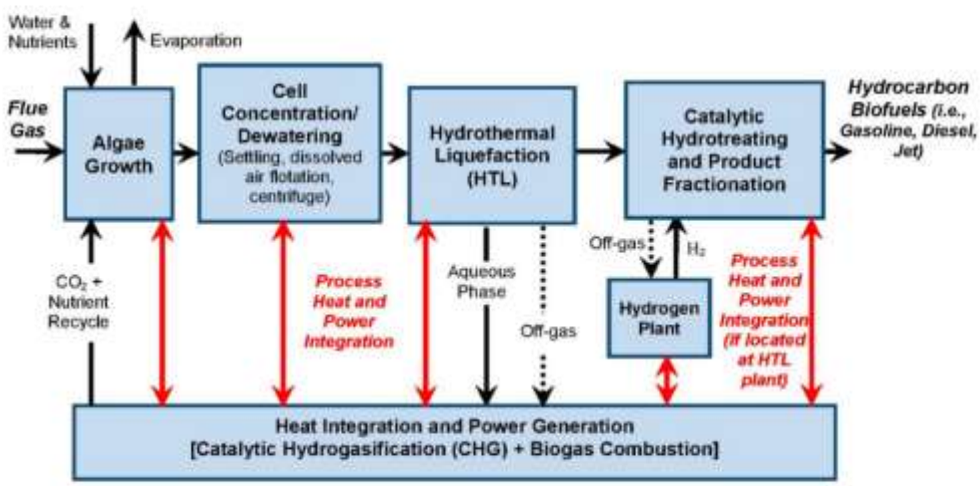

Figure B- 22. Schematic of Hydrothermal liquefaction technology

Stage of development: Full scale demonstration at Metro Vancouver

Source of information: http://www.pnnl.gov/news/release.aspx?id=4317

Company: Orege (France)

Technology: Orege - SLG Advanced Dewatering

General description: A patented technology that improves conditioning of municipal and industrial sludge.

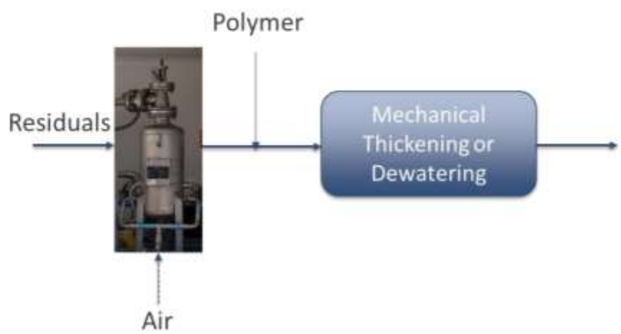

Figure B- 23. Schematic of Orege SLG process

Key features include:

- Reduction of up to 60% in sludge volume and corresponding treatment costs;
- Increase in cake dryness of dewatered sludge by between +3% and +8% depending on the configuration;
- Increase in the treatment rate of existing thickening or dewatering equipment by as much as +150%;
- Reduction of sludge odour;
- Improved sludge quality and valorisation (composting and land spreading);
- Reduced energy consumption of both the sludge workshop;
- Reduced polymer consumption by up to 40%;
- High quality of recovered water (filtrate).

Stage of development: SLG technology is widely used across Europe and the first sale of Orege SLG in North America was to CH2M in February of 2016. There is an ongoing pilot scale demonstration in Ontario, Canada.

Source of information: https://www.orege.com/en/slg/

Company: Metso (Finland)

Technology: Sludge Dewatering Optimizer (SDO)

General description: An automation technology to enable plant operators to operate dewatering equipment with accurate and efficient continuous optimization. A higher solids content of concentrated sludge results in higher thermal energy in the subsequent incineration process, or reduced transportation costs when shipping to a landfill, resulting in improved energy efficiency and environmental sustainability.

Key features include:

- Improved sludge dewatering performance by up to 50%;
- Reduced chemicals consumption;
- Increased process operation efficiency;
- Reduction of laboratory sampling requirements;
- 24/7 real-time data;
- Decreased manual process monitoring requirements.

Stage of development: **N/A**

Source of information: http://www.metso.com

Company: Trojan (International/Ontario, Canada)

Technology: (Trojan) Salsnes^{TM} Filtration

General description: Combines three processes into one compact unit – solids separation, sludge thickening and dewatering. The rotating filter mesh removes >50% TSS, and >20% BOD from effluent and produces drier sludge (20-30% dry matter). It can replace conventional primary treatment and fulfill the EU regulations on primary treatment. With both Enclosed and Open modular systems, unlimited design flow capacity and the option to install indoors or outdoors, a Salsnes Filter system provides flexibility. SFK systems are open for concrete channel installation and can be simply installed into a concrete chamber. SF systems are free-standing and enclosed requiring only a concrete slab for installation. These units can be easily retrofitted into an existing plant or integrated into new construction.

Figure B- 24.Schematic of Salsnes^{TM} filter system

Stage of development: Full scale product are available

Source of information: http://www.salsnes-filter.com/products/

Company: Kemira (Finland)

Technology: Kemicond^{TM} Technology

General description of the innovation:

Technology developed in 2003 by modifying the KREPO Technology and consists of chemical treatment by sulfuric acid and hydrogen peroxide, followed by a two stage dewatering unit.

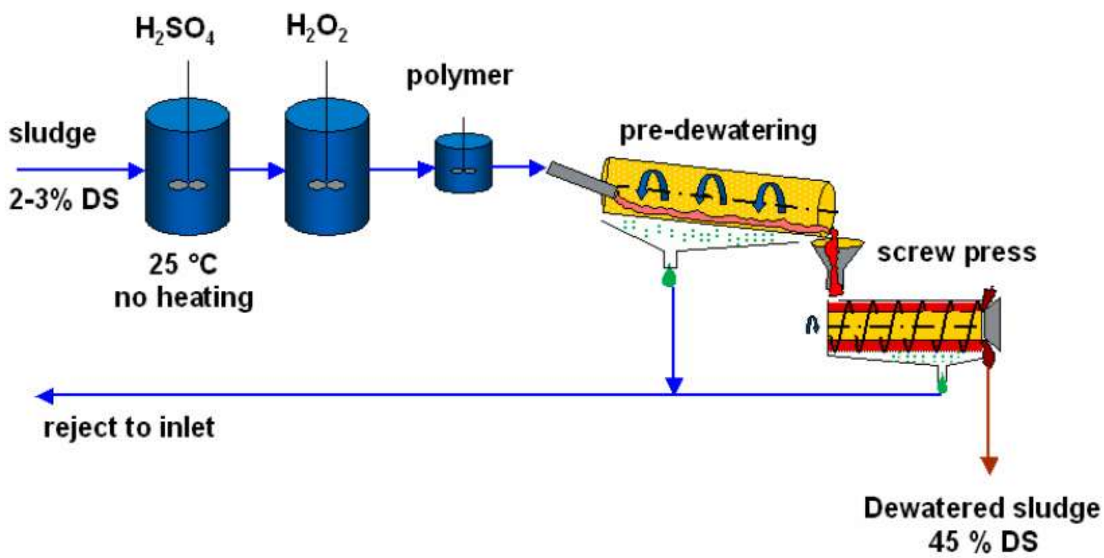

Figure B- 25. Schemtic of Kemicond^{TM} technology (From Karlsson,2007)

Several key steps in Kemira process are:

- The contact time between the chemical and the sludge is 40 to 60 minutes;
- Metals such as iron phosphate and hydroxides are dissolved;
- The peroxide oxidizes the dissolved iron (II) into iron (III);
- The dissolved phosphate can then be re-precipitated as ferric phosphate.

Stage of development: Full scale production

Source of information: WERF Report-Hydromantis

Company: Ovivowater (International)

Technology: Sonolyzer™ AD Pretreatment

General description: Provides sludge reduction via ultrasound cavitation bubbles. Disintegrates sludge by high intensity and low-to-medium frequencies which cause the disintegration of biomass in wastewater through the process of "ultrasonic cavitation".

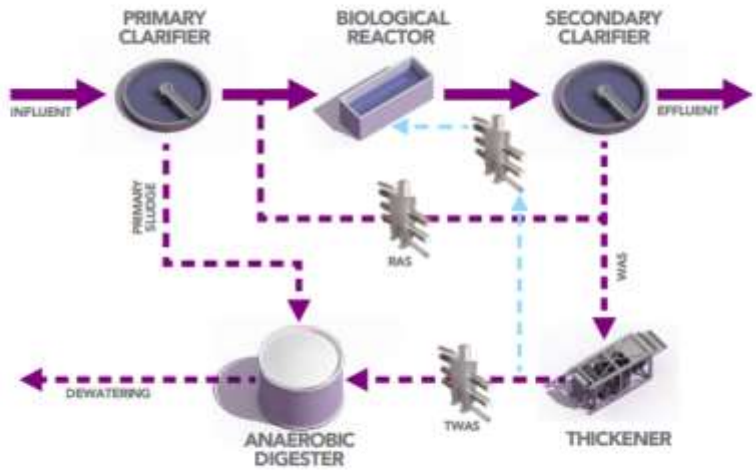

Figure B- 26. Schematic of implementation of Sonolyzer™ in sludge treatment process

Key features include:

- Sludge reduction can be minimized by a factor of 10-20%;
- Increased effective size of digester;
- Decreased cost associated with sludge handling;
- 15-20% biogas production increase;
- No chemicals requirement.

Stage of development: Full scale demonstration has been implemented in Bamberg WWTP, German.

Source of information: http://www.ovivowater.com/product/municipal/municipal-wastewater/sludge-treatment-anaerobic-digestion/sludge-disintegrator/ovivo-sonolyzer-ultrasound-sludge-disintegrator/

Company: Veolia (International)

Technology: ATHOS™

General description: ATHOS™ combines hydrothermal oxidation with biological treatment to mineralize the organic matter in the sludge under moderate conditions of temperature (235 ℃) and pressure (45 bar) in the presence of pure oxygen.

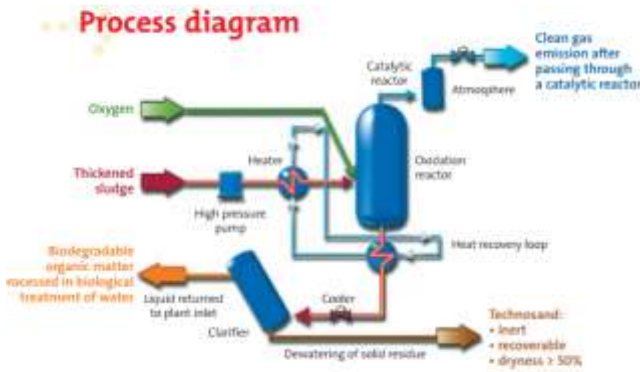

Figure B- 27. Schematic of Athos™ process diagram

Key features include:

- A concentrate of inorganic matter (Technosand) accounting for only 1% to 2% of the initial liquid sludge quantity;
- Zero emission of polluted fumes or harmful by-products;
- Destruction of toxic and malodorous and organic micro-pollutants;
- Reduction of the dewatering stage with no chemical addition;
- Ability to adjust retention time, temperature and the O_2/organic ratio;
- Full integration into the treatment plant and continuous sludge processing.

Stage of development: 5 full scale implementation in EU

Source of information: http://technomaps.veoliawatertechnologies.com/exelys/en/

Company: Veolia (International)

Technology: Solia greenhouse solar sludge dryer

General description: Based on combined solar drying and bio-drying, SOLIA Mix dries and stores sludge in a horticultural greenhouse under continuous ventilation with dry air from the outside. Dewatered sludge and drying sludge are mixed into drying sludge and spread throughout the greenhouse as windrows by the SOLIAMIX™ windrow turner.

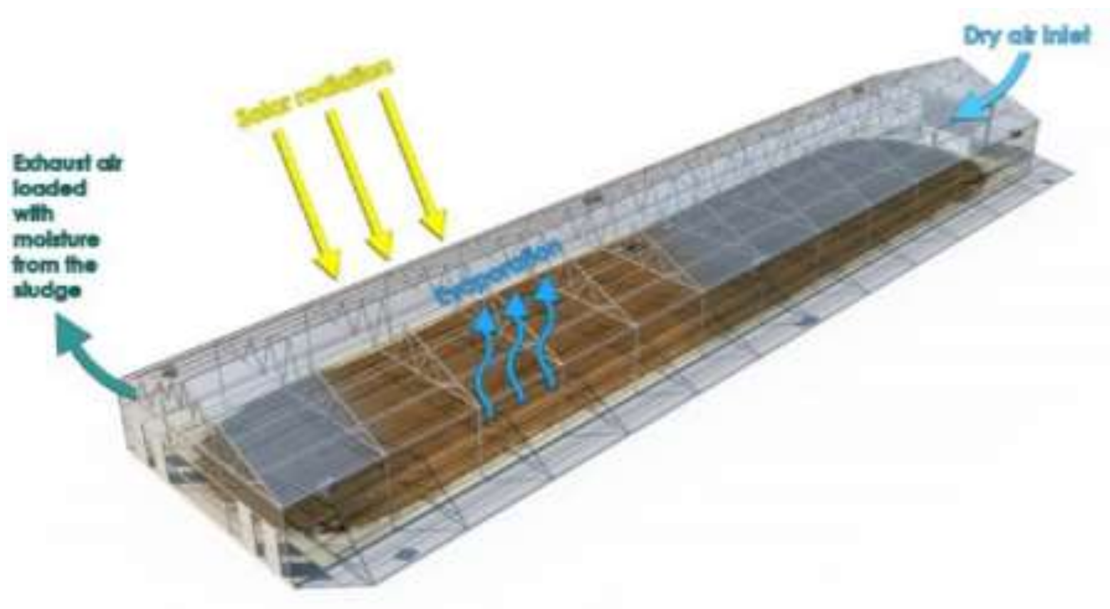

Figure B- 28. Schematic of operating principals of SoliaMix™

Key features include:

- A dry solids content up to 90%, reducing sludge volume and removal costs.
- Increased volume of the sludge turned in one pass;
- Treated sludge quantity is 30% greater for the same surface area;
- Reduction of the drying cycle duration;
- Compact and economical process.

Stage of development: More than 30 full scale implementation globally

Source of information: http://technomaps.veoliawatertechnologies.com/soliamix/en/