



OPTIONS FOR IMPROVED NUTRIENT REMOVAL AND RECOVERY FROM MUNICIPAL WASTEWATER IN THE CANADIAN CONTEXT

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WHY DID WE DO THIS RESEARCH?

Municipal wastewater generated by Canada's expanding population carries a significant load of the nutrients nitrogen (N) and phosphorus (P). Improved scientific understanding and increasing public awareness of the adverse effects of nutrient overload in a watershed is putting pressure on municipalities to introduce or enhance treatment technologies that remove these nutrients from wastewater.

Most conventional nutrient removal processes are energy-intensive and/or require the use of large amounts of chemicals, resulting in high greenhouse gas emissions. Municipalities are seeking processes that accomplish nutrient removal with minimal social impact, environmental impact and financial burden — a “triple bottom line” approach.

Over the past two decades, researchers and practitioners around the world have introduced many improvements to conventional nutrient removal processes and developed new technologies. These include nitrogen removal processes with significantly reduced energy demand, as well as processes for recovery and reuse of water, nutrients and energy from wastewater. However, the adoption of these advancements varies, depending on the size and location of municipalities. In addition, some technologies have not been tested in a Canadian climate, leading to knowledge gaps in practice and regulations.

This 2013-2015 project evaluated and interpreted current research and practice on nutrient removal and recovery to provide a knowledge base for the design, operation and regulation of municipal wastewater treatment plants (WWTPs) in Canada. In order to identify a range of options for removal, recovery and reuse and analyze the extent to which these options can be applied in Canadian conditions, the project explored:

- Achievable limits of nutrient removal
- Types and configurations of treatment systems in use in Canada, with guidance on upgrades
- A province-by-province survey of regulatory drivers regarding effluent quality
- Practice and potential for nutrient recovery in conventional and advanced plants, including return on investment
- The influence of climatic factors in process selection
- Operational and capital costs of upgrades and greenfield plants
- Research and development needs to bring advancements into practice

HOW WAS THE RESEARCH CONDUCTED?

1) LITERATURE REVIEW

Over 400 papers, reports and textbooks regarding nutrient removal, recovery and reuse from municipal wastewater were included in the literature review. The review went back to 2004, except in the cases where information published before the cut-off date was deemed necessary. Research and practice findings were summarized, describing state-of-the-art processes and trends that will become game changers for WWTPs in the near future.

2) ONLINE SURVEY

An online survey of WWTPs included questions about operations and barriers to implementation of nutrient removal, recovery and reuse. The survey provided a snapshot of the economic, regulatory and operational parameters of municipal wastewater treatment in Canada. Sent to 150 municipalities, the survey generated response from 69 municipalities.

3) EXPERT INTERVIEWS

Key experts, including WWTP managers/operators, leading consultants, technology vendors, regulators and leading academics, were interviewed to capture the Canadian context from practice to regulation. These open-ended interviews gauged the opinions of various stakeholders on drivers, barriers, research gaps and the future of nutrient removal, recovery and reuse in Canada and collected more information on processes and performance.

WHAT WERE THE RESULTS?

The levels of treatment attained at WWTPs in Canada can be quite diverse, due to differences in provincial regulations and varying levels of receiving water sensitivity. Coastal plants in British Columbia (BC) and the Maritimes generally do not remove nutrients. The remainder of Canada's treatment systems can be roughly divided into three categories:

1. Throughout Canada, many smaller communities with a population under 3,000 use lagoon systems, often without removal of nitrogen or phosphorus.
2. Municipalities in Eastern Canada tend to employ conventional activated sludge with extended aeration (CAS EA) for removal of organic pollutants and oxidation of ammonia nitrogen to nitrate nitrogen. Some of these plants remove nitrate nitrogen using SND processes. Most plants are removing phosphorus, some to low levels (i.e., below 0.3 mg TP/L) using Chem. P.
3. Municipalities in Western Canada, including the Prairies and central BC, tend to use BNR processes which remove both nitrogen and phosphorus, typically to levels of 15 mg TN/L and 1 mg TP/L.

No definite answer was found on whether a Chem. P or BNR approach is better for phosphorus removal. Both processes, when well designed and operated in Canada, have been shown to offer comparable levels of reliability and effluent TP levels at 0.5 mg TP/L. This level can drop further when tertiary filtration is incorporated into either process.

Chem. P is very compact and reasonably simple to control, which reduces the initial investment cost. However, the operational costs are higher, particularly given the rising market prices of chemicals that need to be transported and stored. BNR processes have lower long-term operational costs and are less dependent on fluctuations in chemical pricing. BNR processes work best with fresh wastewater that is rich in organic matter (a carbon source for bacteria), but require the use of larger tankage and more experienced operators. The removal of nitrate nitrogen should also be implemented to ensure stable biological P removal.

Since there is no universal justification for choosing between chemical or biological phosphorus removal, process selection should be based on local conditions, including existing tankage, wastewater characteristics, chemicals availability, biosolids management options and long-term carbon footprint. Frequently, the best long-term solution to achieve phosphorus concentrations below 0.5 mg TP/L is to combine Chem. P and BNR. BNR removes most of the phosphorus, and the remaining phosphorus is removed by chemical precipitation, leading to drastic reduction in chemical usage and associated costs.

Another factor influencing the selection of chemical or biological phosphorus removal is the form of phosphorus removed. Chem. P processes produce strongly bound metal phosphates (e.g., iron, aluminum, calcium), which may not be bioavailable when applied to farm lands. Full recovery of phosphorus can only be made by generating ash through incineration. In BNR processes, phosphorus is trapped in bacterial cells and can be easily extracted and recovered later on, and is fully bio-available in land application.

LIMITS OF NUTRIENT REMOVAL

In ecologically fragile areas where nutrients discharge must be reduced, wastewater treatment plants are being equipped with a variety of polishing processes, all of which remove remaining suspended solids from treated wastewater. The most popular polishing processes are sand filters, which often include iron or aluminium salts for further soluble phosphorus removal on the filter. Methanol can also be dosed to filters to support bacteria growth and facilitate nitrate nitrogen removal (i.e., post-denitrification). With the available post-treatment and best available solids separation (i.e., such as membrane ultrafiltration and reverse osmosis), the current limit of nutrient removal that can be achieved with this technology is 0.01 mg TP/L and below 3 mg TN/L.

ACRONYMS:

- Total phosphorus (TP)
- Total nitrogen (TN)
- Total ammonia nitrogen (TAN)
- Chemical precipitation (Chem. P)
- Biological nutrient removal (BNR)
- Conventional activated sludge -extended aeration (CAS EA)
- Wastewater Treatment Plant (WWTP)
- Carbon (C)

Since nitrogen is removed biologically, the lowest possible TN effluent concentration depends primarily on the presence of non-biodegradable soluble organic nitrogen fraction of TN in raw wastewater, which passes to the effluent unchanged. Examples of attainable removal of TP, total ammonia nitrogen (TAN) and TN are shown in Table 1.

PROCESS	TP mg P/L	TAN mg N/L	TN mg N/L
CAS EA	5	<3	25
CAS EA + SND + CHEM. P	0.3	<1	<7
BNR	<0.5	<1	<7
CAS EA + SND + CHEM. P + FILTER	<0.1	<1	<7
BNR + POST-DENITRIFICATION + CHEM. P + ULTRAFILTRATION MEMBRANE	0.01	<1	<3

Table 1. Attainable removal of total phosphorus, total ammonia nitrogen and total nitrogen in various process configurations.

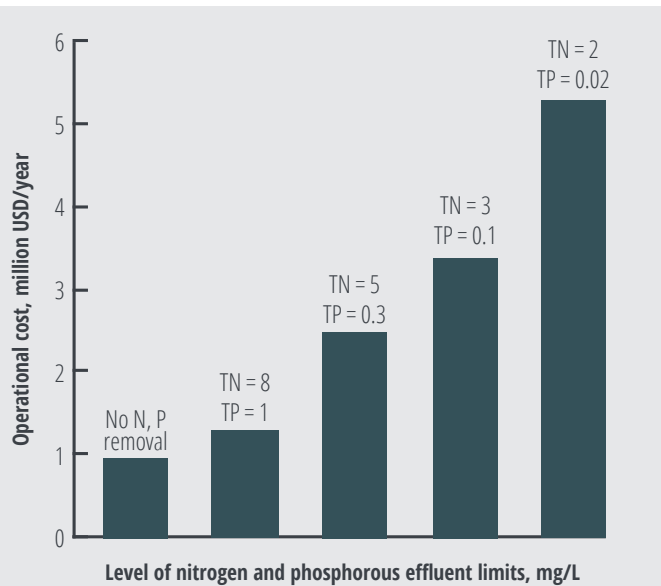


Figure 1. Annual operating costs for nutrient removal at 40 ML/d WWTP at increasing effluent quality requirements (developed after Falk et al., 2013)

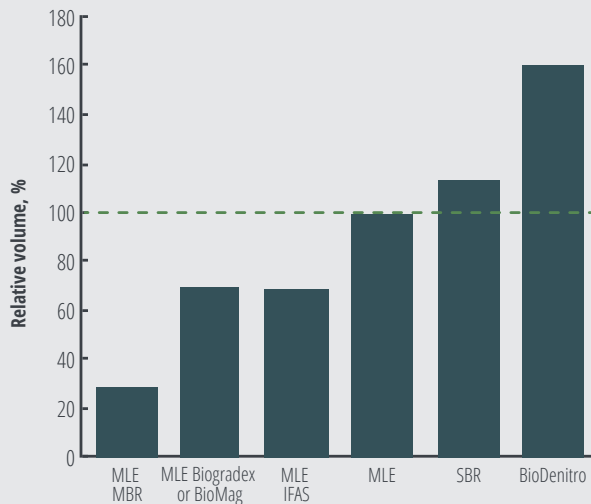
The removal of nutrients to very low levels was found to be costly compared to conventional treatment. Achieving effluent TP below 0.3 mg/L and TN of 5 mg/L almost triples the operational costs of conventional treatment without dedicated nutrient removal¹. The cost doubles again when the treatment goal is reduced to 2 mg N/L and 0.01 mg P/L. This translates into a net present value of USD200 per kg for removal of 1 kg of TP down to effluent level of 1 mg/L at WWTPs serving a population of 150,000. Removal of 1 kg of phosphorus from 1 mg/L down to 0.01 mg/L in the effluent would cost another USD560 per kg of phosphorus.

Since nutrients discharged from municipal wastewater point sources typically constitute only 5% to 20% of the total load of nutrients in the watershed, this is a high price to pay for a relatively small incremental reduction of load to the receiver. Watershed partnerships in the USA and Ontario demonstrated that the cost per kilogram of nitrogen or phosphorus removed from the watershed by agricultural conservation practices is 7 to 10 times lower than the cost of nutrient removal to very low levels from municipal wastewater^{2,3}.

MOVING FORWARD

WWTPs in growing municipalities often lack the space to install nutrient removal technologies or to expand capacity. New design options retain more biomass in the existing system, thus achieving higher removal rates per m³ of the reactor (see Figure 2). This may be facilitated by the use of vacuum degasification of mixed liquor (Biogradex), which allows adequate removal of TN while increasing biomass concentration. Membrane bioreactors (MBR), which retain biomass with a membrane rather than by settling it in a clarifier, offer up to 75% reduction of the required volume, compared to conventional nitrogen removal like the modified Ludzack-Ettinger system. However, despite improvements, it remains an energy intensive and expensive process, as the membranes must be changed every 8 years.

The integrated fixed film activated sludge (IFAS) method combines the features of suspended biomass and biofilm. It is essentially a BNR system with added plastic media that provide a surface for biofilm growth and provides up to 30% volume reduction. Even though the additional costs of media purchase are comparable with the construction costs of additional tankage, IFAS is often considered for plants without space constraints, due its higher reliability during rapid changes of operational conditions like temperature drop or wet weather flow.



NOTE:

MLE - Modified Ludzack-Ettinger, the simplest nitrogen removal process with separate nitrification and denitrification tanks; MBR - Membrane bioreactor, membrane filtration used instead of final clarifiers; Biogradex and Biomag - process modification improving settling in final clarifiers; IFAS - Integrated fixed film activated sludge, employs simultaneously bacteria growing in suspension and on plastic media; SBR - Sequencing bioreactor, due to alternating operational conditions process combines all reactor zones and final clarifier in one tank; BioDenitro - example of conventional activated sludge process with simultaneous nitrification/denitrification (CAS + SND).

Figure 2. Relative volume of various nitrogen removal processes.

Two new technologies that may decrease energy consumption have not yet entered the Canadian market: Anammox and Aerobic granular sludge (AGS) processes.

Processes based on Anammox bacteria employ autotrophic microorganisms for ammonia-nitrogen removal using only nitrite nitrogen and some alkalinity under non-aerated conditions. Only half of the initial nitrogen load has to be oxidized in aerobic conditions, and only partially to nitrite nitrogen, instead of fully to nitrate nitrogen. Anammox-based processes may reduce the cost of energy for nitrogen removal by 35% and carbon requirements by 90%.

Anammox processes have become state-of-the-art methods for treatment of concentrated, typically warm sludge dewatering liquor (SDL), and are used in over 100 installations worldwide. There are two installations in planning stage in Canada. Adapting the Anammox process to treatment of the main stream municipal wastewater, which is much colder and has lower ammonia concentration than SDL, has become a priority. The process has to be better understood before it can be applied in Canadian conditions of more dilute and colder spring-thaw wastewater. Application of the main stream Anammox offers potential for achieving energy self-sufficiency. A proposed WWTP schematic that generates such energy self-sufficiency for a plant, while reducing its carbon footprint, is presented in Figure 3. In this schematic, the plant would utilize bioaugmentation of the main stream, with biomass from the side stream.

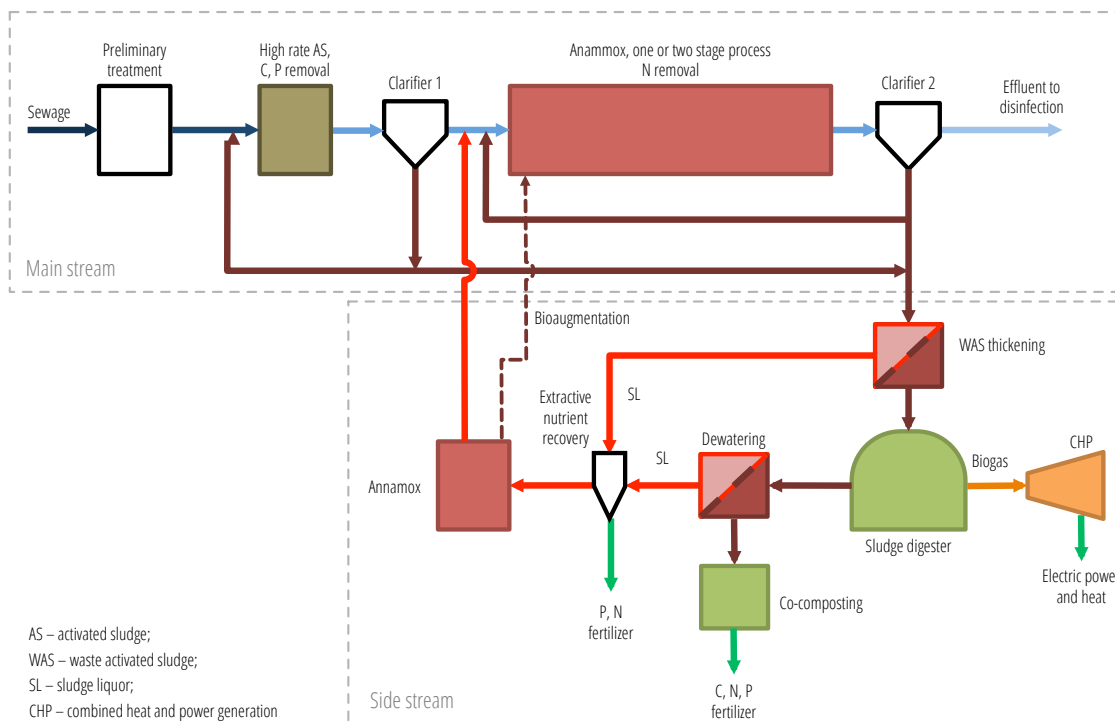


Figure 3. Process diagram of an energy self-efficient WWTP (based on Schaubroeck et al., 2015).

The second group of new processes are aerobic granular sludge (AGS) processes. There are 6 full scale AGS plants in The Netherlands, Poland, Portugal and South Africa that use specific hydraulic reactor configuration and sequencing batch process operation to create and maintain granules composed of bacteria found in conventional BNR. The specific distribution of different groups of bacteria within the granules allows the process to simultaneously remove nitrogen and phosphorus in one aerated tank. The granular biomass settles within minutes, significantly reducing the volume compared to conventional flocculent biomass, which must employ large secondary clarifiers. AGS may also save up to 50% of electric energy due to lower specific aeration requirements to oxidize a unit of COD (chemical oxygen demand). A major issue slowing the implementation of AGS in North America is a lack of explicit performance measures to design full scale reactors that promote granulation, particularly when upgrading existing continuous flow plants.

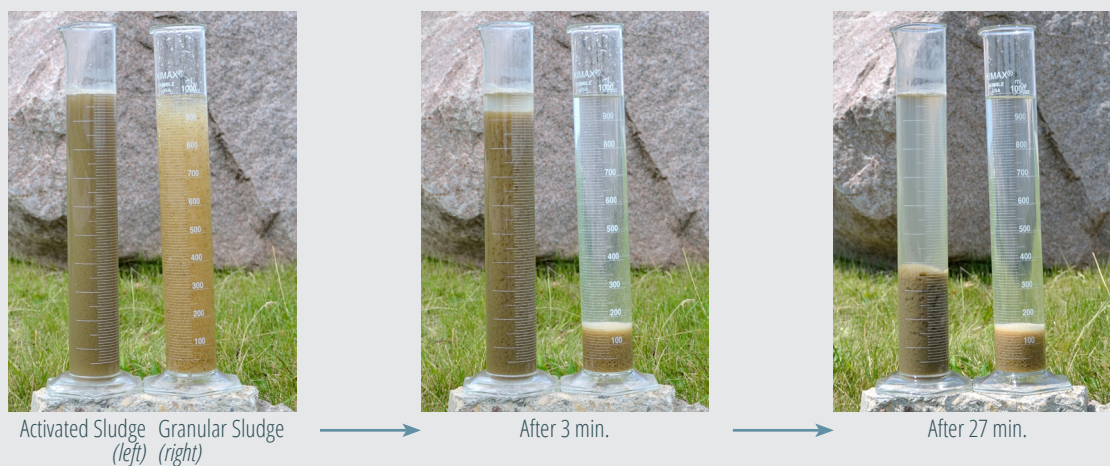


Figure 4. Comparison of settling properties of aerobic granular sludge and activated sludge. Photo: T. Devlin, University of Manitoba

RECOVERY AND REUSE

Economic incentive is one of the most important drivers for municipal wastewater nutrient recovery. With Canada’s population approaching 36 million, there will be approximately 43,000 tons of phosphorus discharged annually in municipal wastewater. Recovery of that total would reduce almost 1 million tons of greenhouse gas emissions and could generate a revenue stream that could offset the costs of nutrient removal.

Many WWTPs are regulated to low effluent phosphorus limits and use chemicals like ferric to avoid nuisance scaling in the treatment stream. Most often the economic calculation in these conditions favors magnesium-based recovery of phosphorus over ferric precipitation. Saskatoon WWTP (capacity of 120,000 m³/d) uses Ostara Pearl process — a Canadian technology, to produce 250 tons/year of high quality struvite fertilizer. The return on investment in 11 plants currently practicing phosphorus recovery from waste activated sludge or anaerobically digested sludge liquor in North America varies between 7 and 14 years, and depends on the severity of prior scaling, the attained improvement in dewaterability of sludge and the impact of phosphorus recovery on stabilization of effluent phosphorus concentration.

Two of the several approaches to phosphorus recovery are presented in Figure 5. Recovery from waste activated sludge or from anaerobically digested sludge dewatering liquor can yield at best only 40 to 45% of the phosphorus load coming in with the raw wastewater. Recovery from ash offers almost 90% recovery of phosphorus. However, it is not yet widely practiced because strong chemicals are needed to release phosphorus from ash, which makes the process uneconomical at current fertilizer prices. Recovery from sludge liquor, on the other hand, is relatively simple and provides product at a competitive price. Figure 6 illustrates potential forms of recovered struvite in systems recovering P from anaerobically digested sludge.

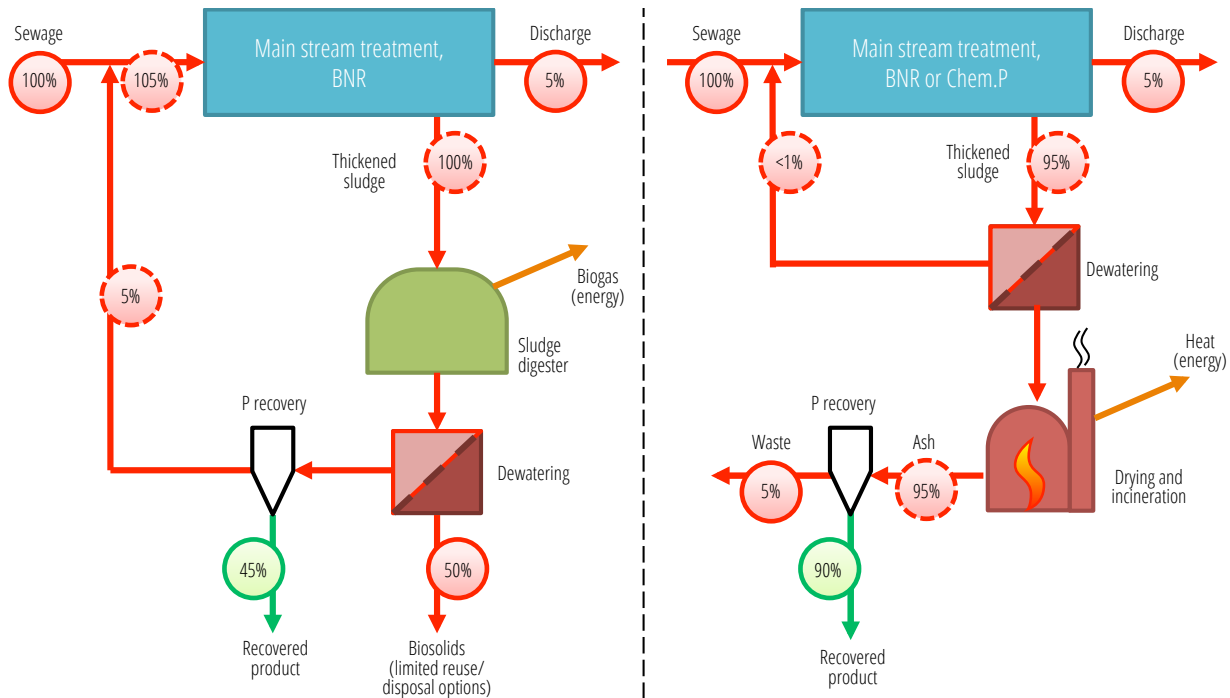


Figure 5. Potential P recovery approaches. In circles percent of P load coming to the plant.



Figure 6. Various form of recovered struvite. From left: Ostara Pearl, electrochemical method, AirPrex.
 Photo: D. Kruk, University of Manitoba

While the number of phosphorus recovery installations continues to increase, nitrogen recovery is practiced in only a handful of plants in the European Union. Nitrogen recovery is economically feasible only under special conditions, such as when recovered ammonia has immediate use onsite. Otherwise, the combined unit costs of producing ammonia and then removing it from wastewater using an Anammox process are much lower than the unit cost of ammonia recovery, making nitrogen recovery uneconomical.

Spreading biosolids generated during treatment on farm land is the simplest and the most common way to reuse nutrients. However, there is rising public concern about the quality of solids generated, due to inadequate scientific information about the potential impact of emerging substances of concern. Increasing urban sprawl is also necessitating non-odorous agricultural practices. There is also a research gap regarding the practical availability of phosphorus and nitrogen in biosolids to plants, especially biosolids from WWTPs practicing chemical P removal vs biological P removal.

This knowledge is important to establish, and therefore regulate, maximum dose of biosolids, to provide optimum fertilization of land without risking increased runoff of nutrients. It is expected that land application of solids will continue to be an important avenue for nutrient reuse in Canada; however, the form of applied solids must be commensurate with local conditions. This is why slow release fertilizers, such as those generated by extractive phosphorus recovery, have developed a niche market in Canada. At present the market can take any amount of struvite fertilizer generated at the treatment plants in Canada.

WHAT ARE THE IMPLICATIONS FOR STAKEHOLDERS AND DECISION MAKERS?

Many Canadian facilities can significantly decrease their nutrient load through relatively low-cost changes to process operations. These facilities have an opportunity for proactive improvement ahead of the regulations due to conditions at the plant (e.g., oversized tanks, decreased pollutant loads, extended aeration time). The stricter effluent standards should be introduced gradually and should be equitable to all contributors to the nutrient load in the watershed, including agricultural contributors.

An overhaul of Canadian WWTPs provides an opportunity to introduce the latest nutrient removal technologies, which will significantly reduce energy and chemical demand and will prepare plants for long term operation independent of market fluctuations.

Extractive phosphorus recovery from concentrated liquid streams is an economically vital and mature technology alternative in plants experiencing operational difficulties due to scaling of equipment. Recovery reduces costs of maintenance and overall cost of phosphorus removal, while simultaneously providing for a more stable operation, improved dewatering of solids and generating a value-added product (quality fertilizer) with a ready market. Regulators should provide incentives rather than mandate recovery processes, because the cost to benefit ratio is site specific.

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