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Resource Recovery

FINAL
REPORT

Towards a Renewable Future: Assessing Resource Recovery as a Viable Treatment Alternative State of the Science and Market Assessment

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TOWARDS A RENEWABLE FUTURE: ASSESSING RESOURCE RECOVERY AS A VIABLE TREATMENT ALTERNATIVE

STATE OF THE SCIENCE AND MARKET ASSESSMENT

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ABSTRACT AND BENEFITS

Abstract:

Extractive nutrient recovery is defined as the production of chemical nutrient products devoid of significant organic matter. It represents a complementary strategy for managing nutrients in multiple waste streams. In doing so, energy and resources are used to accumulate and produce a chemical nutrient product that is recyclable and has a resale value that could potentially help offset operating costs while reducing nutrient production from raw materials for agricultural or other uses. These products include a variety of nitrogen, phosphorus, and iron compounds; however, products like phosphorus-enriched biosolids are excluded from this current report.

This report represents the state of the science review of extractive nutrient recovery technologies with a special emphasis on bridging the knowledge gap currently faced by utilities when considering nutrient recovery for nutrient management. A complementary interactive electronic technology summary matrix is also available. Based on the review of technology, it is proposed that extractive nutrient recovery will likely be most viable if employed within a three-step framework including accumulation, release, and extraction steps.

At the time of this report (2015), phosphorus recovery in the form of struvite was the most established technology for facilitating extractive nutrient recovery at full-scale water resource recovery facilities (WRRFs). Nitrogen only recovery is also feasible but has not been implemented extensively at WRRFs. Taking this into account, it is estimated that the domestic wastewater treatment industry can optimistically bring between 100,000 and 210,000 metric tonnes of P₂O₅/yr (as struvite) and up to 220,000 metric tonnes N/yr to the fertilizer market.

Using historical market data, this suggests that the wastewater treatment industry can optimistically meet between 2 and 5% of the total P₂O₅ fertilizer demand, between 30 and 100% of the specialty ornamental P₂O₅ fertilizer demand, up to 2% of the total N fertilizer demand, and between 30 and 194% of the specialty and ornamental N fertilizer demand. The corresponding estimated market price for the nutrient products (2012 U.S. dollars) is approximately U.S.\$1.25 to 2.50 /kg of N and U.S.\$5.80 to 7.50/kg of P.

Strategies that could be used to facilitate the implementation of struvite recovery and other extractive nutrient recovery technologies are provided. These strategies include performing a complete benefits analysis. This analysis should quantify reductions in supplemental carbon requirements, reduction in aeration requirements, reduction in biosolids production for nutrient recovery versus conventional alternative, reduction in costs associated with mitigating nuisance precipitate formation, impacts to sludge dewaterability, and benefits associated with manipulating the N and P content of the biosolids.

Benefits:

- ◆ Identifies barriers that prevent utilities of various sizes from using existing commercially available technologies to recover phosphorus.
- ◆ Discusses development of strategies that can be used to circumvent barriers against implementing extractive nutrient recovery.
- ◆ Presents a critical compendium of extractive nutrient recovery technologies and introduces a three-step framework to facilitate more rapid adoption of extractive nutrient recovery.
- ◆ Provides a description of the market potential for recovered chemical nutrient products.
- ◆ Provides a framework for selecting a nutrient recovery and, depending on the conditions at the WRRF, establishes whether keeping phosphorus in biosolids is less or more beneficial than concentrating the phosphorus in an inorganic phase such as struvite.

Keywords: Barriers to adopt existing technologies, nutrient removal/recovery, struvite, nitrogen, phosphorus, extractive nutrient recovery, market assessment, sustainable nutrient management.

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LIST OF ACRONYMS

AAPFCO	American Plant Food Control Officials
A/AD	Anoxic/Aerobic Digestion
AEM	Anionic Exchange Membrane
ANFO	Ammonium Nitrate and Fuel Oil
ATAD	Autothermal Aerobic Digestion
BOD	Biochemical Oxygen Demand
CAD	Conventional Aerobic Digestion
CEM	Cation Exchange Membrane
Cl	Chloride
CO ₂	Carbon Dioxide
COD	Chemical Oxygen Demand
CSTR	Continuous Stirred Tank Reactor
ED	Electrodialysis
EBPR	Enhanced Biological Phosphorus Removal
HGMS	High Gradient Magnetic Separation
IFA	International Fertilizer Industry Association
K	Potassium
LIFT-TEP	Leaders Innovation Forum for Technology – Technology Evaluation Program
MES	Microbial Electrolysis Cell
MET	Microbial Electrochemical Technologies
MFC	Microbial Fuel Cell
N	Nitrogen
NH ₃	Ammonia
O&M	Operation and Maintenance
P	Phosphorus
PAO	Phosphorus Accumulating Organism
PFRP	Process to Further Reduce Pathogens
PNSB	Purple Non-Sulfur Bacteria
PP	Polypropylene
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate

PHV	Polyhydroxyvalerate
PTFE	Polytetrafluorethylene
PSRP	Process to Significantly Reduce Pathogens
PVDF	Polyvinylidene Fluoride
RAS	Returned Activated Sludge
SGN	Size Grade Number
SRT	Solids Retention Time
TERRY	Tool for Evaluation Resource Recovery
TFI	The Fertilizer Institute
TOrC	Trace Organic Contaminant
TN	Total Nitrogen
VFA	Volatile Fatty Acid
WAS	Waste Activated Sludge
WERF	Water Environment Research Foundation
WRRF	Water Resource Recovery Facility

EXECUTIVE SUMMARY

ES.1 Project Overview

Implementation of extractive resource recovery technologies at water resource recovery facilities (WRRFs) has been limited to date (2015). This research sought to facilitate a more widespread adoption of resource recovery at WRRFs. Three main objectives were defined for this purpose:

1. Characterize factors influencing the adoption of extractive resource recovery systems.
2. Provide guidance on the implementation of extractive resource recovery technologies at WRRFs with a special emphasis on phosphorus.
3. Experimentally evaluate innovative extractive nutrient recovery technologies with an emphasis on phosphorus recovery.

ES.2 Project Approach and Schedule

For Objective 1, the project team performed an extensive review of peer reviewed literature regarding extractive nutrient recovery. The project team also surveyed nine commercial technology providers to supplement existing peer reviewed data. In this survey, the technology providers were asked to provide process principles where applicable, technological (including technical performance) details to the extent possible, prior experiences in the implementation of technology where applicable, and operational and management costs associated with technology implementation as well as research and development efforts to the extent possible. A comprehensive assessment of the chemical nutrient product market and historical pricing was also performed for the United States. These data were compiled into a comprehensive literature review (this report) and an electronic interactive technology matrix (Resource Recovery Technology Matrix – Nutrients).

For Objective 2, the project team surveyed a total of 20 utilities. In this survey, the utilities were asked to self-identify challenges associated with implementing extractive nutrient recovery. Operating data for pilot and full-scale testing were also requested. Data from Objective 2 were used to compile detailed case studies that provide guidance as to the implementation of extractive nutrient recovery via struvite crystallization. Information from these case studies was also used to develop the Tool for Evaluating Resource Recovery (TERRY – Phosphorus). Findings from this phase of research are summarized in WERF report NTRY1R12b, *Towards a Renewable Future: Assessing Resource Recovery as a Viable Treatment Alternative – Case Studies Report*.

For Objective 3, researchers at the University of Queensland, Australia performed research on two innovative concepts focused on enhancing nutrient recovery at WRRFs. The first project involved optimizing phosphorus release and availability during and after solids stabilization. The second project involved quantifying the fate of nitrogen, phosphorus, and potassium (K) in enhanced phosphorus removal systems with a focus on determining whether electrodialysis could be used to recover nitrogen and potassium from sidestreams. Impacts on sludge settleability and dewaterability were also investigated. Results from this phase of research are summarized in WERF report NTRY1R12c, *Towards a Renewable Future: Assessing Resource Recovery as a Viable Treatment Alternative – Innovative Extractive Nutrient Recovery Technologies*.

ES.3 Lack of Knowledge as Well as Limited Finances Can Limit Implementation of Extractive Nutrient Recovery at WRRFs

Strategies that can be utilized to navigate the barriers against implementing extractive nutrient recovery are summarized in Figures ES-1, ES-2, and ES-3.

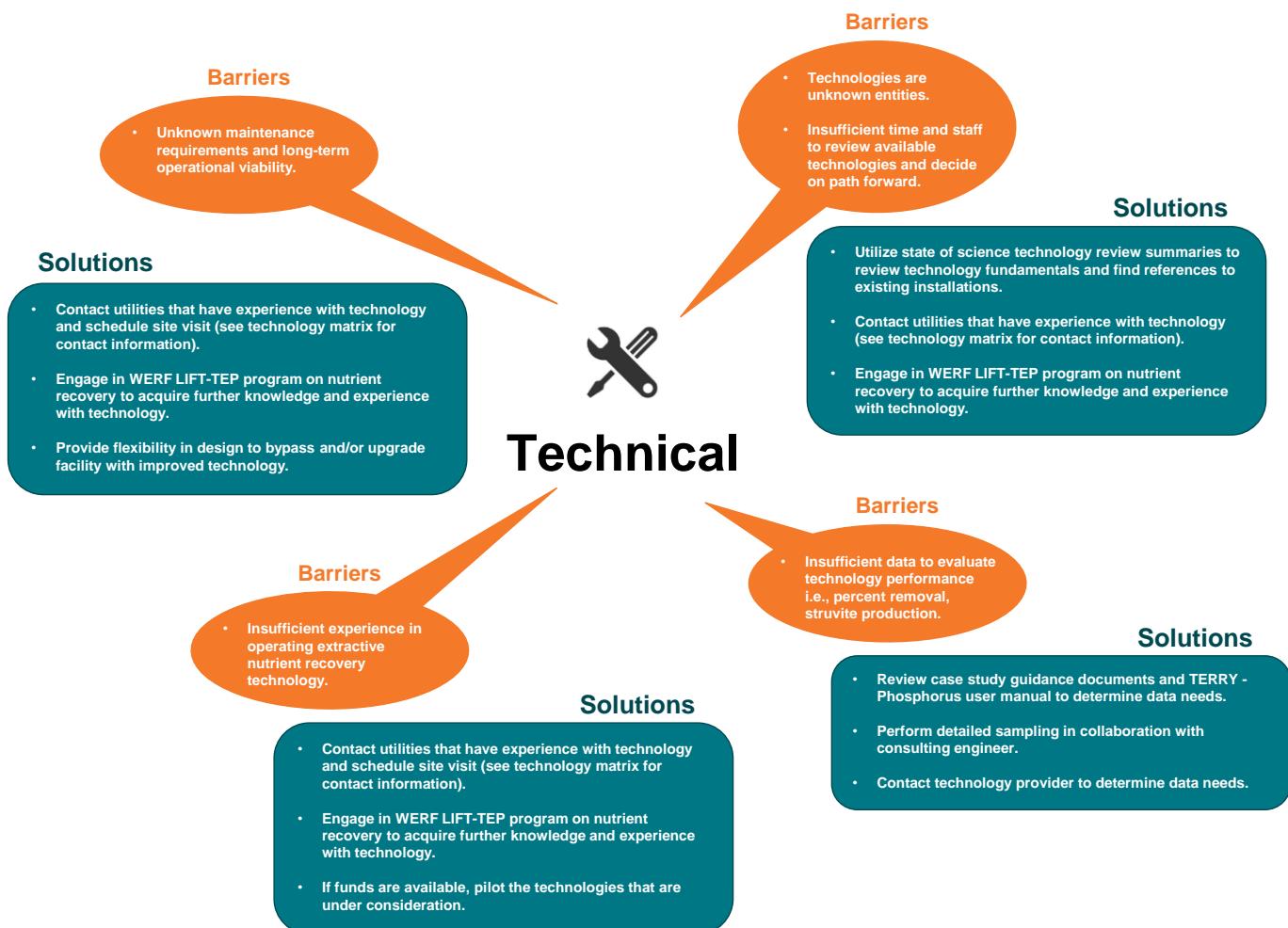


Figure ES-1. Strategies for Navigating Technical Barriers Associated with Implementing Extractive Nutrient Recovery.

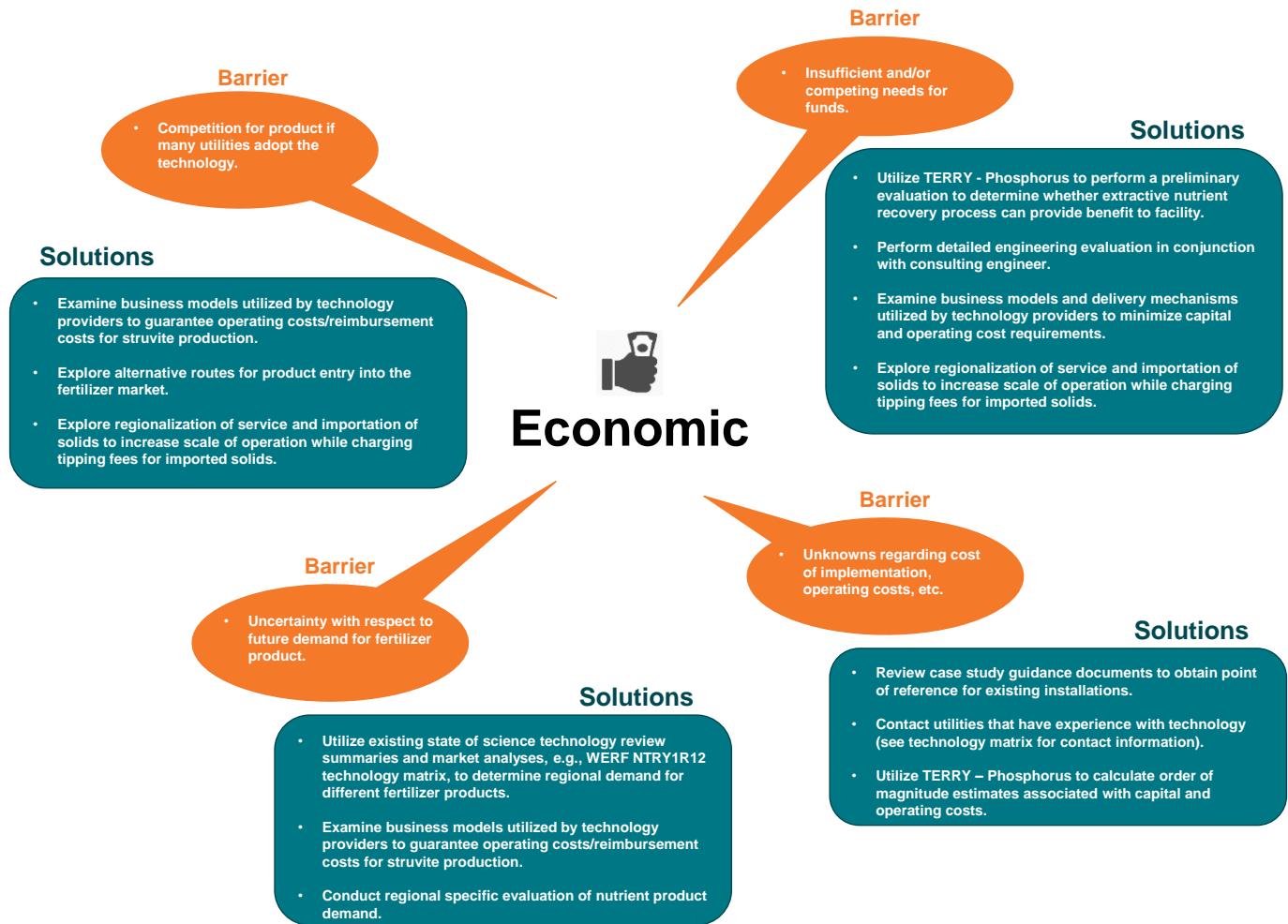


Figure ES-2. Strategies for Navigating Economic Barriers Associated with Implementing Extractive Nutrient Recovery.

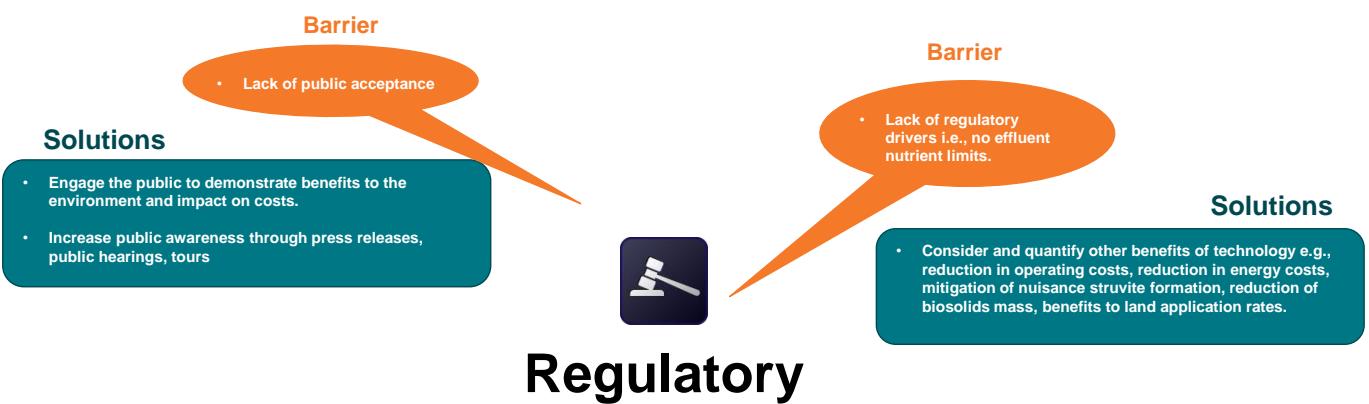


Figure ES-3. Strategies for Navigating Regulatory Barriers Associated with Implementing Extractive Nutrient Recovery.

ES.4 A Three-Step Framework for Implementing Extractive Nutrient Recovery is Recommended

A three-step framework of accumulation, release, and extraction for process configuration and technology selection is recommended (Figure ES-4). Accumulation processes can be used to concentrate dilute quantities of nutrients in the mainstream flow. Release processes can be used to generate nutrient rich, low flow streams. Extraction processes generate a chemical nutrient product with low organic content.

Using this approach, process designers can institute operational flexibility into any nutrient recovery system. Through use of this framework, extractive nutrient recovery technology can also be used to complement the most commonly established nutrient recovery technology i.e., biosolids production.

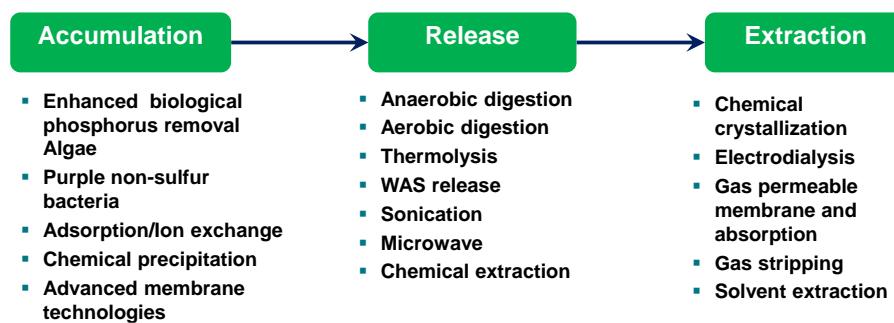


Figure ES-4. Three-Step Framework for Implementing Extractive Nutrient Recovery.

Magnesium struvite crystallization was noted to be the most mature extraction process for extractive nutrient recovery. At the time of this report, there were six vendors that provide technology options for performing struvite recovery at WRRFs. The commercial technologies include Airprex™, Crystalactor™, Multiform Harvest™, NuReSys™, Pearl™ and Phospaq™ (Table ES-1). Globally, there are over 20 full-scale facilities that are performing struvite recovery. Full-details and reference information regarding these technologies, as well as a list of references and contact information, is provided in the complementary Resource Recovery Technology Matrix – Nutrients.

Table ES-1. Summary of Struvite Recovery Technology Providers.

Name of Technology	Pearl®	Multiform Harvest™	NuReSys™	Phospaq™	Crystalactor™	Airprex™
Type of reactor	Upflow fluidized bed	Upflow fluidized bed	CSTR	CSTR with diffused air	Upflow fluidized bed	CSTR with diffused air
Name of product recovered	Crystal Green®	Struvite fertilizer	BioStru®	Struvite fertilizer	Struvite, Calcium-phosphate, Magnesium-phosphate	Struvite fertilizer
% Efficiency of recovery	80-90% P 10-40% NH3-N	80-90% P 10-40% NH3-N	>85% P 5-20% NH3-N	80% P 10-40% NH3-N	85-95% P 10-40% NH3-N	80-90% P 10-40% NH3-N
# of full-scale installations (2012)	8	2	7	3	4	3

CSTR – completely stirred tank reactor

ES.5 There Exists Significant Demand for Chemical Nutrient Products Resulting from Extractive Nutrient Recovery

Since over 85% of all nutrient products are associated with the agricultural sector, it is appropriate for extractive nutrient recovery technologies to seek to produce products that have value in the agricultural sector. For use in the agricultural sector, recovered products (dry) would need to have at least 95% total solids, have no/minimal odors, be present in uniform distribution (e.g., 1.0, 2.0, 2.5, or 3.0 mm), have dust content less than 1% by weight, and have a minimum bulk density of 720 kg/m³.

Historical data analyses of pricing for comparable chemical nutrient products indicated that nutrient prices have remained relatively steady over the past 50 years, with fluctuations directly linked to the price of grains (food and feed commodities) and the supply of natural gas from the petrochemical industry. Based on this historical dataset, the current estimated market price for nutrients (2012 U.S. dollars) is approximately U.S.\$1.25 to 2.50 /kg of nitrogen (N) and U.S.\$5.80 to 7.50/kg of phosphorous (P).

The agricultural fertilizer market in the U.S. is approximately 54 million U.S. tons of product annually or 49 million metric tonnes of product. Of this market, specialty and ornamental agriculture accounts for between 5-8% of total P₂O₅ fertilizer demand and approximately 1% of total N fertilizer demand, which corresponds to a market of approximately 200,000 to 325,000 metric tonne P₂O₅/year and approximately 115,000 metric tonne TN/year (Recall conversion for P to P₂O₅ = multiply by 2.29).

From this work, it is estimated that the domestic wastewater treatment industry can optimistically bring between 100,000 and 210,000 metric tonnes of P₂O₅/yr (as struvite) and up to 220,000 metric tonnes N/yr to the fertilizer market. This suggests that the wastewater treatment industry can optimistically meet between 2% and 5% of the total P₂O₅ fertilizer demand, between 30 and 100% of the specialty ornamental P₂O₅ fertilizer demand, up to 2% of the total N fertilizer demand, and between 30 and 194% of the specialty and ornamental N fertilizer demand.

ES.6 Struvite Products Have Unique Characteristics That Can Improve Marketability and Value Versus Traditional Fertilizers

Struvite can be produced as either magnesium struvite or potassium struvite. Both types of struvite have an extremely slow release of phosphorus, and have very low water solubility and very low trace metal/pathogen content. Because of the low water solubility, direct application of struvite pellets may not be suitable for agricultural row and grain crops; however, this can be circumvented by dissolving the struvite in acidic solutions for these applications. The slow release aspect of struvite is however a benefit for turf, horticulture, and ornamental producers. Therefore there is significant potential to utilize and market struvite within niche markets (e.g., nursery production, nursery growing media, turf application).

The value of struvite will be dependent on region specific demand, nutrient content and physical properties. For the purpose of this work, it was assumed that struvite value would be tied to phosphorus content. This results in a predicted value ranging from \$U.S. 0.75 to \$1.00 per kg of struvite. It should be noted that this value represents the upper limit of what can be expected for the product on a retail market and does not take into account cost offsets due to transport and/or markups from the vendor/broker. Further, the physical nature of the recovered product would also influence the ability to extract this value, with less refined products having lower market value.

ES.7 Implementing Struvite Recovery at WRRFs Can Result in Multiple Benefits

Adoption of extractive nutrient recovery technologies is typically favorable when the payback periods are less than 10 years and when implementation of the recovery technology provides multiple benefits to the WRRFs. Consequently it is important to quantify these benefits, which include:

- ◆ Mitigating the impact of the sidestream nutrient content on the mainstream nutrient removal process and providing a factor of safety for mainstream EBPR.
- ◆ Minimizing nuisance struvite formation and regaining infrastructure capacity.
- ◆ Reducing chemical and energy costs.
- ◆ Reducing chemical sludge production (if metal salt addition is practiced).
- ◆ Manipulating the nutrient (phosphorus and nitrogen) content of biosolids.
- ◆ Improving sludge dewaterability.

CHAPTER 1.0

INTRODUCTION

1.1 Project Rationale

Wastewaters are increasingly being viewed as a renewable resource whereby value added products (e.g., water, nutrients, bioplastics, metals, and energy) can be extracted and reused. By recovering nutrients, WRRFs can reduce overall energy consumption, improve treatment efficiency, and gain alternative revenue streams that offset operational and capital costs (Mulder, 2003; Shu et al., 2006). While WRRFs can recover multiple chemical products, the industry has focused on two essential macro nutrients, nitrogen (N) and phosphorus (P), for recovery due to their ubiquitous presence in wastewaters and regulatory requirements that dictate reductions in their concentrations before release into the environment.

Conventionally, N removal relies on the conversion of reactive nitrogen to dinitrogen gas, whereas phosphorus removal is facilitated by the production of phosphorus rich biomass or chemically precipitated sludge. Unfortunately, the production of these essential nutrients relies on processes that are unsustainable over the long-term. The reactive nutrient N (i.e., ammonia) is produced via the energetically intensive Haber-Bosch process, whereas phosphorus is mined from non-renewable elemental deposits. If WRRFs could recover and reuse the N and P present in wastewaters, society could decrease our reliance on non-renewable energy resources and provide sustainable sources of key agricultural nutrients.

Although there appears to be a general consensus that resource recovery is beneficial for the wastewater industry, there remain technical, social, and economic challenges towards an industry-wide adoption of this approach (Guest et al., 2009). These barriers revolve around a lack of knowledge (technical, economic, and institutional) due to the need for new skills to operate the physiochemical-based processes, a lack of viable commercialization routes, and a limited understanding of fertilizer markets. For instance, although there are multiple recovery options, a systematic evaluation of treatment efficiencies, costs, energy balances, and recovered product yields is currently absent. The true market value of recovered nutrient products (e.g., biosolids, chemical nutrient products) is also unclear and needs to be elucidated.

In this work, the project team focused on reviewing the technical and economic benefits associated with extractive nutrient recovery, which are defined as nutrient recovery processes whereby chemical nutrient products devoid of organic matter are produced. Furthermore, while a variety of possible recovery processes and products for this report were analyzed, the current and emerging processes for recovering phosphorus based nutrients from wastewaters were the primary focus.

1.2 Industry Barriers Against Extractive Nutrient Recovery Processes

Nutrient recovery and reuse is not a new concept. It has been applied in different forms in the past (e.g., land application of biosolids and reuse of secondary effluent for irrigation); however, extraction of a chemical nutrient product such as struvite has not been widely adopted within the wastewater treatment industry. To better understand why WRRFs have resisted the adoption of these recovery technologies, multiple municipalities, utility staff, engineers, and regulators were queried. Furthermore, workshops were conducted with

participants at WEFTEC 2012, WEFTEC 2013, and WEFTEC 2014 and their opinions and experiences have been summarized. Based on their responses, the key barriers against the adoption of extractive nutrient recovery processes for WRRFs are summarized in Figure 1-1.

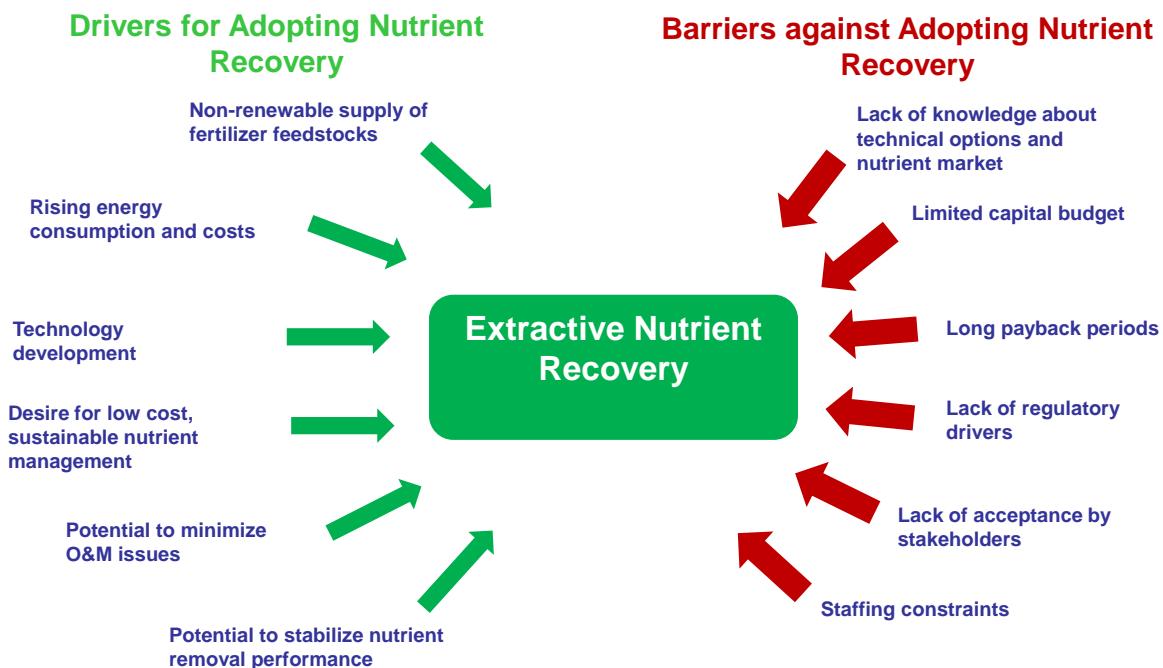


Figure 1-1. Drivers and Barriers Against Adoption of Extractive Nutrient Recovery at Municipal WRRFs.

As can be seen, WRRFs face extensive barriers to adopting nutrient recovery processes. These barriers include a lack of technical knowledge about the variety of processes available, the long-term financial/economic costs, and a lack of regulatory drivers.

Since the nutrient recovery process is technical and requires a variety of processes to produce a final product, there is a lack of knowledge about the different options. For example, some of the technologies are unknown to the different entities, and there is confusion in regard to their appropriate location at either the mainstream or a side stream. Municipalities have insufficient time and staff to review the available technologies and decide on a path forward. There are gaps in the technology performance in regard to percent removal and product production. The long-term maintenance requirements are unknown, as well as the long-term operational viability of these processes. Currently, the operators lack sufficient experience in operating and troubleshooting extractive nutrient recovery technologies.

There are multiple economic barriers that inhibit the adoption of nutrient recovery technology. Pursuing extractive nutrient recovery is difficult when there are insufficient and/or competing needs for funds. There is also little data on the costs of implementation and operation. Concerning the final nutrient products produced, there is uncertainty in the future demand for their product. Since the agricultural fertilizer market is new territory for WRRFs, there are concerns with the future demand, competition, and the product quality and consistency. WRRFs also need to understand how to sustainably distribute product, whether the market is localized or export oriented, and price points of the products. There is also a limited understanding of how nutrient recovery will impact biosolids use and value. Furthermore, there is little understanding of how the fertilizer market will respond to WRRFs entering the fertilizer market in masses.

There is a lack of regulatory drivers (effluent limits) that could be driving uptake of these technologies. The recovery of nutrients involves new regulatory challenges, as fertilizers are regulated differently than biosolids. Furthermore, there are concerns with public resistance to recovered products due to the fact that the products are recovered from wastewater, and concerns with meeting health regulations in regard to pathogen and metal content.

Fortunately, there are drivers which are pushing the wastewater industry to implement nutrient recovery. The rising cost of energy and the increasing cost of extracting non-renewable nutrients have increased the value of recovered nutrients, making recovery options more attractive. Furthermore, researchers are developing new technologies and are improving processes which reduce the operational costs and increase the product recovery efficiency. More importantly, the adoption of these technologies can help plants mitigate operation and maintenance issues. For example, struvite recovery WRRFs can reduce the formation of nuisance struvite and vivianite and reduce chemical costs needed for phosphorus removal.

CHAPTER 2.0

CRITICAL REVIEW OF EXTRACTIVE NUTRIENT RECOVERY TECHNOLOGY OPTIONS

2.1 Summary of Extractive Nutrient Recovery Technology Options

Nutrient recovery for WRRFs involves three main steps (Figure 2-1). These steps are nutrient accumulation, nutrient release, and nutrient extraction.



Figure 2-1. Three-Step Framework for Enabling Extractive Nutrient Recovery from Dilute Wastewater.

Since nutrient contents in most municipal wastewaters are relatively low (1-200 mg/L) (Martin Jr et al., 1983; Mamo et al., 2007; Markou et al., 2011), and the efficiency of nutrient recovery technologies is lower at these concentrations, accumulation processes are generally located in the mainstream. Nutrients are first accumulated using a variety of biological, chemical, and physical processes. For example, mature accumulation technologies include biological accumulation and chemical precipitation, whereas more novel accumulation processes include magnetic separation and purple non-sulfur bacteria (PNSB). The accumulated nutrients are then released via biological, thermal, chemical, or physical processes to a small liquid flow that can then be subjected to treatment to remove residual organic matter and solid contaminants. Ideally, nutrient concentrations are greater than 100 mg/L after the release of the nutrients. Release processes include anaerobic digestion, bioleaching, liquid extraction, etc. Finally, the third stage involves the extraction and recovery of nutrients as liquid or solid products. Since recovery processes require a high nutrient concentration for the effective recovery of nutrients, these processes are usually located on sidestreams. Products can range from biosolids and biomass to biogas, biofuels, and nutraceuticals. The advantage of employing a multi-stage process is that each stage can be operated and optimized separately as there is no one size fits all solution for extractive nutrient recovery.

In this review, technology availability is divided into three major classifications: 1) technologies for nutrient accumulation; 2) technologies for nutrient release; and 3) technologies for nutrient extraction/recovery. Critical review in this manner can allow for independent analysis of different technologies without being limited to specific application constraints. Along these lines, technologies have also been categorized as embryonic, innovative, and established. Embryonic technologies are defined as those still in the laboratory or pilot stage and operating well below commercial rates with no full-scale demonstration units; innovative technologies are those operating at a demonstration or full scale, capable of evaluation for commercial application, but with very limited full-scale deployment; and established technology is classified broadly to include commonly applied processes.

This review is limited to major recoverable N-P-K nutrients from wastewater and does not look at metal, water, or energy recovery as a primary goal. However, it is expected that the approach employed in this review can be translated for additional resources that can be

recovered from waste streams. Because this review is focused on N-P-K-based recovery products, an introduction on the traditional linear approaches to nutrient use is included.

2.2 Traditional Linear Approaches to Nutrient Use

Nitrogen, phosphorus, and potassium are life essential nutrients that are ubiquitous in the natural environment. These nutrients are cycled locally (P and K) as well as globally (N) and the local availability of these nutrients can have a significant impact on ecosystem structural and functional traits (Penuelas, 2012). Anthropogenic inputs of nutrients through high yield farming applications augment existing reactive nutrient fluxes and can create an imbalance whereby the quality of the natural system is diminished due to the increased nutrient load (Vitousek et al., 2009). When one considers that nearly 90% of the phosphate rock mined worldwide is used as fertilizers (Brummer et al., 2005), and that crops have limited nutrient uptake efficiency (40% for N and 45% for P) (Tilman et al., 2002), it is clear that a large fraction of anthropogenic nutrient inputs from soil fertilization can be directly discharged as atmospheric and aquatic pollutants.

Nutrients can also enter the environment from indirect sources like human and animal agriculture waste. It is estimated that the total phosphorus content in excreted human waste (urine and feces) is approximately 22% of the global phosphorus demand (Mihelcic et al., 2011). Therefore, if the nutrient content of wastes is not adequately treated before discharge, localized nutrient imbalances can develop in receiving water bodies. This fertilization effect can lift growth limitations in these water bodies and cause eutrophication, which negatively impacts flora and fauna in estuaries and lakes (Smith et al., 2009) and results in the formation of oxygen depleted zones. Along with the environmental impact, eutrophication can also have major economic impacts by damaging valuable marine fisheries and impairing water bodies used for potable water supply and recreation.

Removal of nutrients from wastes has largely focused on exploiting nutrient cycling reactions whereby reactive forms of nutrients are converted to un-reactive forms (e.g., ammonia to nitrogen gas). Sequestration of nutrients into a form that is not readily bioavailable is also commonly used for removing P and K from wastes (Metcalf & Eddy et al., 2002). This approach assumes a linear usage cycle (Figure 2-2), which inherently posits that energy and resources are cheap and renewable. This is not the case. For instance, phosphate rock, the main source of phosphorus, is non-renewable and nearly 90% of the world's estimated phosphate rock reserves are found in just five countries: Morocco, Iraq, China, Algeria, and Syria (Jasinski, 2012). Similar to phosphorus, potash ores have a limited distribution globally, with the bulk of the world's potash mined in Canada and Europe (Jasinski, 2012). This is reflected in the cost of potassium based fertilizer prices which have quadrupled between 2007 and 2009 (Manning, 2010).

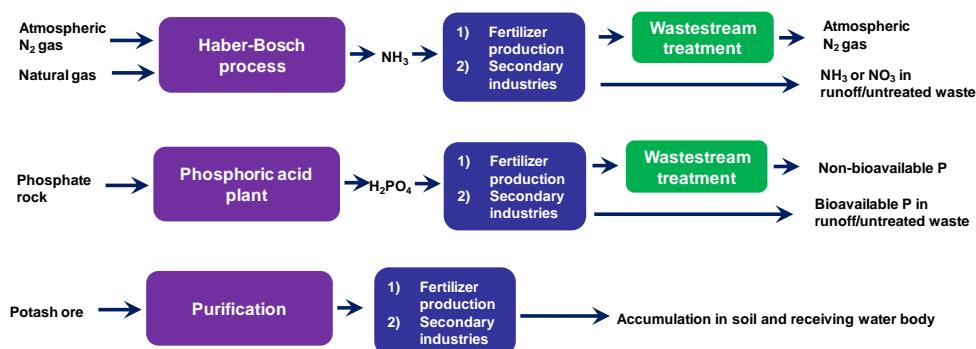


Figure 2-2. Linear Approach to Nutrient Use.

While nitrogen is a renewable resource, the process by which ammonia is industrially synthesized (Haber-Bosch process) makes use of hydrogen from natural gas. As a result, the production of nitrogen based fertilizers from atmospheric nitrogen is an energetically intensive process that is dependent on the price and supply of natural gas (Woods et al., 2010).

Unfortunately, the current processes for the generation of these three essential nutrients assume that our resources are inexhaustible, and the continued management of nutrients through a linear cycle disregards our society's long-term sustainability. Ultimately the only viable approach to this problem is to shift from a reliance on nutrient cycling to processes where reactive nutrients are recovered and reused in a sustainable fashion.

Capitalizing on waste streams as renewable sources for N-P-K recovery is an integral component of any integrated nutrient management plan that is geared towards instilling resource independence and breaking the linear use cycle (Wilsenach et al., 2003; Guest et al., 2009). However, in order to employ nutrient recovery for nutrient management, the processes must have treatment efficiency comparable to that of conventional treatment options to ensure regulatory compliance, be cost competitive (capital and operating) with conventional nutrient removal technologies, and have a market for the recovered nutrient product(s).

In the past decade, research and commercialization of nutrient recovery technologies for N-P-K have increased tremendously. Consequently, it is necessary to critically compare candidate-technologies, their nutrient recovery efficiencies, and product qualities with a view to advancing application of these technologies. In this review, research needs are addressed by identifying research gaps, evaluating current and future potential for nutrient recovery, and delineating paths and barriers for implementation of the nutrient recovery technologies.

2.3 Nutrient Accumulation Technologies

Nutrient accumulation technologies aim at recovering soluble N-P-K from wastewater with low nutrient concentrations (2-20 mg/L). As nutrient discharge limits can require effluents to contain less than 0.1 mg TP/L and 3 mg TN/L, accumulation options must ideally be capable of sequestering nutrients to produce effluents meeting these low concentration requirements (Neethling et al., 2010; Sengupta et al., 2011). Biological, physical, and chemical accumulation techniques can be used for this purpose. Chemical accumulation techniques are largely limited to P, with biological methods being used for N-P-K. Physical accumulation via sorbents can be used for all three nutrients.

2.3.1 Prokaryotic Accumulation

Biological nutrient accumulation can be facilitated by microorganisms like polyphosphate-accumulating organisms (PAOs; members of the Proteobacteria phylum), purple non-sulfur bacteria (PNSB) (Lu et al., 2011) and cyanobacteria (Vieira et al., 2012) (Figure 2-3). Enhanced biological phosphorus removal (EBPR) using heterotrophic PAOs is the most widely used biological phosphorus accumulation process in WRRFs. In this process, 80-90% of soluble P is removed from the mainstream flow and accumulated as internal polyphosphate granules by the PAOs. PAOs can accumulate 20-30% phosphorus by weight (Parsons et al., 2008). EBPR requires alternating anaerobic and aerobic/anoxic conditions, sufficient but not excessive solids retention time for PAO retention (< 3-4 day), operation between pH 7 and 8 (Pastor et al., 2008) (Li et al., 2008), and sufficient carbon (in the form of volatile fatty acids (VFAs)) to drive the reaction. Practical experience has indicated that carbon (measured as biological oxygen demand (BOD)) to phosphorus ratios of 25 or higher in the bioreactor influent are required to achieve a high-level removal of phosphorus (Liu et al., 1997), and that pre-fermentation of wastewater to produce VFAs or external addition of

VFAs is often beneficial and sometimes necessary to ensure proper EBPR operation (Yuan et al., 2012). EBPR has also been demonstrated to remove greater than 90% phosphorus from various types of industrial wastewaters (Yuan et al., 2012). Once accumulated, the PAO enriched sludge can be settled and recovered for subsequent processing through release and extraction steps. Phosphorus accumulation using PAOs is an established technology.

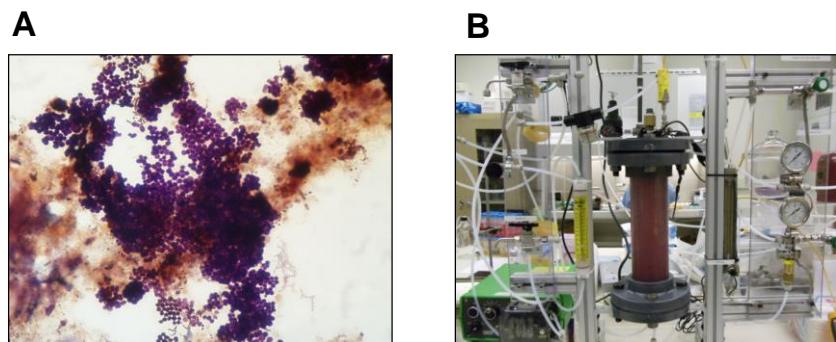


Figure 2-3. Nutrient Accumulating Prokaryotic Microorganisms.

A – Polyphosphate-Accumulating Organisms (PAOs), B – Photobioreactor with Purple Non-Sulfur Bacteria (PNSB). Battelle, 2012a.

Photoautotrophic or heterotrophic PNSB and cyanobacteria can also be used to accumulate nutrients via storage as proteins or polyphosphates. These organisms are suitable for treating wastewater with high organic matter content to produce a nutrient rich biomass, (Lu et al., 2011). Cyanobacteria such as blue-green algae are particularly suitable for the luxury uptake of nitrogen with the protein content reported up to 80% of the dry weight, as 8-12% N and 1% P (Benemann, 1979; Markou and Georgakakis, 2011). PNSB have a high tolerance for heavy metal exposure, as they co-accumulate heavy metals along with nutrients from wastewater (Giotta et al., 2006). Recent work has shown that PNSB employed in a photobioreactor lab-scale configuration can achieve 90% nitrate removal (initial concentration 30 mg N/L) and 90% phosphate removal (initial concentration 1.4 mg P/L) (Battelle, 2012a). Despite these recent advances, there is still limited information on nutrient accumulation and application of PNSB and cyanobacteria. As these technologies are embryonic and promising, particularly for nitrogen accumulation, further research is warranted.

2.3.2 Algae-Accumulation

Algae are unicellular or multicellular, autotrophic, photosynthetic eukaryotes that have received significant attention worldwide as a valuable source of biomass for energy, because of their high growth rates over other terrestrial plants (Demirbas, 2001) and ability to capture atmospheric carbon dioxide. These organisms can also be used to simultaneously accumulate nutrients, as they require less than one-tenth of the area to recover phosphorus compared to terrestrial crops/pastures (Shilton et al., 2012). Nutrient accumulation is dependent on algal physiology, predominant form, and concentration of nutrients (N and P), light intensity, pH, and temperature. Reports have suggested that the nutrient content of algal dry biomass could reach up to 2% N and 3.3% P (Powell et al., 2008; Fenton et al., 2012).

Algae-based systems can be suspended or non-suspended. In non-suspended system, algae are immobilized on a resin or as a biofilm. The algae immobilized surface reduces nutrient load in the wastewater via adsorption and/or precipitation on the surface of the material as well as through nutrient uptake by biomass. These non-suspended systems have been successfully tested in high nutrient agriculture streams such as dairy, poultry, and swine manure wastewater (Fenton and Ó hUallacháin, 2012). Suspended algae configurations are

used in facultative and high rate algae ponds. In the un-mixed facultative ponds, the residence time can range from 20 to 100 days whereas in the high rate shallow ponds, residence times can range between 4 to 10 days while gentle mixing is provided via paddle mixers (Lundquist et al., 2010). In a recent review, tubular photo-bioreactor with suspended algae was found to be the most promising option for producing algal biomass in full-scale applications (Powell et al., 2008) (Figure 2-4). Briefly, in this tubular photo-bioreactor setup the wastewater is pumped into a small equalization reservoir. From the reservoir the algae and wastewater are circulated through a tubular photo-bioreactor, where the nutrients are accumulated in the algae. The algae are then returned to the reservoir, and a portion of the liquid mixture is removed to harvest the algae.

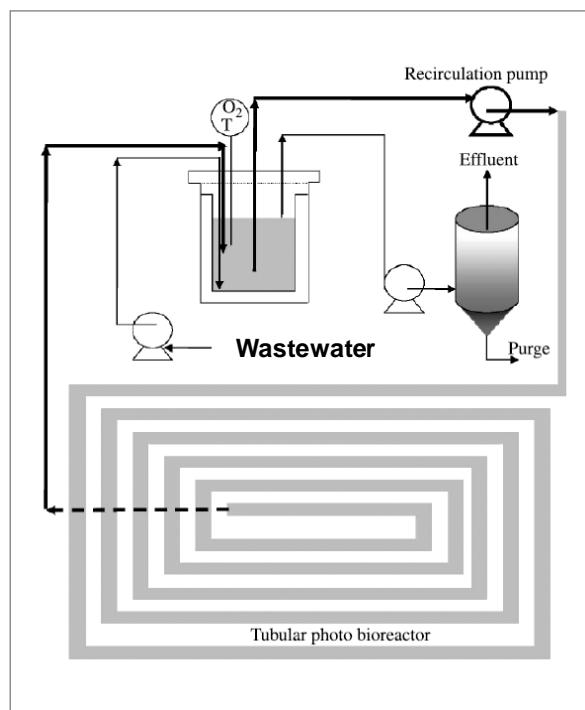


Figure 2-4. Conceptual Process Flow Diagram for Microalgae Photobioreactor Used for Nutrient Accumulation.
Adapted from Gonzalez et al., 2008.

Optimal pH for growth of algae is in the range of 7.5-8.5 while temperatures between 15 and 30°C are generally optimal for algae (Waller et al., 2012) with lower temperatures resulting in decreased growth (Teoh et al., 2010). As carbon dioxide (CO₂) is consumed by algae during photosynthesis, the pH of the wastewater can increase, resulting in conditions that are more favorable for the precipitation of phosphorus with available cations (such as calcium or magnesium) and volatilization of N as ammonia (Larsdotter et al., 2007); however, it is important to note that photosynthesis in isolation will not increase the pH to above 10.5 or 11 where phosphorus precipitation with calcium is favored.

Floating algal farming is an embryonic nutrient removal/accumulation process from wastewater. This approach may be most appropriate in coastal regions where nutrients that are discharged directly to seas and oceans from agriculture activities (Trent et al., 2012) can be recovered. The salinity gradient between wastewater and seawater has the potential to drive forward osmosis and help concentrate nutrients and dewater harvested algae. Though engineering feasibility of this technology is low, if implemented it may present more favorable economics compared to onshore algal cultivation due to the absence of the significant land cost component.

Nutrient accumulated algae can be used as a substrate for nutrient release techniques, or direct application as an animal feed or fertilizer. Due to the small particle size of algal cells and their typical growth as small colonies or single cells, harvesting of algal biomass is considered a major challenge for the full-scale production of algal based nutrient accumulation (Sturm et al., 2011). Future economic evaluation of this option should consider the multiple benefits, including nutrient recovery, carbon sequestration, and biofuel production. It is likely that the economics of application will only be positive in scenarios where all three benefits are maximized.

2.3.3 Plant Nutrient Accumulation

Nutrient accumulation can also be performed using wetlands (Figure 2-5). In this system, nutrient accumulating plants grow on the water surface, creating anaerobic conditions in the surrounding water. The anaerobic conditions drive digestion reactions where organic matter is metabolized to produce nutrients that can be accumulated by the plants (Oron et al., 1985). These plants, however, must be routinely harvested to ensure that the accumulated nutrients are not recycled.

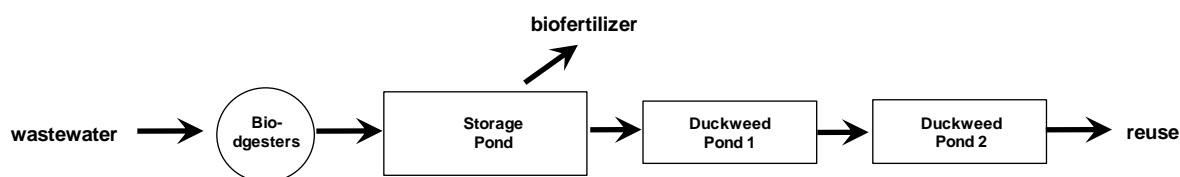


Figure 2-5. Conceptual Process Flow Diagram for Plant Based Nutrient Accumulation.
Adapted from Mohedano et al., 2012.

The wetlands can be subsurface or surface flow type and the plants can be submerged, emergent, floating leaved, or free-floating type (Vymazal, 2007; Vymazal, 2011). The free-floating plants have high capacity for nutrient accumulation as they grow on the surface of the water rather than rooted in the sediments. The roots of these plants are kept suspended in the water column and allow accumulation of the nutrients from the wasters. There are three plants which are currently being examined, on different scales, for the various phases for treating waste treatment and recovering nutrients: water hyacinths (*Eichhornia crassipes*), duckweeds (*Lemna minor*, *Landoltia punctata* and *Spirodela polyrrhiza*) and various emergent macrophytes (Shilton et al., 2012).

Nutrient removal efficiency for plant accumulation varies with each plant type, wastewater characteristics, environmental factors (temperature and dissolved oxygen), and type of wetland. The minimum water temperature is 7°C, with optimum temperatures ranging between 25°C and 31°C, while the optimum pH is between 6 and 8 (Saeed et al., 2012). Both water hyacinths and duckweed can tolerate high nutrient loads and have a high nutrient removal rate (N and P removal > 70 %) (Malik, 2007) with N and P accumulation in the range of 1 to 3% (Shilton et al., 2012); however, nutrient removal can be negatively affected when duckweed growth is limited.

The plant-accumulation system is potentially a low cost system for nutrient recovery with an additional benefit of reducing organic matter from wastewater. However, large areas are required, and regular harvesting is required which increases operating cost. The area required by plants to recover nutrients is dependent on percentage of phosphorus content and areal biomass productivity. Reported biomass yield (tonne/ha/yr) for water hyacinths and duckweed suggest that they have 10 times higher yield, require 100 times smaller area (m²), and accumulate 10 times more phosphorus than terrestrial crops (switchgrass and maize) (Shilton et al., 2012). The plants can be used as a feedstock for biofuels, as a fertilizer (which

directly recycles nutrients), or processed through an appropriate nutrient release technology (Gunnarsson et al., 2007). While the cost of directly applying water hyacinths as a fertilizer is low, the cost of processing water hyacinths for a biofuels feedstock will remain expensive and energy intensive similar to other biofuel feedstocks. In summary, while this technology can be classified as innovative, further research is required in plant biotechnology to improve nutrient uptake with fewer biomass and area requirements compared to other biological based nutrient accumulation systems.

2.3.4 Chemical Accumulation through Precipitation

Chemical accumulation of nutrients can be accomplished via coagulation and flocculation, where soluble nutrients (PO_4^{3-}) and nutrients bound to colloids (0.01-1 μm) are destabilized to form chemical flocs, which are then settled in clarifiers (Figure 2-6). The commonly used metal coagulants are either aluminum or iron based and focus on extracting phosphorus from dilute wastewater. Other coagulants like calcium, natural and synthetic organic polymers, and pre-hydrolyzed metal salts such as poly-aluminum chloride and poly-iron chloride (Metcalf & Eddy et al., 2002) can also be used for this purpose but generally have a high cost (Table 2-1). The optimum pH is dependent on the type of coagulant used; however, due to the heavy use of biological processes in WRRFs, operation at a pH range between 6.0 and 8.0 is typical. As this process is effective for removing soluble and particulate phosphorus, it is heavily used as part of a multi-point injection process for controlling phosphorus discharge from WRRFs and is classified as an established technology.

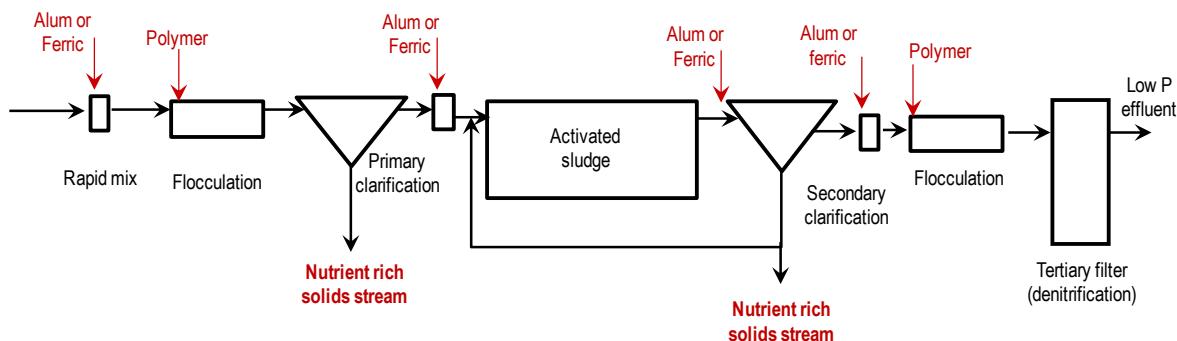


Figure 2-6. Multi-Point Injection Approach for Chemical Accumulation/Removal of Phosphorus from Wastewater.

Table 2-1. Chemical Accumulation of Phosphorus Using Metal Ions and its Operating pH Range.

Metal	Precipitant Containing Nutrients	pH Range
Ca^{2+}	$\text{Ca}_2(\text{PO}_4)_2$, $\text{Ca}_5(\text{OH})(\text{PO}_4)_3$, CaHPO_4	≥ 10
Fe^{2+} and Fe^{3+}	$\text{Fe}_3(\text{PO}_4)_2$, $\text{Fe}_x(\text{OH})_y(\text{PO}_4)_3$	6.0 - 8.5
Al^{3+}	$\text{Al}_x(\text{OH})_y(\text{PO}_4)_3$	6.0 - 8.5

Metal ions can also be delivered through sacrificial iron or aluminum anode electrodes through electrocoagulation (Meunier et al., 2004). The coagulants, when added to water, hydrolyze rapidly and form multi-charged polynuclear complexes with enhanced adsorption characteristics. The efficiency of rapid mixing, the pH, and the coagulant dosage determine which hydrolyzed species is effective for treatment (Bratby, 2006). The age of the floc also impacts removal efficiency, especially if the metal floc is recycled with the return activated sludge (RAS) (Neethling, 2008). Once suspended particles are flocculated into larger particles known as sludge, they can usually be removed from the liquid by

sedimentation, provided that a sufficient density difference exists between the solid (sludge) and the liquid fraction.

Along with nutrient removal, the process also removes organic matter, pathogens, virus, and other inorganic species such as arsenic and fluoride. Other advantages are ease of operation, flexibility to changing conditions and low capital cost to reduce effluent phosphorus concentration to less than 1 mg/L (De Haas et al., 2000). Disadvantages associated with chemical accumulation through precipitation include high operating costs, increased salinity in the effluent (mainly in the form of either chloride or sulfate), increased sludge production (up to 35% on a volume basis) (De Haas et al., 2000), and inhibitory effects on the biological process such as anaerobic digestion following coagulation process (Liu et al., 2011). It should be acknowledged that the sludge produced from chemical accumulation techniques are agronomically less useful due to high metal-P affinity (Cox et al., 1997), low bioavailability, and phytotoxic nature of higher aluminum concentrations. Consequently, if this technique is to be applied as part of a nutrient recovery strategy, the subsequent release step must increase the bioavailability of the bound nutrients, and the metal concentrations should be monitored and limited to avoid phytotoxic properties.

2.3.5 Adsorption\Ion Exchange

During adsorption and ion exchange, ions are transferred from the solvent to charged surfaces of insoluble, rigid sorbents suspended in a vessel or packed in a column (Figure 2-7). The sorbents are porous material containing interconnected cavities with a high internal surface area to capture ions through chemisorption. During ion-exchange, a selective preference for an ion in aqueous solution is based on magnitude of the valence (e.g., a higher valence has a better selectivity for phosphate), diffusivity of the ion, and physical properties of the sorbents such as functional group and pore size distribution. This process can recover soluble nitrogen, phosphorus, or potassium from wastewater. Spent sorbents are regenerated using low cost, high concentration cations or anions such as sodium, sulfate, or chloride. For this process to be viable, sorbents and ion exchange material must have a high affinity for nutrients versus other ions present in the wastewater.

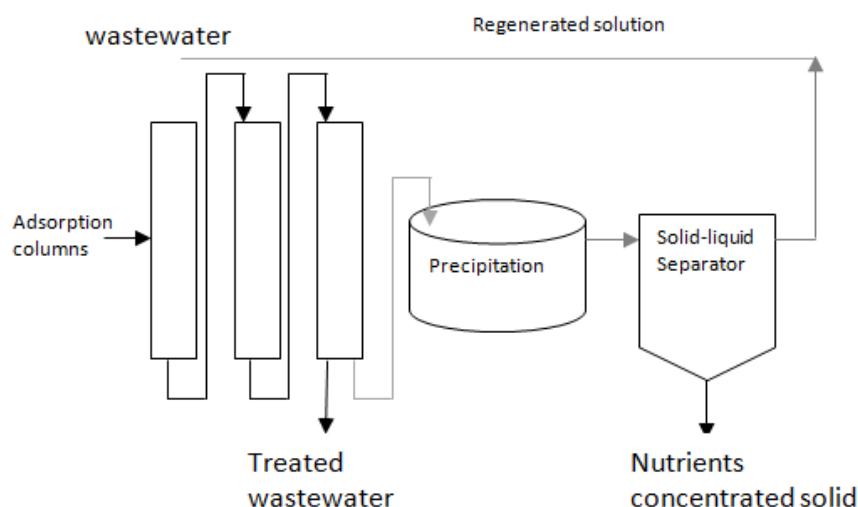


Figure 2-7. Conceptual Process Flow Diagram for Adsorption and Ion-Exchange for Nutrient Accumulation.

This technology is suitable for wastewater with a range of nutrient concentrations (1-2000 mg/L) and relatively low in solids (< 2000 mg/L). For low-strength wastewater such as domestic treatment plants and artificial lakes where nutrient concentration is less than 5 mg/L, advanced engineering polymeric sorbents are employed. Such sorbents can reduce phosphorus load to 50-100 µg/L (Sengupta and Pandit, 2011). Wastewater with an acidic pH

(< 8.0) is preferred to improve nutrient solubility and maximize adsorption on the resin. For concentrated waste streams ($> 2000 \text{ mg L}^{-1}$), typically red mud, metal oxide/hydroxide, and zirconium sorbents are used for phosphorus recovery and modified zeolite and clinoptilolite for N and K recovery. Recent work with nano-enhanced reactive iron media also shows promise for the removal of phosphorus via tertiary filtration applications (Saber, 2011). Maximum phosphorus loading capacity reported is 57 gP/kg for zirconium loaded orange waste gel (Biswas et al., 2008) and 21.52 gN/kg for nitrogen using clinoptilolite (Sprynskyy et al., 2005).

The potential advantages of this technology are its ability to achieve high phosphorus removals from the effluent ($\text{PO}_4^{3-} < 0.1 \text{ mg/L}$) from high-strength wastewater (Donnert et al., 1999), no additional sludge is produced, and wastewater pH remains unaffected. Chemicals required for the regeneration of the sorbents, bio-fouling, the large amount of resin required for removal below detection limits, and competitive foreign ion adsorption are some of the challenges for full scale implementation. To reduce regeneration cost, some studies have focused on the processes which do not require chemicals for regeneration, i.e., bio-regeneration (Jung et al., 2004; Wei et al., 2011). Additionally, this process can be potentially categorized as a hybrid nutrient accumulation and extraction technique since the nutrient laden sorbent/ion exchange medium can potentially be directly reused in agricultural applications (Ganrot, 2005). Due to the limited extent of deployment for extractive nutrient recovery, this technology is classified as an innovative technology.

2.3.6 Magnetic Separation

In this hybrid approach, soluble nutrients are accumulated from the wastewater by employing adsorption to a carrier material that has magnetic properties (e.g., adsorbent coated magnetite, zirconium ferrate, carbonyl iron, or iron oxide) (Figure 2-8). Once sequestered from solution, the nutrient-laden carrier material can be recovered by applying a magnetic field using high gradient magnetic separators (HGMS) to separate the particulate matter from the wastewater (Ishiwata et al., 2010; Merino-Martos et al., 2011). HGMS relies on an electrically generated magnetic field with the electrical wires running parallel to the flow of the suspension carrying particulates (i.e., magnetic field is perpendicular to the flow path). The binding forces between the nutrient to be removed and the carrier material must exceed the hydrodynamic forces which are exerted on the particle by the fluid. If not, the components to be removed will be disrupted from the magnetic carrier.

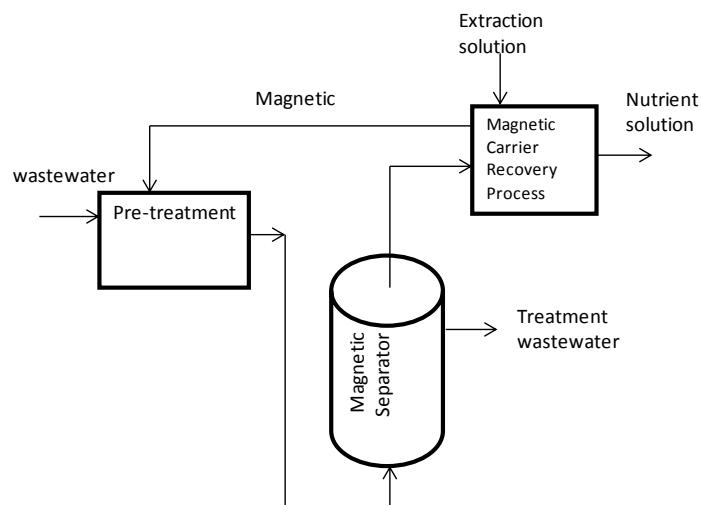


Figure 2-8. Conceptual Process Flow Diagram for Magnetic Separation and Accumulation.

The magnetic carrier can be regenerated via chemical extraction techniques (Van Velsen et al., 1991). This process can simultaneously recover soluble N, P, or K from wastewater using specific adsorbents bound to the magnetic carrier. The process has been tested at full scale to recover phosphorus from a domestic treatment plant (Van Velsen et al., 1991). The process had a high recovery (> 90%) within an hour and with effluent phosphorus concentration < 0.5 mg L⁻¹ (Van Velsen et al., 1991; Shaikh et al., 1992; Ito et al., 2009; Merino-Martos et al., 2011). This process does not interfere with the biological process and hence it can be installed at any stage of advanced resource recovery processes. The magnetic carriers commonly used are magnetite (Van Velsen et al., 1991; Shaikh and Dixit 1992), zirconium ferrate (Ishiwata et al., 2010), carbonyl iron (Merino-Martos et al., 2011), and iron oxide (Merino-Martos et al., 2011). Advantages of this process are high elimination performance, compact process, and low power input techniques (Van Velsen et al., 1991). There is limited published information on this embryonic technology and additional research is required to fill these gaps. For example, significant questions remain as to selecting the optimum carrier material for the desired contaminant, determining the optimal particle concentration and sizes and understanding how variable wastewater characteristics affect the separation process.

2.4 Nutrient Release Technologies

Once accumulated, nutrients must either be released or directly extracted to a recovered product. Both biological and chemical release methods can be used. Thermal techniques, though discussed separately in this section, are commonly used in conjunction with chemical techniques for complete nutrient release into a soluble form. This review focuses primarily on release from animal waste (manure) and biological streams (activated sludge) which are naturally high in nutrients, but otherwise too bulky, contaminated, or unstable to use directly, or which have been intentionally concentrated in nutrients (see previous section).

2.4.1 Biological Release

Anaerobic digestion is the most commonly established process for stabilization, organic solids destruction, pathogen destruction, and energy recovery in the form of methane (Wilkinson, 2011) (Figure 2-9). Anaerobic digestion also facilitates the release of nutrients from biomass. In this process, organic N is converted to ammonium and organic phosphorus is hydrolyzed to soluble phosphorus with the extent of conversion dependent on the conditions employed during digestion. Anaerobic digester designs vary widely, but for agricultural and high-solids processes, the designs can be divided according to their feed (Batstone et al., 2011):

- ◆ Largely soluble (< 1% solids; lagoons, high-rate anaerobic processes, anaerobic membrane processes).
- ◆ Slurry (1-6% solids; complete mix).
- ◆ High solids (>6-10%; plug flow, leach bed).

The optimum operating temperature for anaerobic digestion is between 35 and 40°C for mesophilic bacteria and between 55-60°C for thermophilic bacteria. The optimum pH is in the range 6.5-7.5. The residence time of the process varies with the substrate and is in the range of 20 to 30 days.

During the process, organic N is mineralized to ammonium and organic phosphorus is released as soluble phosphates (Mehta et al., 2012). The extent of nutrient release from the organic matter depends on the degree of material digestion. Released nutrients remain soluble, are bound to form inorganic compounds or adsorbed on solid surfaces in the digestate. Studies on manure showed that most of the organic phosphorus is released; however, less than 10% of this remained soluble following digestion (Güngör et al., 2008;

Mehta and Damien, 2012). Typically, the soluble content of the phosphorus in most municipally digested wastes ranges from 50-500 mg/L. The corresponding N content ranges from 40-1000 mg/L. (Batstone and Jensen, 2011). The digested solids are typically dewatered to reduce solids handling costs and the resulting nutrient rich sidestream can be a feedstock for nutrient extraction/recovery techniques.

The remaining fraction of particulate bound nutrients and residual organics are also recovered as biosolids. These biosolids have value as nutrient amendments for agricultural purposes; however, application of biosolids is increasingly being regulated due to odor issues, possible transfer of metals to soil and crops, and public perception. Additionally, agronomic nutrient application limits are being developed to limit nutrient runoff from land application sites. This will further constrain biosolids land application rates. However, advances in biosolid formulations, such as limed biosolids that have been amended with clay, have developed new markets for biosolids (American Water Works Association. et al., 2006).

Since a purified nutrient stream is far more valuable for use in nutrient recovery applications, there is a need to utilize processes that selectively enhance solubilization of nutrients. One example of this type of process is the selective release of phosphorus through a waste activated sludge enhanced release process. In this technique, phosphorus is preferentially released from PAOs in waste activated sludge prior to digestion through short-term incubation in the presence of volatile fatty acids (Figure 2-9). Use of waste activated sludge enhanced phosphorus release processes generate a phosphorus-rich load that is ammonia limited. This stream can be subsequently combined with the liquid stream resulting from anaerobic digestion. The benefit of using this process is that it helps eliminate the formation of nuisance struvite and vivianite.

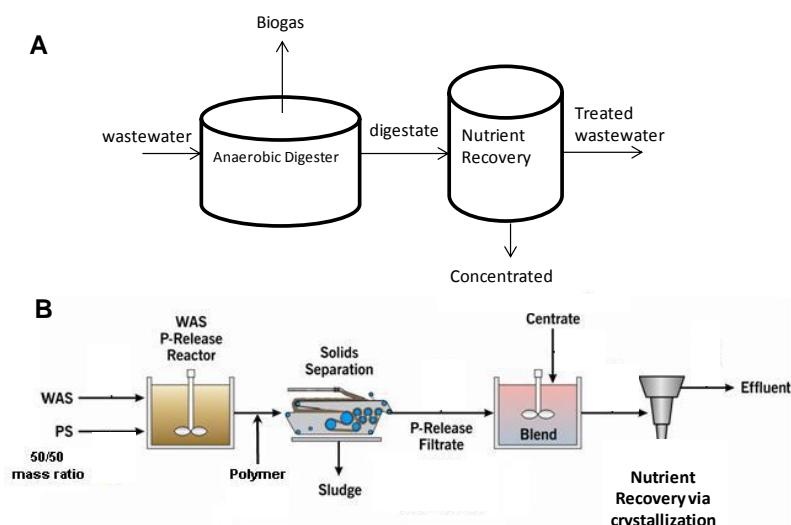


Figure 2-9. Conceptual Process Flow Diagram for A) Anaerobic Digestion, B) Enhanced Waste Activated Sludge P Release.

Adapted from Latimer et al., 2012.

Nutrient release from biosolids can also be facilitated by aerobic digestion processes (conventional aerobic digestion (CAD), anoxic/aerobic digestion (A/AD), autothermal aerobic digestion (ATAD)) (Grady et al., 1999). In these established processes, volatile solids reduction and nutrient release is achieved by retaining biomass at SRTs in excess of 20 days, at pH ranging from 4.5-7.0, under aerobic conditions. Aerobic digestion can be performed at mesophilic temperatures (35° and 40°C; CAD and A/AD) or at thermophilic temperatures (45-65°C; ATAD). Aerobic digestion results in the production of an ammonia and nitrate rich

digestate, with the nitrate concentration dependent on the alkalinity present in the digester. Similar to aerobic digestion, organic phosphorus is hydrolyzed to soluble phosphorus with the extent of conversion dependent on the conditions employed during digestion. Drawbacks of employing aerobic digestion include high power costs associated with aeration, inability to recover energy as methane, poor settleability of solids, and high potential for nuisance chemical scaling on diffusers and conveyance equipment.

2.4.2 Thermochemical Stabilization and Chemical Release

Thermochemical processes like wet oxidation, incineration, gasification, or pyrolysis can be used to selectively retain nutrients in biomass for subsequent chemical release technologies (Figure 2-10). This class of processes involves three main steps. First the waste stream (either wastewater or solid waste) is thermochemically processed to produce a char. For the second step, the char undergoes a chemical release process to extract the nutrients. This chemical release process generally involves the use of strong acids and bases and/or high temperatures and pressures. Finally, once the nutrients are released, a variety of nutrient recovery processes are used to concentrate the desired nutrients.

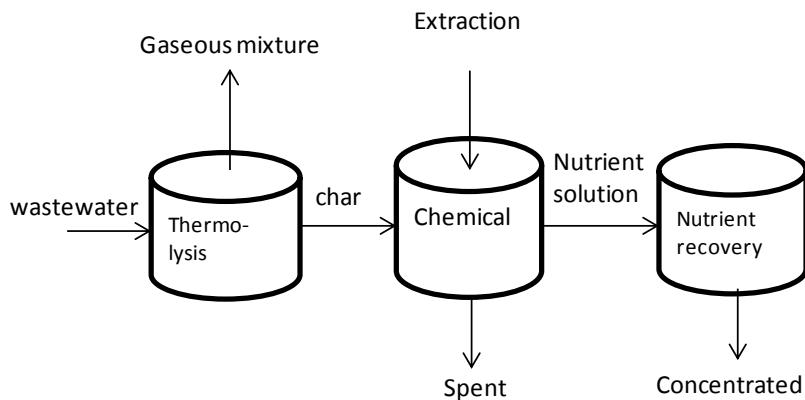


Figure 2-10. Conceptual Process Flow Diagram for Thermochemical and Chemical Release Processes.

The initial thermochemical process produces a char that retains most P and K, but N is lost in the gas stream. Wet oxidation is carried out at moderate temperatures (180–315°C), and at pressures from 2–15 MPa (Blocher et al., 2012). Metals are oxidized to their highest valency and phosphorus to P₂O₅ (Stendahl et al., 2003). The degree of oxidation depends on the temperature and pressure selected. Incineration and gasification occurs in the presence of oxygen above 800°C while pyrolysis operates under a limited supply of oxygen, and at relatively low temperatures (<700°C). Pyrolysis can be designed to retain the majority of P and K nutrients in char or an oil by-product. N can also potentially be retained in the solid or liquid by-product. Nutrient content of the char varies by temperature, reactor design, substrate, and operating pressure of the reactor for the thermochemical process (Wise et al., 2012).

The char can then be further treated thermally in the presence of chloride salts. Heavy metals are converted to heavy metal chlorides which vaporize, and are removed from the char (Hermann, 2009). The heavy metals are often captured during flue gas treatment. The process has disadvantages as it removes large proportion of K from the char as potassium salts (Li et al., 2003). Additionally, incineration ash can only be used if combusted at low temperatures (<700°C) (Thygesen et al., 2011), which does not minimize nitrous oxide emissions. They require combustion at >900°C (Gutierrez et al., 2005).

Chemical release involves the addition of acids or bases to char, digested solid waste or wastewater, at moderate temperature ($< 200^{\circ}\text{C}$) and/or pressure to release nutrients into a leachate. The chemical extractants typically used are inorganic acids (H_2SO_4 , HCl , HNO_3), organic acids (citric and oxalic acids), inorganic chemicals (e.g., ferric chloride solution) and chelating agents (e.g., ethylenediaminetetra acetic acid-EDTA). Undesired compounds, including heavy metals, are also released to the leachate (Veeken et al., 1999). Additional processes are often required to extract and recover nutrients from the leachate. There are a number of commercial processes for coupling thermochemical stabilization with chemical release as shown in Table 2-2. The major differences among these technologies are in applied extraction chemicals, pressure, temperature, and the starting material used (sludge or char) (Sartorius et al., 2012).

The Seaborne, Sesal-Phos, Biocon, Sephos, Pasch, Stuttgarter Verfahren, and Loprox/Phoxnan processes dissolve nutrients and heavy metals using acids at a pH below 3, while Cambi, Krepco, and Aquareci process are operated at high temperature ($> 100^{\circ}\text{C}$) and pressure (> 5 bar) for nutrient dissolution. The dissolved ions (nutrients and heavy metals) are then sequentially separated via crystallization (Seaborne, Stuttgarter Verfahren, Sephos, Sesal-Phos, and Krepco), membranes (Loprox/Phoxnan), solvent extraction (Meyer et al., 2004), and ion-exchange (Biocon). In these processes, various P-based inorganic compounds are produced, which must be rigorously tested for heavy metal contamination before they can be used in agriculture. The main challenges to implementing this technology are the relatively high operating costs including chemical costs. The potential need to remove heavy metals from products can also increase the costs associated with implementing this release technology.

2.4.3 Bio-Leaching

Bio-leaching is an embryonic release technology that relies on the solubilization of nutrients and heavy metals from solid substrates either directly by the metabolism of leaching microorganisms or indirectly by the products of metabolism. The microorganisms can be mesophiles such as *Acidithiobacillus thiooxidans* and *Acidithiobacillus ferrooxidans*; thermophiles such as *Sulfobacillus thermosulfidoxidans*; and heterotrophic microbes such as *Acetobacter*, *Acidophilum*, *Fusarium*, *Penicillium*, and *Aspergillus* (Pathak et al., 2009). These microorganisms have unique capabilities which allow them to survive in acidic environments and to carry out oxidation of insoluble iron and sulfur compounds, which reduces the pH and releases complex nutrients and heavy metals.

To bioleach nutrients from sewage sludge, phosphate rock and ash, energy sources such as FeSO_4 (Couillard et al., 1993; Pathak et al., 2009) or FeS_2 (Wong et al., 2004), and elemental sulfur (Pathak et al., 2009) have been added to a mesophilic mixture containing *At. ferrooxidans* and *At. thiooxidans* strains (Pathak et al., 2009). The optimum temperature for growth of these mesophiles is in the range $20\text{--}40^{\circ}\text{C}$ and pH in the range 1.0-4.5 (Pathak et al., 2009). Because of the low operational pH, the process is highly efficient in inactivating pathogens (Couillard and Mercier 1993). It has also been found that process configurations that allow continuous bioleaching (e.g., CSTR retention time < 3 days) are superior to batch reactions with retention times up to 16 days. Bioleaching is a low cost process due to the ability to use elemental or chemically bound sulfides (e.g., mineral metal sulfides), which are ubiquitous in the waste streams. The major disadvantage of this process is that the release efficiencies for nitrogen and phosphorus ($< 40\%$) are low as compared with that of heavy metals ($> 60\%$) (Couillard and Mercier 1993; Wong et al., 2002; Wong et al., 2004; Mercier et al., 2006; Pathak et al., 2009; Lü et al., 2011).

2.5 Nutrient Extraction and Recovery Technologies

Upon release to a soluble form (e.g., N-NH₄⁺, P-PO₄⁻³ and K-K⁺), physicochemical methods can be used to extract and recover the nutrients. This review focuses on extraction and recovery techniques that produce an inorganic fertilizer that can be reused in agricultural applications.

2.5.1 Chemical Precipitation/Crystallization

Chemical precipitation via crystallization is a phase change process to convert insoluble components into a particulate, inorganic compound. This is a sidestream process, as the precipitation requires a nutrient rich liquid, and generally a sludge dewatering liquor is used. During this process, supersaturation conditions are created in the nutrient rich dewatering liquid through a change in temperature, pH, and/or addition of metal ions (Le Corre et al., 2009). Because of these conditions, precipitation of select products can be performed. Struvite (MgNH₄PO₄.6H₂O) crystallization is an example of this technique being applied to simultaneously recover N and P from nutrient rich streams (Figure 2-11) (Jagadeeswaran et al., 2005; Massey et al., 2009; Yetilmmezsoy et al., 2009). Typically, struvite contains 12% P and 5% N with minimum heavy metal or biological contamination (Antonini et al., 2012). Magnesium (Mg²⁺) is added to wastewater in the form of MgCl₂, Mg(OH)₂, or MgO to increase pH and create supersaturation conditions which are amenable for struvite (MgNH₄PO₄.6H₂O) formation. Alternatively, potassium struvite can also be precipitated by altering the added reagents and the nutrient molar ratio of the specific nutrients (Wilsenach et al., 2007).

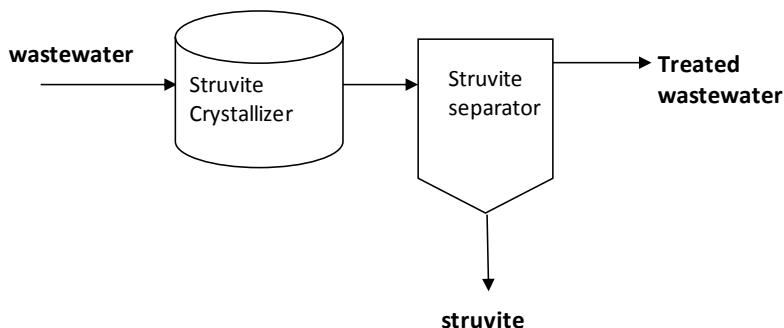


Figure 2-11. Conceptual Process Flow Diagram for Chemical Crystallization Extraction Process.

This process removes between 80-90% of soluble phosphates and 20-30% of the soluble ammonia from nutrient-rich dewatering liquor (the molar ratio of the Mg²⁺:NH₄⁺:PO₄⁻³ ions in struvite precipitate is 1:1:1) (Le Corre et al., 2009). Since struvite has a specific gravity of 1.7, the crystals can be separated via gravity, mechanical separators, or through the use of an integrated crystallization and separation process. Struvite crystallization is mainly applicable to phosphorus recovery where the effluent is low in solids (< 2000 mg/L) (Schuiling et al., 1999), and relatively high in phosphorus (P-PO₄ > 50 mg/L). The process is operated at short hydraulic residence time (< 60 min), high pH (8.0-9.0) and temperature (25-35°C) (Le Corre et al., 2009). Due to slow crystal growth rate of struvite, solids retention times need to be high (> 10 days), which assists in forming larger aggregated crystals or granules (Le Corre et al., 2009). A fluidized bed design and/or recycle of crystalline product are commonly applied to enhance solids retention time above hydraulic retention time. Alternative products like calcium phosphate, magnesium potassium phosphate, or iron phosphate can be produced in a similar manner (Graeser et al., 2008). This extraction option is defined as established.

2.5.2 Liquid-Gas Stripping

Gas stripping is a physiochemical process that involves the mass transfer of ammonia from the liquid phase to the gas phase. This transfer is accomplished by contacting the dissolved ammonia with an extractant gas (usually air) and is mainly applicable to nitrogen recovery where the effluent is relatively high in nitrogen ($\text{NH}_4\text{-N} > 2000 \text{ mg/L}$). Air stripping usually requires an elevated temperature ($> 80^\circ\text{C}$) and pH (> 9.5) to increase the proportion of gaseous ammonia in the treated wastewater and decrease the amount of air required (Bonmati et al., 2003). As a result, pre-treatment of the feed is a critical step involving pH adjustment, solid-liquid separation, temperature adjustments, and carbonate removal (Figure 2-12) (Liao et al., 1995; Collivignarelli et al., 1998; Bonmati and Flotats 2003; Ippersiel et al., 2011).

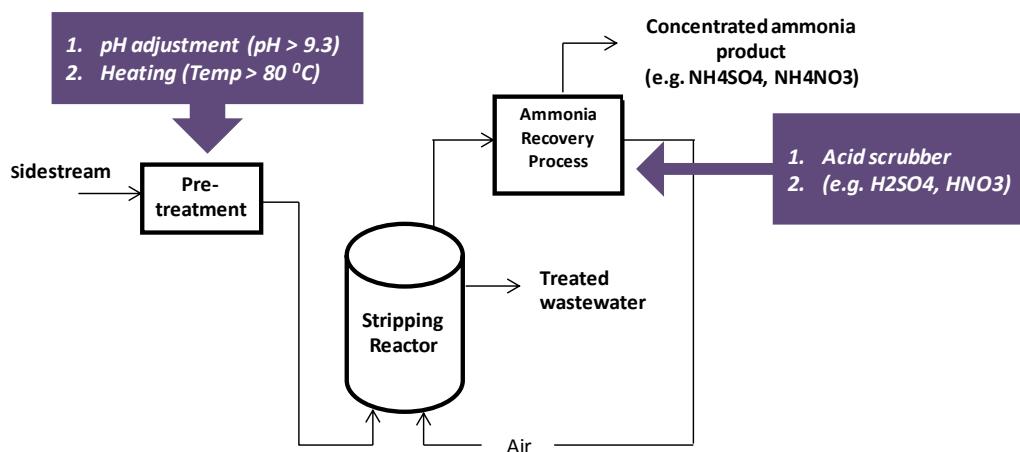


Figure 2-12. Conceptual Process Flow Diagram for Liquid-Gas Stripping Extraction Process.

Ammonia removal efficiencies of up to 98% have been observed using this approach (Collivignarelli et al., 1998; Bonmati and Flotats, 2003; Wang et al., 2010). Application of a vacuum can also help to improve ammonia recovery efficiency (Ippersiel et al., 2011). Recovery of the stripped ammonia occurs via condensation, absorption or oxidation to produce a concentrated fertilizer product. Products from the gas stripping processes include ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$), ammonia salts, or concentrated ammonia solution. The main challenges to implementing this technology are the relatively high operating cost per volume of wastewater treated, need for a concentrated feed, and production of a resulting ammonia-removed wastewater that is high in pH and unsuitable for lagoon storage and/or field application. While this technology has not been extensively applied within the domestic wastewater field, it is an established extraction technology option.

2.5.3 Gas Permeable Membrane and Absorption

Gas permeable membranes can be used to recover nitrogen as ammonia from the liquid phase. In this process, ammonia is transferred by convection and diffusion from the liquid stream across the membrane (Figure 2-13). Ammonia volatilizes through the hydrophobic membrane and is either condensed (EL-Bourawi et al., 2007) or absorbed into an acidic solution (Norddahl et al., 2006; Tan et al., 2006 ; Vanotti et al., 2010). The NH₄-N removal efficiency of the gas-permeable process has been reported higher than 90% (EL-Bourawi et al., 2007). A maximum concentrate ammonia level of 53 gN/L (solution containing ammonia) was reported using gas-permeable membrane in swine wastewater (Vanotti et al., 2005). Sulfuric and nitric acids can be used to recover the ammonia.

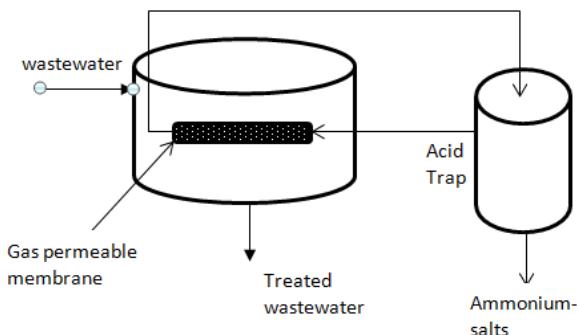


Figure 2-13. Conceptual Process Flow Diagram for Gas Permeable Membrane Extraction and Absorption Process.

Since the process is driven by the difference in partial pressure between the wastewater and the absorbing solution, improved performance can be observed at higher temperatures (up to 80°C) and high ammonia concentrations in the wastewater (Camus et al., 2006; Tan et al., 2006 ; EL-Bourawi et al., 2007). pH is also a crucial factor for ammonia recovery by gas permeable membranes (EL-Bourawi et al., 2007) with pH in excess of 9.0 needed to form free ammonia (NH₃). The membranes in this process are typically hydrophobic and may be comprised of silica (Camus et al., 2006), ceramic (Camus et al., 2006), polyvinylidene fluoride (PVDF) (Tan et al., 2006), polypropylene (PP) (Norddahl et al., 2006), polytetrafluoroethylene (PTFE) (Norddahl et al., 2006; EL-Bourawi et al., 2007; Rothrock, Jr. et al., 2010; Vanotti and Szogi, 2010), and polymer composites. Asymmetric membranes such as PVDF have a lower mass transfer resistance compared to symmetric membranes (Tan et al., 2006). Membranes can be constructed in different configurations including hollow fiber, tubular flat sheet, and spiral-wound cylinders and can be used in submerged or external configurations (Rothrock, Jr., et al., 2010). Selection and application of these membrane materials and configurations depends on resistance against fouling, flexibility, texture, as well as cost and accessibility. The main challenges to implementing this embryonic technology are the relatively low absorption rate per unit surface area as well as the high membrane and high operating cost per volume of wastewater treated. These costs arise from the need to perform pH and temperature adjustments. Additionally, this process may not be suitable for recovering ammonia from complex matrices that contain large amounts of hydrophobic compounds such as fats, oils, and grease.

2.5.4 Liquid-Liquid Extraction

Liquid-liquid extraction is a method to separate compounds based on relative solubility in two immiscible liquids. Nutrients (phosphate or nitrate/nitrite species) can be recovered from wastewater using liquid extraction. In this process, the extractant is dissolved in an organic phase which acts as a diluent. The organic phase with extractant is brought into contact with the wastewater, during which the extractant will sequester the nutrients from the aqueous phase. The organic phase can then be stripped to recover a concentrated nutrient solution (Figure 2-14).

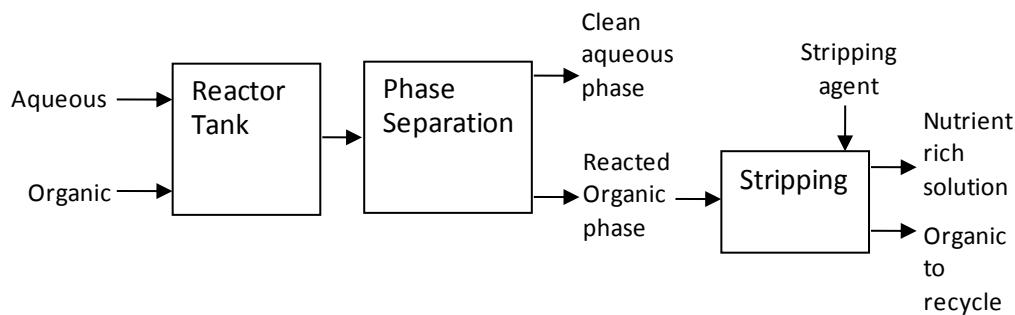


Figure 2-14. Conceptual Process Flow Diagram for Liquid-Liquid Extraction as used for Nutrient Extraction.
Adapted from Battelle, 2012b.

Higher nutrient concentrations and lower solids content of the waste stream can improve the efficiency and economics of the nutrient recovery process as nutrient extraction will be favoured and extractant losses will be minimized (Battelle, 2012b). The process can operate between pH 2.5 and 13 and has an optimal temperature range of 15-32°C (Battelle, 2012b). The number of extraction and stripping stages can also vary depending on the degree of extraction/concentration required. The diluent and extractant are recycled but makeup solution is required to maintain process efficiency. Extraction efficiencies of 80-90% and stripping efficiency of >90% have been achieved in lab scale studies investigating nitrate/nitrite and phosphate recovery (Battelle, 2012b). Another study recently found that a mixture of kerosene and benzylidimethylamine in a 2:1 ratio worked the best for phosphate extraction with 6M sulfuric acid being used as the stripping agent to obtain phosphoric acid as the final product (Mwabonje, 2010).

Advantages for this technology are the simultaneous removal and recovery of nutrients from the waste stream in a single process, the avoidance of waste generation, and the low nutrient concentration levels ($\text{PO}_4^{3-} < 1 \text{ mg L}^{-1}$) that are achievable in the treated water. The cost for the chemicals used as the stripping agent is the primary hurdle for adoption of this technology. However, these chemicals are recovered in the concentrated nutrient-rich solution, so the chemical cost can be offset by value realization for this product. As a result, this process can be classified as an innovative technology for nutrient accumulation and extraction since the concentrated liquid product can potentially be directly reused in agricultural applications.

2.5.5 Electrodialysis

Electrodialysis (ED) is an embryonic extraction technology in which an electrical current is used to separate anion and cations across an ion exchange membrane. Cationic species (K^+ , NH_4^+) move towards the cathode passing through cation-exchange membranes (CEM), which allow only positive species while rejecting the negatively charged species. Anions (e.g., PO_4^{3-}) move towards the anode passing through anion-exchange membranes (AEM), which allow only negative species to pass through and reject ions of the positive species (Figure 2-15). Through this process, cations and anions are obtained in separate concentrated solutions. ED cells can contain up to several pairs of AEM and CEM arranged alternately between electrodes. Additional cells between the electrodes increase current efficiency as they allow multiple “use” of the same electron (for each electron that is transferred, ions must be migrated across all membranes). However, increased membranes also increase the internal resistance, and hence, power consumption.

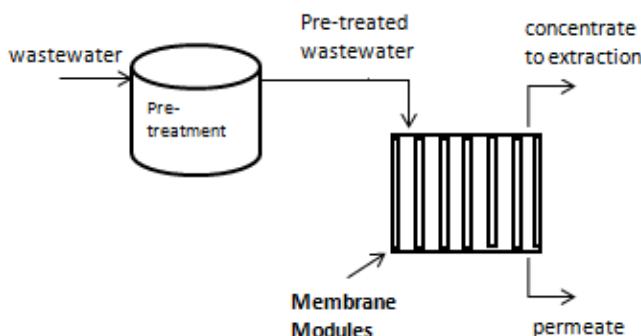


Figure 2-15. Conceptual Process Flow Diagram for Electrodialysis Extraction Process.

Electrodialysis has the potential to recover all nutrients but is most applicable for N and K. P can be effectively removed from concentrated streams using lower cost methods. This option is appropriate for recovering ions from nutrient streams at nutrient concentrations below 2000 mg/L due to potential fouling of the electrochemical cells. ED has been used to recover ammonia from pig manure (Mondor et al., 2008; Mondor et al., 2009; Ippersiel et al., 2011), and source separated urine (Pronk et al., 2006). A maximum ammonium concentration of 14.25 g/L was achieved in the concentrate, which was 10 times the manure. Greater than 99% recovery of K from winery wastewater and wheat leachates has been reported using ED (Decloux et al., 2002; Acevedo-Morantes et al., 2011). Wastewater with an acidic pH (<8.0) is preferred to improve nutrient solubility and maximize ion transfer through membranes. The process requires voltage above 2.0V per cell for optimum performance based on the recovery efficiency and total energy consumption (Mondor et al., 2008; Mondor et al., 2009; Ippersiel et al., 2011).

Successful application of this technology in full-scale facilities may be hampered by the high energy consumption, chemicals required for the regeneration of the membranes, membrane fouling, and heavy metal contamination. Use of bio-anodes and biocathodes could help to reduce energy consumption for electrodialysis by reducing cell potential.

2.6 Evaluating Extractive Nutrient Recovery Technologies

Table 2-2 summarizes the current state of science with regard to extractive nutrient recovery technologies. An accompanying electronic interactive technology matrix and summary containing information regarding the practical application of each option (process flow diagrams where appropriate, references for lab, pilot and full-scale applications) is also provided. This matrix is provided as an electronic amendment to the appendix of this report.

Table 2-2. Extractive Nutrient Recovery Technology Summary.

		Nutrient Recovery (% recovery efficiency)			Operating Conditions			Level of Pretreatment Required	Input	Product (% wt nutrient)	Commercial Process	
		N	P	K	Temp. (°C)	pH	Retention Time					
Embryonic	Accumulation	Algae	√	√	-	15 - 30	7.5 - 8.5	3 - 15 days	Low	Light source	Sludge (1 - 3.2 % P and 1-10% N)	Lemna Technologies
		Cyanobacteria	√	√	-	5 - 40	6.5 - 8	0.5 hr	Low	Carbon source, light	Biomass (8-12% N and 1% P)	-
		Purple non-sulfur bacteria	-	√	-	27-34	6 - 8	0.6 hr	Low	Alginate, light	Biomass (0.05% P)	-
		Magnetic	√	√ (> 90%)	√	25 - 40	8 - 9	< 1 hr	Solid-liquid separation	Magnetic material	Leachate from desorption of magnetic material	SIMFLOC, Smit Nymegen
Extraction	Release	Bioleaching	√	√ (< 40%)	-	20 - 40	1 - 3	< 3 days	Low	Sulfur, iron source, pH adjustment	Leachate	BIOCON
	Extraction	Gas-permeable membranes	√ (> 90%)	-	-	10 - 80	> 9.5	< 1 hr	High (pH and temperature adjustment)	Heat, pH adjustment	ammonium sulfate, ammonium salts concentrated ammonium liquid	-
		Electrodialysis	√	√	√	10 - 40	< 8.0	< 1 hr	Solid-liquid separation	Electricity	Concentrated nutrient solution	GE Water

Table 2-2. Extractive Nutrient Recovery Technology Summary (continued).

			Nutrient Recovery (% recovery efficiency)			Operating Conditions			Level of Pretreatment Required	Input	Product (% wt nutrient)	Commercial Process
			N	P	K	Temp. (°C)	pH	Retention Time				
Innovative	Accumulation	Plant	√	√	√	25 - 31	6 - 8	1 - 4	Low	Light source	Biomass (1 - 3% N and P)	-
		Adsorption/Ion exchange	√ (> 90%)	√ (> 90%)	√ (> 90%)	10 - 40	<8.0	< 1 hr	Solid-liquid separation	Adsorbent	57 g P/kg (Zirconium loaded orange waste gel) and 21.52 g N/kg (Clinoptilolite)	P-ROC, RECYPHOS, PHOSIEDI, RIM NUT BIOCON
	Release	Chemical Release	√	√	√	25-200	1 - 3	< 1 hr	-	Leaching solution, pH adjustment	Leachate (conc. vary with feed)	SEABORNE, STUTTGARTER VERFAHREN, LOPROX/PHOXAN, CAMBI, KREPCO, BIOCON, SEPHOS, AQUARECI, SESAL-PHOS, PASCH
		Thermochemical Release	-	√	√	150 – 1100	all	< 1 hr	Medium (heating required)	Heat	Char (conc. vary with feed)	MEPHREC, ASHDEC, THERMPHOS
		Chemical (Liquid Extraction)	√	√ (> 90 %)	-	15 - 32	2 - 13	0.5 hr	Solid-liquid separation	Na ₂ CO ₃ , NaOH, Aliphatic, Non Volatile Solvents with Extractants	Sodium or potassium phosphate (tribasic) solution (0.8% P)	AD-LLX

Table 2-2. Extractive Nutrient Recovery Technology Summary (continued).

			Nutrient Recovery (% recovery efficiency)			Operating Conditions			Level of Pretreatment Required	Input	Product (% wt nutrient)	Commercial Process
			N	P	K	Temp. (°C)	pH	Retention Time				
Established	Accumulation	EBPR	-	✓ (15-50%)	-	5 - 40	6.5 - 8	0.5 hr	Low	May require external carbon, pH adjustment	Sludge (5 - 7% P)	-
		Chemical (Precipitation)	✓	✓ (> 90 %)	-	25 - 40	6 - 11	< 1 hr	Low	Chemical Al, Fe, pH adjustment	Sludge (1 - 3% P)	-
	Release	Anaerobic digestion	✓	✓	✓	35 – 60	6.5 – 7.5	20 – 30 days	Medium (heating required)	-	Digested slurry (varies with the feed) Biosolids	-
		Liquid-gas stripping	✓ (> 90%)	-	-	>80°C	> 9.5	< 1 hr	High (pH and temperature adjustment)	Heat, pH adjustment	ammonium sulfate, ammonium salts concentrated ammonium liquid	ThermoEnergy Castion™
	Extraction	Crystallization	✓	✓ (> 90%)	✓	25 - 40	8 – 9	< 1 hr	Solid-liquid separation	Mg or Ca, pH adjustment	Struvite (12% P, 5% N), K-struvite Fe or Ca phosphate	DHV CRYSTALACTOR, CSIR, KURITA, PHONIX, OSTARA, BERLINER VERFAHEN, FIX-PHOS, MULTIFORM HARVEST, NURESYS, PHOSPHAQ, AIRPEX

Implementation of extractive nutrient recovery at municipal WRRFs requires careful consideration of a multitude of factors (technical, economic, and social). To help the wastewater industry evaluate potential recovery options, multiple screening criteria were developed. For a preliminary screening, WRRFs are advised to first evaluate their waste stream characteristics and then analyze their potential nutrient products. Table 2-3 provides the initial screening criteria for selecting a technology class based on the waste stream characteristics. The number of checkmarks corresponds to the applicability of the recovery process for the respective waste stream.

Table 2-3. Screening Criteria for Determining Appropriateness of Accumulation, Release or Extraction.

Waste Stream Characteristics		Nutrient Accumulation	Nutrient Release	Nutrient Extraction
Nutrient concentration	high ($>100 \text{ mg L}^{-1}$)	✓	✓✓	✓✓✓
	low ($<20 \text{ mg L}^{-1}$)	✓✓✓	✓	✓
Nutrient form	soluble	✓✓✓	✓	✓✓✓
	particulate or organic substances	✓✓	✓✓✓	✓
Insoluble contaminants	high concentration	✓✓✓	✓✓✓	✓
Soluble contaminants	high concentration	✓	✓	✓

✓✓✓: high, ✓✓: medium and ✓: low

Concerning the potential recoverable nutrient products, the four main product categories are discussed further below. Additionally, WRRFs should consider non-nutrient products as a third factor, because non-nutrient products are expected to play an increasingly important role in the economics of extractive resource recovery. Potential non-nutrient products are discussed in greater detail following the section on nutrient products.

2.6.1 Impact of Waste Stream Characteristics on Technology Selection

As discussed previously, nutrient concentration, nutrient form, particulate contaminants, and soluble contaminants impact the efficiency of nutrient recovery. In general, nutrient accumulation techniques are most suitable for waste streams with low nutrient content ($< 20 \text{ mg/L}$; e.g., municipal wastewaters); however, the solubility of the nutrients as well as the flow capacity can limit the application of physical and chemical techniques due to the large quantity of adsorbent material and chemical needed. If biological accumulation is selected, two options can be considered. Nutrient recovery and recycling can be facilitated by generating biosolids.

Alternatively, if the intention is to produce a chemical nutrient product, implementation of a release technology will be necessary. Generally, biological (anaerobic digestion, enhanced WAS Release, and bioleaching), chemical, and thermal processes are effective methods for releasing particulate and organically bound nutrients into soluble components. In contrast, chemical or thermochemical methods are required to release nutrients accumulated through chemical precipitation methods. The intent of the release technology is to produce a liquid effluent with nutrient content in excess of 100 mg/L.

The presence of contaminants (both soluble and insoluble) can impact the efficiency and economics of the nutrient extraction and chemical product recovery process. If inert solids are present, pre-treatment via solid-liquid separation technology is needed to ensure that the solids content of the waste stream remains below 2,000 mg/L. Removal of soluble contaminants (e.g. heavy metals, Na^+ , Cl^- , Ca^{+2} , carbonates) can be more challenging and may require additional pre or post treatment, which can involve water hardness reduction (softening) and elevated temperature treatment to volatilize metal complexes. In all cases, additional treatment increases the overall cost of the process.

An extensive review of literature has shown that nutrient accumulation and release technologies, except chemical extraction, are widely used for all type of waste streams. Nutrient accumulation and extraction techniques such as crystallization and adsorption are heavily implemented in domestic and agriculture waste stream. Results also indicate that there is a dearth of information regarding the feasibility of employing emerging technologies such as alternative accumulation strategies (e.g., purple non-sulfur bacteria, magnetic separation) and extraction technologies (e.g., gas-permeable membrane and electrodialysis) within the extractive nutrient recovery framework of domestic wastewater.

After evaluating waste stream characteristics, the nutrient and non-nutrient recovery potential should be evaluated. The following section includes a discussion on the potential recoverable nutrients and non-nutrients, which the wastewater industry can use to evaluate the different recovery options and processes.

2.6.2 Potential Recoverable Nutrient Products

A key requirement for industry-wide adoption of extractive nutrient recovery is the need to produce value added chemical products that have use in a secondary market. Since over 85% of all nutrient products are associated with the agricultural sector, it is appropriate for extractive nutrient recovery options to seek to produce products that have value in the agricultural sector. At present, there are four main nutrient products (excluding water) that can be/are being produced from wastewater: 1) biomass, 2) biosolids, 3) char/ash, and 4) chemical nutrient products. Additional detailed discussion of chemical nutrient products is provided in Chapter 3.0.

2.6.2.1 Biomass

Nutrient-rich biomass that is derived from plant, algae and microbial accumulation techniques can be used as animal feedstock, substrates for nutrient release technologies, or as substrates for biofuel production technologies. While WRRF-generated biomass could be used as an animal feedstock, it is unlikely as there would be concerns with safety of the wastewater generated feed, metal concentrations, and pathogens. Direct application of intact biomass for agricultural purposes has also been identified as a possibility; however, research into this application is limited. Furthermore, nutrient release rates from different biomass sources are unknown. As a result, direct reuse of nutrients through agricultural application of intact biomass requires further investigation before widespread adoption.

2.6.2.2 Biosolids

Stabilization of biologically accumulated nutrients and chemically precipitated solids via anaerobic digestion can generate solids and liquid streams (denoted as biosolids) with high nutrient content (1-5% P and 1-10% N). This makes biosolids an attractive product that allows for the reuse of nutrients as well as organic matter as fertilizer (McLaughlin, 2007). Studies have found that biosolids have equal or better performance as agricultural amendments compared with commercial fertilizer (Pritchard et al., 2010). Nevertheless, opponents raise environmental and human health concerns regarding the use of biosolids in agriculture including pathogens, heavy metals, and trace organic contaminants (TOxC).

Control of pathogens in biosolids has been the subject of extensive research which has resulted in the development of processes to significantly reduce pathogens (PSRP) and processes to further reduce pathogens (PRFP), in order to meet environmental regulations aimed at minimizing the impact on human health (U.S. EPA, 2003). Removal of metals from biosolids can be achieved using chemical extraction processes but these techniques can be expensive and often result in the co-dissolution of nutrients and heavy metals which requires an expensive undertaking (Wang et al., 2008). Instead, regulations have focused on limiting the use of biosolids with higher metal contents.

At present, the presence and impact of TOrC in biosolids is the subject of active research (Higgins 2010; Maier, 2011). It is known that hydrophobic chemicals will accumulate in the solids fraction; however, it is not clear how effective different PSRP and PRFP are for removing these contaminants. As a result, no direct regulations have been promulgated to limit biosolids land application based on TOrC content. As research develops, this may be subject to change.

One of the major challenges of using biosolids as the primary vehicle for nutrient recovery and reuse in the wastewater industry is the expense associated with transport of biosolids to the reuse or disposal site. As the moisture content of biosolids is normally 80-90% (Metcalf & Eddy et al., 2002), it is very costly to transport biosolids from urban to rural regions where land application sites are typically located (Batstone and Jensen, 2011). This is clearly exemplified by examining the current value of nutrients in biosolids (~ \$U.S. 8 per tonne) versus the cost of transport (\$U.S. 30 per tonne to transport 50 km in the U.S.). While transport costs are higher in Europe and lower in Australia, these additional costs depend on the price of fuel and are an impediment to further adoption of biosolids as the primary vehicle for nutrient recovery. Therefore, the use of processes to further dewater digestate/biosolids into pelletized or granulated fertilizer products is useful; however, these processes require a significant energy expenditure, with a minimum of 800 kWh of energy (as gas) required to evaporate one tonne of water. Solar drying can help to reduce this to 30 kWh of electricity per tonne of water evaporated, but is limited to suitable climates.

Another challenge to the use of biosolids as the sole product for nutrient reuse and recovery is the development of regulations that limit land application based on N and P soil content. These regulations will require utilities to increase storage capacity or look for alternative site, for land application, which may drive up costs. Extractive nutrient recovery can potentially complement the existing paradigm of nutrient recovery and reuse using land application of biosolids. By extracting N and P from biosolids, extractive nutrient recovery can allow utilities to manage the N and P content of the biosolids to more closely match local application needs. Since the extracted chemical product is stable with minimal organic content, it will be cheaper to store and can potentially be sold in a secondary market. Furthermore, as previously mentioned, biosolids can be amended to increase their alternative uses. For example, the Water Corporation in Western Australia has developed a lime-amended biosolids/clay blend slow release fertilizer that is specific for acidic sandy soils.

2.6.2.3 Char and Ash

The use of char and/or ash from thermochemical processes for soil amendment is becoming increasingly popular because of its potential benefits of soil carbon sequestration, heavy metal immobilization, improvement of soil quality, increase of crop yield, mitigation of nutrient leaching, and organic contaminant remediation (Lehmann et al., 2011; Park et al., 2011). This product can also be reused within the construction industry, but in this scenario the nutrient content is not exploited. Similar to biosolids, ash and char reuse as agricultural amendments will be limited by the heavy metal content. While chemical release and subsequent extraction can be used to exploit the nutrient content by producing chemical nutrient products, post-treatment requirements to volatilize heavy metals will limit the utility of this product (Lehmann et al., 2011).

2.6.2.4 Chemical Nutrient Products

Nutrient extraction technologies can recover nitrogen and phosphorus into particulate or soluble, inorganic fertilizer products that are readily useable for agricultural applications. At present, struvite is the primary focus of several commercial technologies. In addition to struvite, other products like calcium phosphate, (hydroxyapatite), iron phosphate (vivianite), phosphoric acid, ammonium sulfate, ammonium nitrate can be recovered.

Struvite has been widely cited as a suitable slow-release fertilizer. It is sparingly soluble in water and research suggests that it has comparable performance as a fertilizer to phosphate-rock based fertilizer products (Johnston et al., 2004; Ryu et al., 2012). Overuse of struvite can result in magnesium accumulation in soil; however, this can be managed using accurate fertilization (Gell et al., 2011) and selection of crops that tend to accumulate magnesium (e.g., grains, legumes, dairy cattle). One benefit of struvite recovery is that the levels of heavy metals in recovered struvite are significantly lower than the regulatory limits (Munch et al., 2001; Di Iaconi et al., 2011; Liu et al., 2011; Forrest et al., 2008). Additionally, it has been found that struvite products with low moisture content have negligible pathogen and TOrC content (Antakyali 2011; Decrey et al., 2011).

Nitrogen recovery through liquid-gas stripping, gas permeable membrane and electrodialysis can produce an aqueous ammonia solution which can be used as a fertilizer or for the denoxification of exhaust gases of power stations and waste incinerators. The aqueous ammonia can further be converted into solid inorganic fertilizer such as NH_4NO_3 or $(\text{NH}_4)_2\text{SO}_4$. At present, the economic feasibility of nitrogen only recovery is low, largely due to high chemical cost to adjust pH, the heat required for phase change (NH_3 from NH_4^+), and well as the relatively low cost of ammonia produced via the Haber-Bosch process. This could change in the future with the rising costs of treatment for nitrogen and natural gas availability and cost (gas is used to manufacture ammonia through the Haber-Bosch process).

Another nitrogen recovery option for WRRFs could involve recovered methane. It could be stream reformed into hydrogen gas for the Haber-Bosch process. This would produce ammonia, which is used for a variety of fertilizers; however, implementing this process would be prohibitively expensive for WRRFs. It may be possible to target nitrogen products to specific niche markets, which may increase the value of the recovered product. A detailed review of the current U.S. market for chemical nutrient products recovered from WRRFs is provided in Chapter 3.0.

Many of the chemical nutrient products that can be recovered from wastewater will typically contain some combination of N-P-K, and other elements. At present, the worth of these recovered chemical nutrient products is largely set based on the content of the primary nutrient (likely P). This approach neglects to account for the economic and environmental advantage gained through the recovery of the other elements. Economic evaluations of extractive nutrient recovery for nutrient management can be viewed as economically infeasible when these additional benefits are not considered. To facilitate more widespread adoption of extractive nutrient recovery, it is essential that the industry develop and adopt a framework that accounts for all recovery benefits and not simply focus on the primary nutrient content (Guest et al., 2009; Molinos-Senante et al., 2011).

2.6.3 Potential Recoverable Non-Nutrient Products

In addition to nutrients, wastewater contains significant energy in the form of organic matter. This organic matter can potentially be recovered as energy in the form of methane (requires anaerobic metabolic) or via electricity (requires microbial fuel cell; MFC). The organic matter can also be potentially recovered as biofuels or other industrial chemicals (e.g., polyhydroxyalkanoates, volatile fatty acids). At present, the direct economic benefit of extractive nutrient recovery is limited to the resale value of the chemical nutrient product(s) recovered and the O&M savings resulting from the reduction of chemical use at a treatment facility. Similarly, extractive recovery of industrial chemicals from waste streams is limited by the small scale of production which can make this approach infeasible. The opportunity currently exists to develop options that facilitate the simultaneous recovery of multiple resources (e.g., nutrients and industrial chemicals), thereby improving the overall economic viability of extractive resource recovery and making it an attractive treatment option.

The key to unlocking the resource potential of waste streams is the selection of processes that complement each other. An example of this synergy is the scenario where biological accumulation of nutrients is used to produce a nutrient rich biomass. During release of the nutrients, the organic matter in the biomass can be used as feedstock for energy or carbon recovery, or as a source of organic matter for soils. Indeed, this has been historically accomplished in the wastewater industry by employing cogeneration to make use of the caloric content of methane produced during anaerobic digestion. An alternative approach is to employ fermentation to selectively produce volatile fatty acids, which are then used for phosphorus and nitrogen removal. The fermentate can also potentially be used for waste activated sludge enhanced phosphorus release processes. These scenarios represent the most common strategies employed for simultaneous nutrient, energy, and/or carbon recovery. A similar paradigm can be used for coupling innovative and embryonic technologies to maximize multiple resource recovery.

2.6.3.1 Biogas and Biofuel

Algae and duckweed biomass can also be used as feedstock for energy (e.g., biofuels or biogas). Algae are an attractive option for energy and nutrient recovery because they have a high growth rate, sequester carbon dioxide (2 kg CO₂/kg algae) (Lundquist et al., 2010), and can be processed into multiple high demand byproducts including biodiesel, bioethanol, and hydrogen (Menetrez, 2012). Although algae cultivation ponds require relatively small footprints for cultivation relative to other terrestrial crops, these cultivation ponds are drastically larger than traditional wastewater ponds. Despite these advantages, the large scale cultivation of algae is inhibited by high energy, water, and nutrient (100 g N/kg algae) demands (Clarens et al., 2011). Two of these resources are present in waste streams (water and nutrients) so it may be prudent to situate algal cultivation farms within close proximal distance to waste streams (municipal, industrial, and agricultural) where algae cultivation can serve as a nutrient polishing step. In this scenario, nutrients from waste streams can be used to meet cultivation needs instead of using synthetic fertilizers. By using waste stream nutrients, the water and nutrient burden of the algae farm can be minimized. Additionally, the excess nutrients present in the processed biomass can be extracted into a chemical nutrient product and reused onsite or sold. The lipids from the algae can also be extracted and converted to biodiesel with the remaining biomass used to generate methane (Figure 2-16). In this process the algae are cultivated on wastewater in high-rate growth ponds. The algae are removed in a clarifier and gravity thickened. The algae biomass is then processed to extract the lipids for transesterification. The resulting residuals from the lipid extraction process are sent to the anaerobic digester, where methane is recovered and used for electricity.

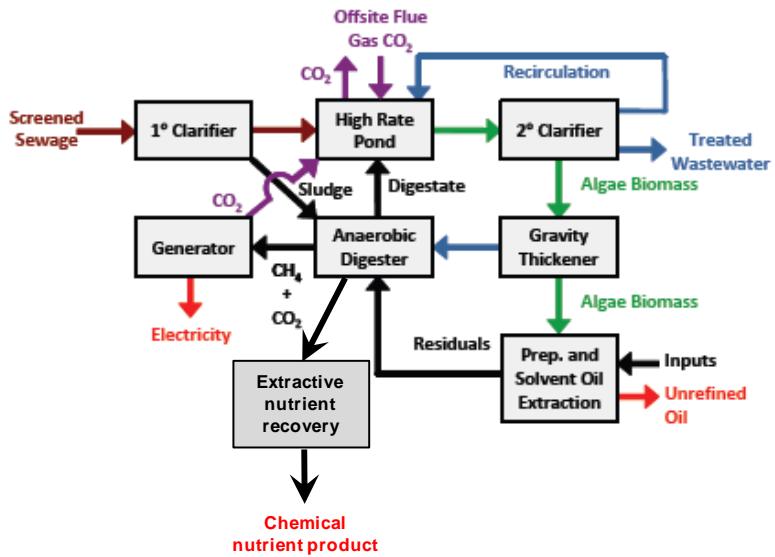


Figure 2-16. Conceptual Process Flow Diagram for Simultaneous Nutrient and Energy Recovery Using Algae.

A – Nutrient, Biogas and Biofuel Recovery, B – Nutrient and Biogas Recovery.

Adapted from Lundquist et al., 2010.

There may also be market potential for using recovered chemical nutrient products from waste streams as the source of nutrients for algal farms that cannot be closely situated to the waste stream. In this scenario, the chemical nutrient products would replace synthetic fertilizers.

It is unlikely that a single algal species could be used for algal cultivation due to the heterogeneous nature of wastewaters. Therefore, for growth on wastewaters, a mixed algae culture would be likely. Processes would have to be developed to optimize lipid contents and minimize the impact of invasive species such as rotifers, fungi, and bacteria (Mata et al., 2010).

Assuming conservative estimates of biodiesel conversion efficiency from the algae biomass, the cost of one liter of algae-based biodiesel is currently estimated to range from approximately U.S. 2.11 to 2.74 per liter (U.S. 8.00 to 10.38 per gal) (Menetrez, 2012). Since the current costs of algae biofuels is uncompetitive with traditional fuels, algal biofuel companies have expanded into alternative markets such as personal care, cosmetics, food additives, and animal feed (Heliae 2013; Solatube, 2013). In order to improve the economics of algae-based biofuel applications, it will be necessary to account for the benefits gained from nutrient recovery and biogas production during economic feasibility studies. Together with technological advancements in growth techniques, reactor configurations and the use of organisms with higher lipid yield, it is expected that the cost of algae production will decrease as the scale of production increases. However, it will likely take over 10 years of research development before this option is mature enough to be considered viable (Lundquist et al., 2010).

Key research needs at this point include development of more thorough understanding of which reactor configuration is best for mass cultivation for biofuels, development of appropriate biomass separation devices/technologies, and development of multiple biomass to oil conversion options. Additionally, detailed characterization of algae production rates and operating cost data for the complete system (production to extraction) is needed for proper evaluation of additional value of this process.

2.6.3.2 Polyhydroxyalkanoates

Organic carbon can also be recovered in the form of internal storage products like polyhydroxyalkanoates (PHA). These PHAs are precursors to thermostable biodegradable plastics and are primarily composed of polybetahydroxybutyric acid (PHB) and poly-betahydroxyvaleric acid (PHV), although up to 80 other forms are possible (Punrattanasin, 2001). Extensive reviews of PHA production have been presented elsewhere (Choi 1997; Salehizadeh et al., 2004; Castilho et al., 2009; Moita et al., 2012). To produce PHA at commercial quantities using wastewater, mixed microbial fermentation is actively being researched as a cost effective production strategy (Moralejo-Garate et al., 2011). In this approach, a mixed community of PHA producing organisms is selectively enriched using alternating carbon rich and carbon limited conditions to stimulate PHA production. Results from these mixed microbial fermentation studies indicate that yields ranging from 0.08 to 0.4 g PHA/g substrate can be observed provided that proper environmental conditions are present. These conditions include two-stage redox operation, carbon, N and P limitation, which are commonly found in municipal WRRFs.

The market price of industrially relevant PHA ranges from approximately \$U.S. 13 to 15 per kg PHA (Castilho et al., 2009). The price of comparable biodegradable plastics ranges from \$U.S. 5 to 10 per kg product (Choi, 1997). There is a need to reduce production costs. The use of low value waste streams and mixed microbial fermentation represents an opportunity to help reduce the cost of PHA production by up to 40% (Choi, 1997). As the organisms involved with PHA production typically coincide with phosphorus accumulation, it may be feasible to develop a sidestream processes that exploits PHA production in the WAS from these systems. However, as with biofuel systems, additional research should characterize typical production rates and operating cost data for the complete system (production to extraction). Additionally, understanding the minimum market demand and product specifications required for commercial manufacturing in this sector as this will help determine whether regionalization of wastewater treatment facilities is needed.

2.6.3.3 Hydrogen, Hydrogen Peroxide, and Sodium Hydroxide

Microbial electrochemical technologies (MET) including microbial electrodialysis cells (MES) can be used to produce industrial chemicals like hydrogen, hydrogen peroxide and caustic solutions (Logan et al., 2012). For hydrogen production, an electric current is applied to an anaerobic cell. This electrical energy, together with the energy produced by the organism at the anode, is used to generate hydrogen gas at the cathode (denoted as electrohydrogenesis) (Cheng et al., 2007). Hydrogen peroxide and sodium hydroxide can also be generated in a MES in which a CEM is used to allow for the preferential accumulation of a caustic solution in the cathodic chamber. In the absence of oxygen at the cathode, hydrogen peroxide will also be produced (Logan and Rabaey, 2012). These non-nutrient products provide an additional benefit of electrolysis cells that are used for extractive nutrient recovery. While this technology is embryonic in nature, the potential to simultaneously produce multiple value-added products make this a high priority research area. As with other products, there is a need to understand the minimum market demand and product specifications required. Development of capital and operating costs is also needed for scale-up considerations.

2.6.3.4 Nutraceuticals

Mass cultivation of algae for nutraceutical purposes should also be considered within the context of extractive nutrient recovery. This industry is mature, produces over 5000 million tonnes of biomass, and has significant water and nutrient demands. While it is not expected that this industry can directly use wastewater, it represents a potential market for recovered chemical nutrient products and reuse water. These chemical nutrient products can

replace synthetic fertilizers. If there is indeed a viable market for this option, specialty pricing of the recovered chemical nutrients may be possible.

2.6.3.5 Other Products

Biological release methods like anaerobic digestion can also be coupled with processes to produce methanol and other products from digester gas (e.g., sulfide, sulfur). For example, sulfur is both a plant and animal nutrient, and is a common component of different fertilizers. These alternative non-nutrient recovery products can provide add-on value to these technologies, but they are embryonic in nature and require further study before they can be implemented.

2.7 Considerations for Implementing Extractive Nutrient Recovery

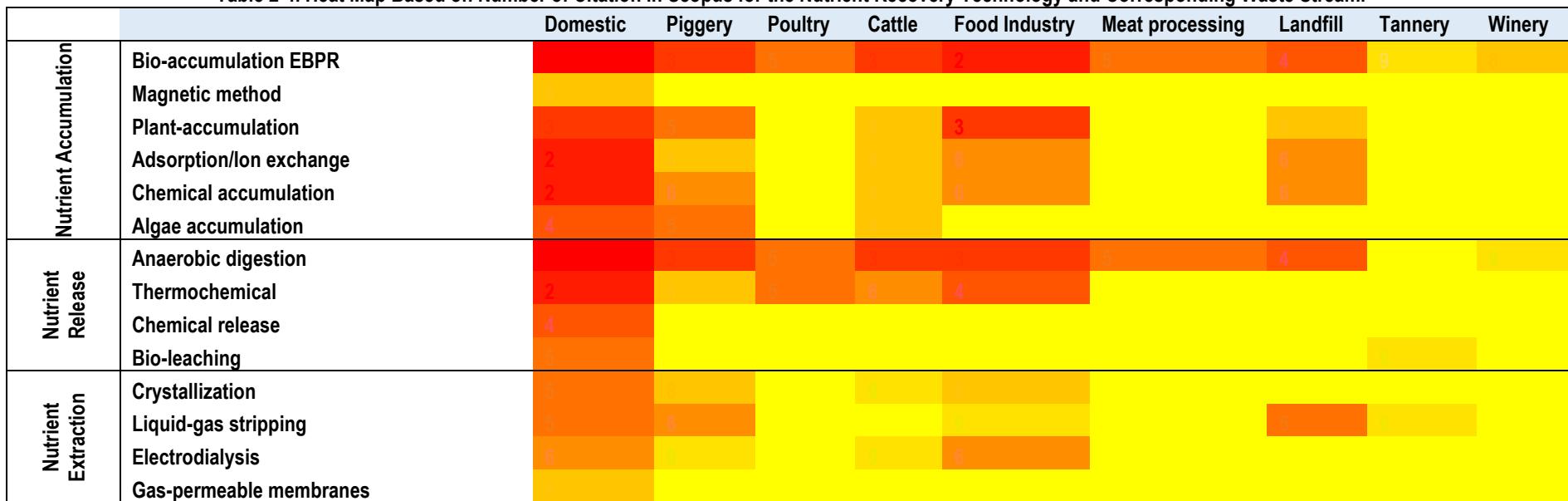
As mentioned previously, adoption of extractive nutrient recovery will also depend on several other considerations such as engineering feasibility, capital cost, technology maturity and reliability, information credibility and availability, operating cost, safety issues, and environmental concerns and benefits. A review of citations for existing work related to extractive nutrient recovery demonstrates that the vast majority of work has focused on domestic wastewater treatment applications (Table 2-4). This indicates that there is tremendous opportunity for implementing extractive nutrient recovery in other industries. It also suggests that the wastewater treatment industry can and is serving as a proving ground for research and development of commercial extractive nutrient recovery technologies. This factor can be used to the industry's advantage by developing research and development innovation hubs where facilities act as leaders of early technology deployment (pilot-scale). This can bring innovative science as well as serve as a potential revenue source for entrepreneurial facilities.

As can be seen from Table 2-4, engineering feasibility is very high for technologies such as anaerobic digestion, chemical precipitation, and EBPR since these technologies have a proven track record and are widely used in municipal wastewater treatment. Struvite crystallization and tertiary filtration also have high feasibility, as these processes are less complex and easy to scale-up and are increasingly being applied across the globe in municipal and industrial applications. Additionally, biological based treatment tends to be more economic with respect to extractive nutrient recovery processes. However, widespread application will be dependent on site specific constraints such as degradability of the feed and precipitation of phosphates in the case of anaerobic digestion, and large land requirement in the case of plant based accumulation.

As nutrient management and recovery is interlinked with water and energy issues, extractive nutrient recovery objectives must align with the emerging plants of the future concept whereby advanced wastewater treatment facilities meet stringent effluent nutrient limits while maximizing water reuse and energy recovery. At a minimum, extractive nutrient recovery processes must focus on being sustainable, whereby process inputs (water, chemicals, energy) are minimized. To facilitate this, further analyses of these options must also include a comprehensive economic and environmental assessment whereby energy and water related impacts are included.

It should also be acknowledged that the products recovered from municipal WRRFs are not likely to be a major revenue source for the industry. Instead, the economic value of the products lies in their ability to help to offset treatment costs. The benefit from recovery will also be site specific and will be based on the products recovered and the local demand for niche products.

Table 2-4. Heat Map Based on Number of Citation in Scopus for the Nutrient Recovery Technology and Corresponding Waste Stream.



Legend:



Table 2-5. Summary of Technology Feasibility.

	Engineering Feasibility	Capital Cost	Technology Designation	Information Credibility and Availability	Operating Cost	Safety issues	Environmental Concerns	Environmental Benefits
Nutrient Accumulation	Plant-accumulation	Medium	Low	Innovative	Medium	Low	Low	reduce COD and BOD
	Algae accumulation	Medium	Low	Innovative	Medium	Low	Low	reduce COD and BOD
	EBPR accumulation	High	Low	Mature	High	Low	Low	–
	Chemical accumulation	High	Low	Mature	High	High	Low	–
	Adsorption/Ion-exchange	Medium	Medium	Embryonic	Low	Medium	Low	–
	Magnetic separation	Low	High	Embryonic	Low	Low	Low	–
Nutrient Release	Anaerobic digestion	High	Medium	Mature	High	Low	Medium	Produces energy, reduce GHG emission, reduce COD and BOD
	Thermochemical	Medium	High	Innovative	Medium	High	High	Destroys toxic organic matter and biological contaminants, reduce volume of waste
	Extraction/leaching	Medium	High	Embryonic	Low	High	Medium	Heavy metals can be separated from waste
	Bio-leaching	Medium	Low	Embryonic	Low	Low	Medium	–
Nutrient Extraction	Crystallization (struvite)	High	Medium	Innovative	High	Medium	Low	–
	Liquid-gas stripping	Medium	High	Embryonic	Low	High	High	–
	Electrodialysis	Low	High	Embryonic	Low	High	Medium	–
	Gas-permeable membranes	Low	High	Embryonic	Low	High	Medium	–
	Liquid-Liquid Extraction	Medium	High	Innovative	Medium	High	Medium	Simultaneous removal and recovery of nutrients

2.8 Future Research Directions

Data describing the design, operation, and economic assessment for pilot or full scale implementation is not widely available for most nutrient recovery technologies, except for established and some innovative technologies such as struvite crystallization and plant accumulation. Full scale implementation experience is lacking for the other innovative technologies such as adsorption/ion exchange, plant accumulation and chemical extraction, whereas further pilot scale studies are required for embryonic technologies such as electrodialysis, gas permeable membrane, and magnetic methods. Prioritized research needs for these technologies are provided in Table 2-6.

Diversification of the chemical nutrient products that are recovered is also needed. It is expected that future product demands will require the production of chemical products that have high nutrient content, low moisture, extremely low heavy metal, and pathogens contamination. These emerging needs can potentially limit the use of manure, biosolids, and ash/char as the primary vehicle for nutrient recovery. Instead, it may be more appropriate to couple biosolids, manure, and ash/char production with extractive nutrient recovery technologies to help manage nutrient content of these bulk organic products as well as benefit from the chemical products. Identification of the most relevant chemical product will require consideration of local agricultural and industrial demands.

At present, there is no single technology that is perfect for complete nutrient (N-P-K) recovery; however, this does not preclude the development of an integrated process for this purpose. It is expected that integrated technologies will increase the capital costs required by municipalities. Consequently, this dictates that O&M costs of these technologies be low. Further research into decreasing the operating costs of N-P-K technologies is needed. This may focus on finding alternative sources of chemical inputs required for the process. Alternatively, research into efforts where chemical nutrient products and non-nutrient products are recovered may improve the economics of resource recovery.

Table 2-6. Summary of Research Needs to Facilitate Adoption of Extractive Nutrient Recovery.

		Existing Knowledge	Need for Future studies
Technology Development	Plant-accumulation	✓✓	✓✓✓
	Algae accumulation	✓✓	✓✓✓
	EBPR accumulation	✓✓✓	✓
	Chemical accumulation	✓✓✓	✓
	Adsorption/Ion-exchange	✓	✓✓
	Magnetic separation	✓	✓
	Anaerobic digestion	✓✓✓	✓
	Thermochemical	✓✓	✓
	Extraction/leaching	✓	✓
	Bio-leaching	✓	✓✓✓
	Struvite Crystallization	✓✓	✓✓
	Liquid-gas stripping	✓	✓
	Electrodialysis	✓	✓✓✓
	Tertiary filtration	✓✓	✓✓
	Gas-permeable membranes	✓	✓✓✓
	Liquid-Liquid Extraction	✓	✓✓✓
Product Development	Char	✓✓✓	✓✓
	Potassium concentrated product	✓	✓✓✓
	Biomass from plant and bio-accumulation	✓	✓✓
	Nitrogen concentrated product	✓	✓✓✓
	Biosolids	✓✓✓	✓
	Non-nutrient by-products	✓	✓✓✓

✓✓✓: high, ✓✓: medium and ✓: low

CHAPTER 3.0

MARKET ANALYSIS OF RECOVERED CHEMICAL NUTRIENT PRODUCTS

3.1 Identification of Chemical Nutrient Product(s)

As noted in Chapter 1.0, production of a chemical nutrient product with resale value is an essential requirement for industry-wide adoption of extractive nutrient recovery. For this study, six chemical nutrient products that can or have previously been recovered from waste streams were identified for further investigation (Table 3-1). The six identified chemical nutrients are struvite, hydroxyapatite, vivianite, phosphoric acid, ammonium nitrate, and ammonium sulfate. Collectively, these products contain N and P as well as micronutrients including magnesium, sulfur, iron, and calcium. The nutrient products can be present as a liquid or as a solid and have uses in the agricultural and industrial fields.

In cases where products are not currently commercially produced, comparable existing products in the agricultural field were used to identify potential markets and characterize sale trends (AAPFCO et al., 2010). For instance, the comparable products for struvite (diammonium phosphate and monoammonium phosphate) and hydroxyapatite (triple super phosphate) were identified based on the primary nutrient in which they would likely be marketed to supply (phosphorus). In the case of vivianite, no suitable agricultural product was identified; however, it is anticipated that vivianite could potentially be used as a niche iron source in the agricultural sector. This focus on agricultural use is justified since over 85% of all nutrient products are associated with the agricultural sector. It is acknowledged that use of nutrient content as the sole criteria for identifying comparable products has drawbacks; however, due to the absence of peer reviewed data regarding physical characteristics and nutrient release and uptake properties for the recovered chemical nutrient products, it is not currently possible to use multiple criteria for product comparisons. As further data are developed and published on the recovered chemical nutrient product properties, identification of alternative comparable products is likely.

Table 3-1. Summary of Chemical Nutrient Products Resulting from Extractive Nutrient Recovery Processes.

Common Name of Recovered Chemical Nutrient Product %TN-%TP-%P ₂ O ₅ - %K- %Mg- %Ca- %Fe- %S	Expected Physical Form	Extraction Process	Comparable Commercial Product(s)		Use	Ref.
			%TN-%TP-%P ₂ O ₅ - %K- %Mg- %Ca- %Fe- %S	%TN-%TP-%P ₂ O ₅ - %K- %Mg- %Ca- %Fe- %S		
Struvite $\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$ 5-13-28-0-10-0-0-0	Dry, solid 1-3 mm	Chemical crystallization (e.g., CRYSTALACTOR, CSIR, KURITA, PHONIX, OSTARA, BERLINER VERFAHEN, FIX-PHOS, MFH, Airprex, NureSys)	Diammonium Phosphate $(\text{NH}_4)_2\text{HPO}_4$ 18/21-20/23-46/54-0-0-0-0-0	Monoammonium Phosphate NH_4HPO_4 9/12-21/27-48/62-0-0-0-0-0	Agricultural and ornamental crop fertilizer – source of phosphorus; if slow release nature of the phosphorus is proven and accepted, then the product may have niche uses in ornamental crop production (e.g., turf, nursery production); however this would be a negative to agricultural usage as its physical hardness makes it difficult to dissolve and use in liquid fertilization	Royal HaskoningDHV 2012; Multiform Harvest Inc 2012; NuReSys bvba 2012; Ostara 2012; Paques 2012; Procorp LLC 2012
			Ammonium polyphosphate (denoted as NP) 10-14-34-0-0-0-0-0		Industrial – none identified during cursory search	
Hydroxyapatite $(\text{Ca}_5(\text{PO}_4)_3(\text{OH})$ 0-19-42-0-0-40-0-0	Dry, solid 1-3 mm	Chemical crystallization (e.g., CRYSTALACTOR)	Triple superphosphate $\text{CaH}_4\text{P}_2\text{O}_8$ 0-20/26-46/61-0-0-15/17-0-0		Agricultural and ornamental crop fertilizer – niche applications may need to be found where the combination of calcium and phosphorus is deemed acceptable	HaskoningDHV 2012
					Industrial – commonly used as a filler to replace amputated bone or as a coating to promote bone growth into prosthetic implant; sorbent for heavy metal contained in flue gas	
Vivianite $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ 0-12-28-0-0-0-33-0	Dry, solid ¹	No commercial process	No large-scale comparable product identified (denoted as General Iron Compounds)		Ornamental crop fertilizer – source of iron to reduce the occurrence of chlorotic color (yellowing), used in turf and nursery applications	
					Industrial – has been used as an inexpensive blue pigment for arts and crafts	

Table 3-1. Summary of Chemical Nutrient Products Resulting from Extractive Nutrient Recovery Processes, (continued).

Common Name of Recovered Chemical Nutrient Product %TN-%TP-%P ₂ O ₅ - %K- %Mg- %Ca-%Fe-%S	Expected Physical Form	Extraction Process	Comparable Commercial Product(s) %TN-%TP-%P ₂ O ₅ - %K-%Mg- %Ca-%Fe-%S	Use	Ref
Phosphoric acid H_3PO_4 0-27-62-0-0-0-0	Liquid	No commercial process	Phosphoric acids H_3PO_4 0-13/33-30/76-0-0-0-0-0	Agricultural and ornamental crop fertilizer Industrial – commonly used in rust removal from surfaces of metals, as an additive to acidify foods and beverages (like various colas), as an ingredient in over-the-counter anti-nausea medications; used as the electrolyte in phosphoric acid fuel cells, can assist in applications requiring the de-scaling of boilers and heat exchanger tubes	Donatello et al. 2010
Ammonium nitrate NH_4NO_3 35-0-0-0-0-0-0	Liquid	Liquid-gas stripping (e.g., Castion™, VEAS)	Nitrogen Solutions NH_4NO_3 26/32-0-0-0-0-0-0	Agricultural and ornamental crop fertilizer Industrial – has been used as an oxidizing agent in explosives; is used in instant cold packs	Evans 2007
Ammonium sulfate $(NH_4)_2SO_4$ 21-0-0-0-0-0-24	Dry, solid Liquid	Liquid-gas stripping (e.g., Castion™, VEAS, AmRHEX)	Ammonium sulfate $(NH_4)_2SO_4$ 21-0-0-0-0-0-24 (solid) 6/7-0-0-0-0-0-7/10 (liquid) (denoted as Ammonia aqua)	Agricultural and ornamental crop fertilizer Industrial – used as an agricultural spray adjuvant for water soluble insecticides, herbicides, and fungicides; used as an ingredient for many vaccines; used as a food additive (acidity regulator in flours and breads); used in flame retardant materials because it lowers the combustion temperature and increases the production of residues or chars	Environmental Technology Evaluation Center 2000

¹No commercial source/uniform size

3.2 Chemical Nutrient Product Requirements

For recovered chemical nutrient products to be widely used by blenders and end users, there are several characteristics that are preferred (Alexander, 2012). First, the product should have a consistent nutrient composition that should also be in a plant available form. The product should also have no objectionable odors or pathogen content. If a solid product is being considered, the total solids content should be greater than 95% with a dust content of less than 1% by weight. In this work, dust is defined as a disintegrated product that is a nuisance to the user. The solid product should also have a uniform size distribution (approximately, 1.0, 2.0, 2.5, or 3.0 mm depending on the market being approached) and a bulk density of approximately 720 kg/m³ (45 lb/ft³). Desirable physical characteristics are driven by the properties of the existing fertilizer products as standardized spreading equipment already exists to store, handle, and apply these products, both in solid and liquid form. Product uniformity can also help users of blended products ensure an even spreading pattern during application. In general, solid products will be preferred due to transport costs and because the more concentrated the product, the higher value it possesses.

Fertilizer size is an important characteristic that affects fertilizer application and end use. Fertilizer size is expressed as the size guide number (SGN), which is 100 times the median diameter of the fertilizer granules. Fertilizer component sizing depends on the particular end use, with agricultural (and certain landscape) products allowing for larger granules (2-3 mm, 200-300 SGN), while specialty turf (e.g., golf courses) may require 1-1.25 mm (100-125 or smaller SGN). Since fertilizer users require specific sizes for different applications, it is imperative that WRRFs deliver consistently sized materials. Screening can be used to select and achieve the desired particle size range because particles that are too small or large can be returned to the incoming sludge (Tchobanoglous et al., 2003). For struvite production, Ostara is able to produce Crystal Green® with a high uniformity in four different SGNs ranging from 100 to 350 (Ostara, 2012). Taken together this suggests that processes to deliver a consistent size are robust and mature. Alternatively, if the fertilizer is applied as a stand-alone product for agriculture and landscape turf usage, the product sizing and bulk density can be more varied. For liquid fertilizers, product bulk density ranging from 1,200 to 1,450 kg/m³ (75-90 lbs/ft³), pH ranging from 6 to 10.5, and freezing point below 0°C is desirable. Additionally, the product should be non-flammable. It should be noted that products that do not meet these criteria (e.g., polyphosphate rich alginate beads) can also be potentially marketed for use in the agricultural section; however, niche marketing will likely be needed in that scenario.

Perhaps the most critical properties of chemical nutrient products that are being used for agricultural purposes are the fertilizer grades and the nutrient release rates. The fertilizer grade includes its minimum guaranteed N-P-K levels of plant available nutrients, and also a guaranteed analysis for any claims for secondary or minor plant nutrients. For fertilizer consumers it is important that fertilizers have specific grades and SGNs. Therefore, for WRRFs to successfully enter the fertilizer market, the recovered fertilizer products would require a similar grade and guaranteed analysis for any specific nutrients. It is important that WRRFs are able to deliver products with fixed grade specifications that do not vary over the year.

The nutrient release rates and curves also need to be provided for the products, to ensure the marketability and proper application of these products. For example, fast release fertilizers (e.g., ammonium nitrate or ammonium sulfate) are typically used to stimulate a short-term

response; however, the nutrients from these products are readily soluble and can be leached from the soil if moisture is applied. In contrast, slow release fertilizers (e.g., monoammonium phosphate and struvite) are sparingly soluble in water, which makes them ideal for carefully managing the amount of nutrient made available to the plant. This also acts to minimize repeat applications since these products last longer, with larger granules having longer release times. As each soil type and crop has specific nutrient needs, there is an opportunity to match chemical nutrient products recovered from WRRFs to niche markets requiring specific nutrient products; however in order to accomplish this, further peer reviewed research is needed to characterize the benefits of using these chemical nutrient products as part of a nutrient fertilization program. At present, data characterizing the nutrient release and uptake rates from struvite, hydroxyapatite, and vivianite are limited, which will limit their marketability in the agricultural sector. It is also important to note that chemical nutrient products extracted and recovered from WRRFs will not likely be able to be marketed in “certified organic” agriculture. This is based on the fact that wastewater sludge is currently listed as a prohibited substance and it is expected that the chemical processes used to extract the nutrients will likely prevent use of these products within this market (Fernandez-Salvador, 2012; King, 2012).

3.3 Chemical Nutrient Product Usage Trends

Based on International Fertilizer Industry Association (IFA) data, the world market for the primary fertilizer nutrients has risen from 33 million U.S. tons (30 million metric tonnes) in 1960 to 170 million U.S. tons (154 million metric tonnes) in 2005 (IFA, 2012). In this same timeframe, fertilizer usage in industrialized countries increased from approximately 28.5 million U.S. tons (25.8 million metric tonnes) to 54 million U.S. tons (49 million metric tonnes), while usage in less developed countries increased from approximately 4.5 million U.S. tons (4.1 million metric tonnes), to 118 million U.S. tons (107 million metric tonnes). The IFA further estimates that nitrogen fertilizer demand will increase at a rate of 1.9% per year through 2015, with phosphorus fertilizer demand increasing at 2.4% per year over the same time period. Demand for potassium based fertilizer is also expected to grow by 3.7% per year through 2015. This data suggests that world fertilizer demand will continue to expand in tandem with increases in population, with Eastern Asia showing the greatest potential for fertilizer demand growth.

Fertilizer usage is expected to increase into the foreseeable future, with estimates of global consumption of 223 million metric tonnes in 2030 and 263 million metric tonnes in 2050 (Alexandratos et al., 2006; Tenkorang et al., 2009). In developed countries, the demand in 2050 is expected to increase by 22%. In contrast, fertilizer demand in 2050 for Latin America, South Asia, East Asia, and developing countries is expected to grow by at least 50% (Alexandratos and Bruinsma, 2006; Tenkorang and Lowenberg-DeBoer, 2009). However, it is essential to understand that these reported values are rough estimates and involve a high level of uncertainty. Nevertheless, this data suggests that world fertilizer demand will continue to expand in tandem with increases in population. Latin America, South Asia, East Asia, and developing countries show the greatest potential for increasing fertilizer demand.

Within the U.S., the demand for nitrogen fertilizer (measured as TN) increased from approximately 6.8 million U.S. tons (6.1 million metric tonnes) in 1968 to 12.5 million U.S. tons (11.3 million metric tonnes) in 1998. Between 1998 and 2008, the demand for nitrogen fertilizer remained steady. In contrast to N demand, phosphorus (measured as P₂O₅) and potassium (measured as K₂O) fertilizer demand between 1968 and 2008 were fairly consistent (Figure 3-1). These national trends (increased N demand and stable P and K demand) are expected to continue

as improved agricultural nutrient management practices and increased use of genetically engineered crops are put into practice. Cumulatively, this data shows that the national market for all nutrient fertilizers in the U.S. is substantial and stable (AAPFCO and TFI, 2010; IFA, 2012). Therefore, the opportunity exists for resale of chemical nutrient products within the agricultural market provided that products with favorable nutrient and physical characteristics are produced.

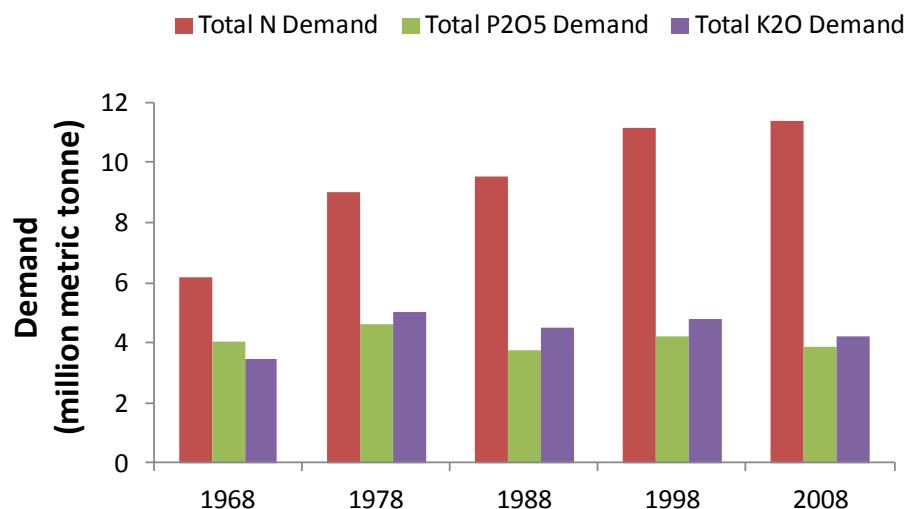


Figure 3-1. Historical Nutrient Fertilizer Demand in the United States.

An examination of the national usage of comparable chemical products (as listed in Table 3-1) from 1998 to 2008 was performed to identify potential trends specific to nutrient products (AAPFCO and TFI, 2010). The data is presented logarithmically in Figure 3-2 and suggests increased use of ammonium polyphosphate (2%), monoammonium phosphate (94%), and phosphoric acid (45%). As these products are analogues for struvite and phosphoric acid, the data suggests that there may be increased national demand for these recovered products. Similarly, increased use of ammonia aqua (67%) and nitrogen solutions (3.3%) and solid ammonium sulfate (20%) indicated potential market demand for soluble and solid forms of ammonium nitrate and ammonium sulfate. A significant increase in national iron compound usage was also observed (77%), which indicates that there may be a demand for vivianite. Interestingly, decreased national use of diammonium phosphate (-29%), and triple superphosphate (-67%) was also observed over the same time period. Since these products are analogues for struvite and hydroxyapatite respectively, it is clear that use of national usage trends for identifying suitable products can present conflicting data. Instead it may be more suitable to look at regional usage trends of comparable product to identify potential markets.

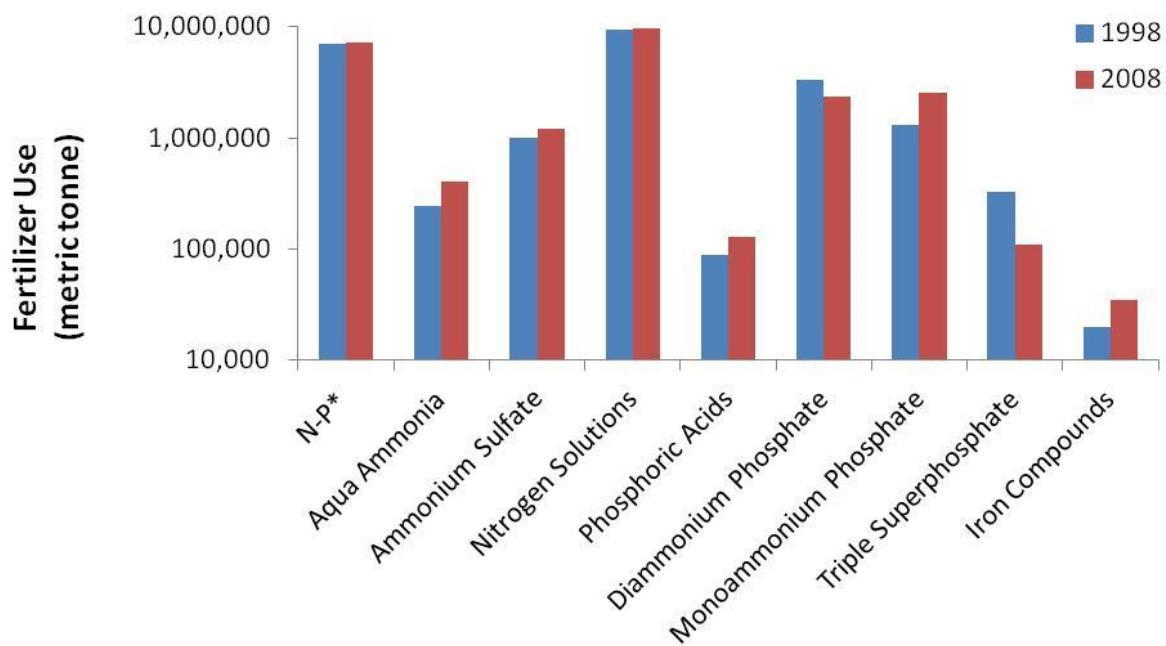


Figure 3-2. Historical Nutrient Fertilizer Use in the United States Based on Comparable Chemicals.

3.3.1 United States Regional Usage Trends

United States regional utilization trends of comparable chemical nutrient products were evaluated based on historical data obtained from the Association of American Plant Food Control Officials Commercial Fertilizer Report (AAPFCO and TFI, 2010). This data indicates that the greatest current demand for nitrogen and phosphorus fertilizer products are in the West North Central (MN, IA, MO, ND, SD, NE, KS) and East North Central (OH, IN, IL, MI, WI) regions, as shown in Figure 3-3, which is driven by the massive acreage of grain crops grown in these regions. The Pacific region (WA, OR, CA) is third in fertilizer demand, followed by West South Central (AR, LA, OK, TX), South Atlantic (VA, NC, SC, GA, FL), Mountain (MT, ID, WY, CO, NM, AZ, UT, NV), East South Central (KY, TN, AL, MS), Mid-Atlantic (NY, NJ, PA,

DE, MD, WV), New England (ME, NH, VT, MA, RI, CT), and Alaska/Hawaii/Puerto Rico respectively.

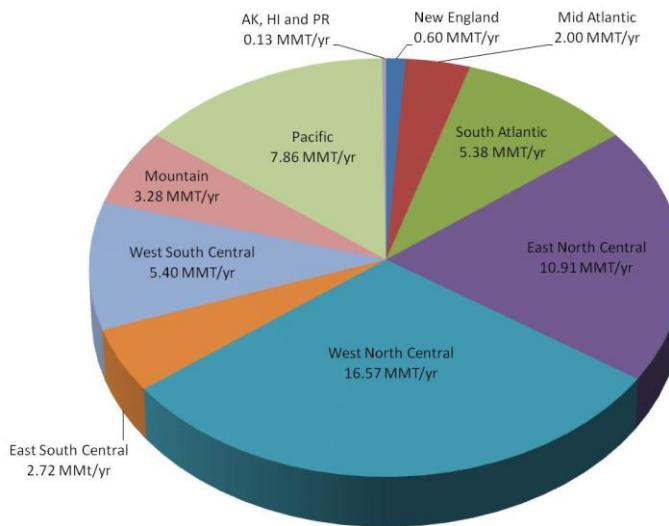


Figure 3-3. Regional Historical Nutrient Fertilizer Use in the United States: 2008.
In million metric tonnes/year.

Figure 3-4 presents the change in the cumulative demand for comparable products (refer to Table 3-1) for these regions from 1998 through 2008. The data shows that fertilizer use was consistent in the Mid Atlantic, East North Central, and Mountain Regions with less than 2% change in overall usage. A net increase in N and P fertilizer over the 10 year period was observed in the New England (80%), West North Central (16%), and Pacific regions (30%), while decreased use was observed in the South Atlantic (-29%), East South Central (-22%), West South Central (-20%), and Alaska/Hawaii/Puerto Rico (-30%).

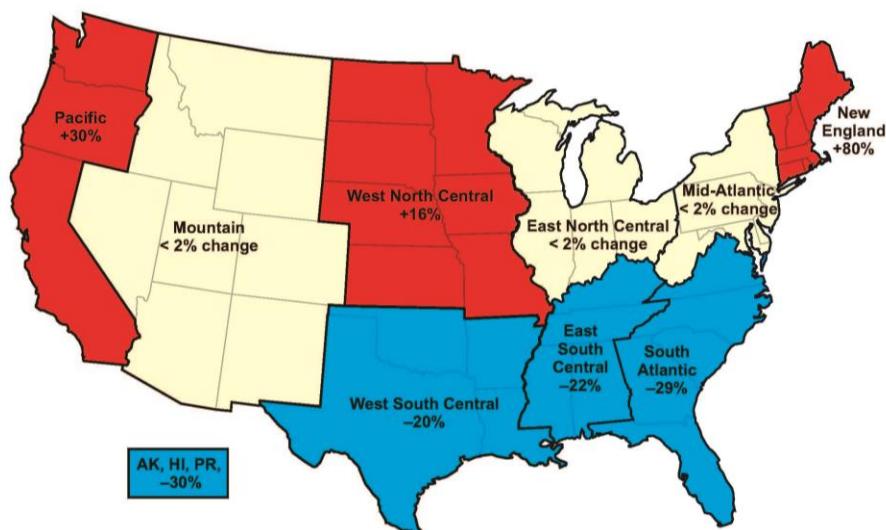


Figure 3-4. Regional Historical Nutrient Fertilizer Use in the United States: 1998-2008 Change in Demand.

Regional demand data for each of the comparable nutrient fertilizer projects are provided in the following sections. Examination of the regional market for each of the comparable products yielded the following trends:

- ◆ Aqua Ammonia – Increased use was observed in the Mid-Atlantic (34%) and Pacific regions (96%). Decreased use was observed in South Atlantic (-68%), East North Central (-90%), West North Central (-60%), and East South Central (-100%). No use of this product was recorded in the New England and Alaska/Hawaii/Puerto Rico regions.
- ◆ Ammonium sulfate – Increased use was observed in the New England (172%), East North Central (40%), West North Central (109%), East South Central (17%), Mountain (29%), and Pacific regions (7%). Decreased use was observed in South Atlantic (-3%), West South Central (-27%), and Alaska/Hawaii/Puerto Rico (-26%) regions. No significant change in use of this product in the Mid-Atlantic region was observed.
- ◆ Nitrogen solutions – Increased use was observed in the New England (51%), East North Central (7%), West North Central (4%), and Pacific regions (34%). Decreased use was observed in Mid Atlantic (-3%), South Atlantic (-15%), East South Central (-5%), Mountain (-2%), and Alaska/Hawaii/Puerto Rico (-20%) regions. No significant change in use of this product in the West South Central region was observed.
- ◆ Phosphoric acids – Increased use was observed in the Mid-Atlantic (193%), South Atlantic (952%), East North Central (212%), West North Central (147%), West South Central (148%), and Pacific regions (41%). Decreased use was observed in East South Central (-90%) and Mountain (-45%) regions. No use of this product was recorded in the New England or Alaska/Hawaii/Puerto Rico regions.
- ◆ Triple superphosphate – Decreased use of this product was observed in all regions (-22 to -96%) except for New England (48%).
- ◆ Ammonium polyphosphate – Increased use was observed in the New England (130%), East North Central (2%), West North Central (14%), and Pacific regions (22%). Decreased use was observed in the Mid Atlantic (-22%), South Atlantic (-8%), East South Central (-31%), West South Central (-12%), Mountain (-20%), and Alaska/Hawaii/Puerto Rico (-18%) regions.
- ◆ Diammonium phosphate – Decreased use of this product was observed in all regions (-20 to -78%) except for the New England (137%) and Alaska/Hawaii/Puerto Rico regions (1%).
- ◆ Monoammonium phosphate – Increased use was observed in the South Atlantic (68%), East North Central (231%), West North Central (157%), East South Central (51%), and Pacific regions (53%). Decreased use was observed in New England (-37%), Mid Atlantic (-52%), West South Central (-14%), and Mountain (-8%). No use of this product was recorded in the Alaska/Hawaii/Puerto Rico region.
- ◆ General iron compounds – Increased use of these products was observed in all regions except for the West North Central (-65%) and Mountain regions (-2%). No use of this product was recorded in the Alaska/Hawaii/Puerto Rico region.

These trends indicate that certain products have a greater regional demand; therefore, WRRFs should consider regional fertilizer usage trends when selecting a nutrient recovery process, as there is a localized market advantage to producing products that require less transportation and storage. For example, the increased demand for slow release phosphorus

products in the South Atlantic, East North Central, West North Central, East South Central, and Pacific regions suggests that WRRFs producing struvite would have a localized market advantage in these regions than compared to the New England, Mid Atlantic, West South Central, and Mountain regions.

3.3.1.1 New England Regional Usage Trends

Historical nutrient fertilizer data for the New England region for 1998 and 2008 are presented in Figure 3-5. The percent change in demand for each product between 1998 and 2008 is provided in Figure 3-6.

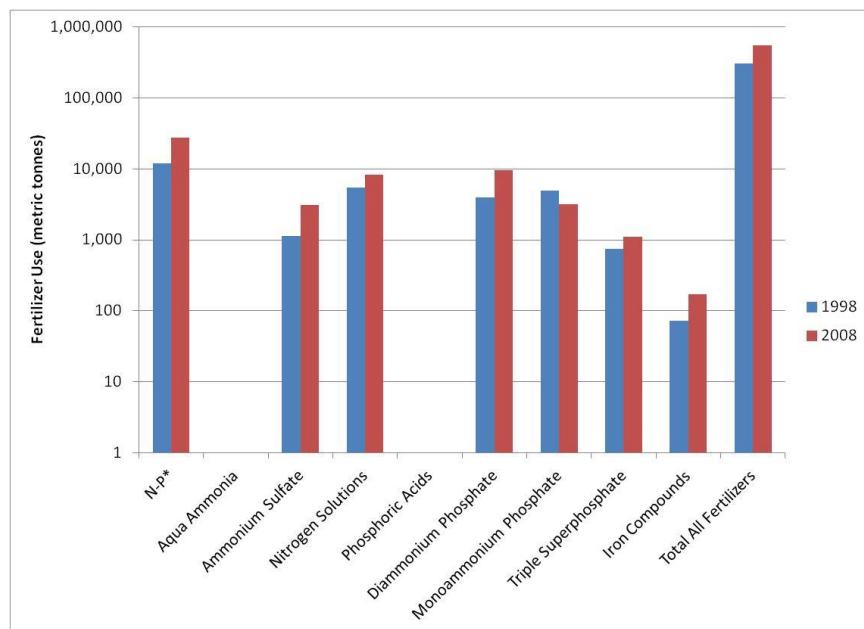


Figure 3-5. Nutrient Fertilizer Use in the New England Region: 1998 and 2008.

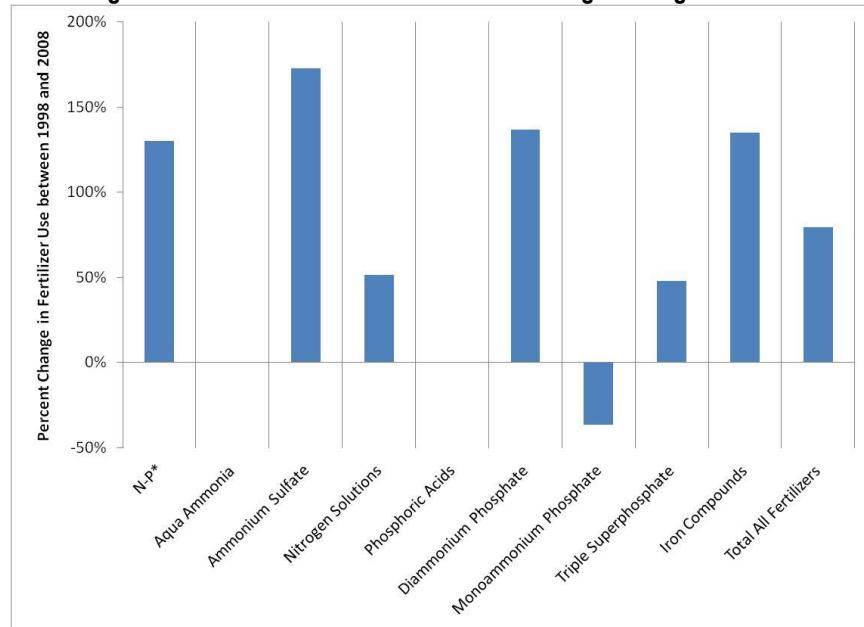


Figure 3-6. Percent Change in Nutrient Fertilizer Use in the New England Region between 1998 and 2008.

3.3.1.2 Mid-Atlantic Regional Usage Trends

Historical nutrient fertilizer data for the Mid-Atlantic region for 1998 and 2008 are presented in Figure 3-7. The percent change in demand for each product between 1998 and 2008 is provided in Figure 3-8.

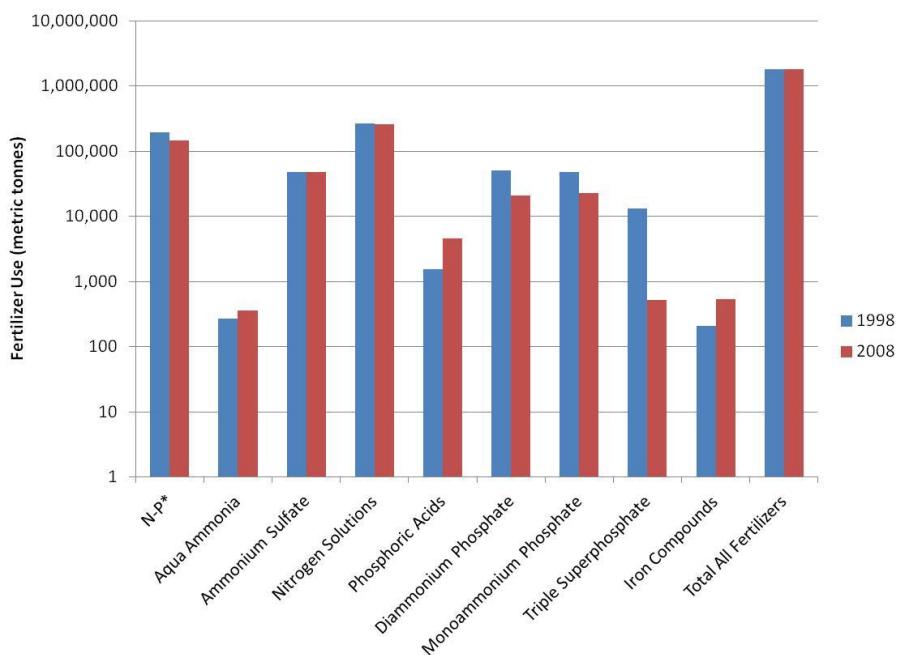


Figure 3-7. Nutrient Fertilizer Use in the Mid-Atlantic Region: 1998 and 2008.

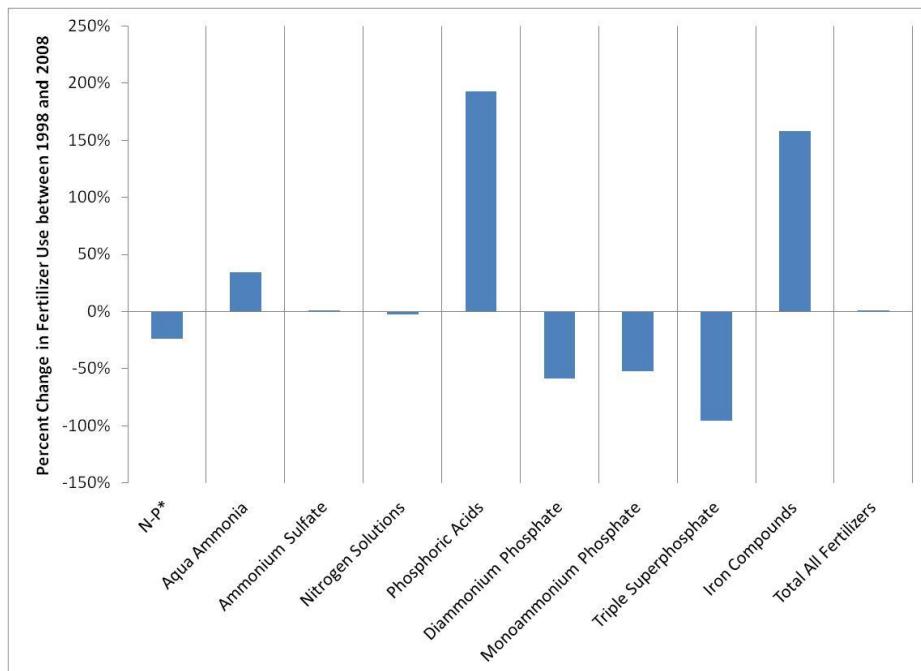


Figure 3-8. Percent Change in Nutrient Fertilizer Use in the Mid-Atlantic Region between 1998 and 2008.

3.3.1.3 South-Atlantic Regional Usage Trends

Historical nutrient fertilizer data for the South Atlantic region for 1998 and 2008 are presented in Figure 3-9. The percent change in demand for each product between 1998 and 2008 is provided in Figure 3-10.

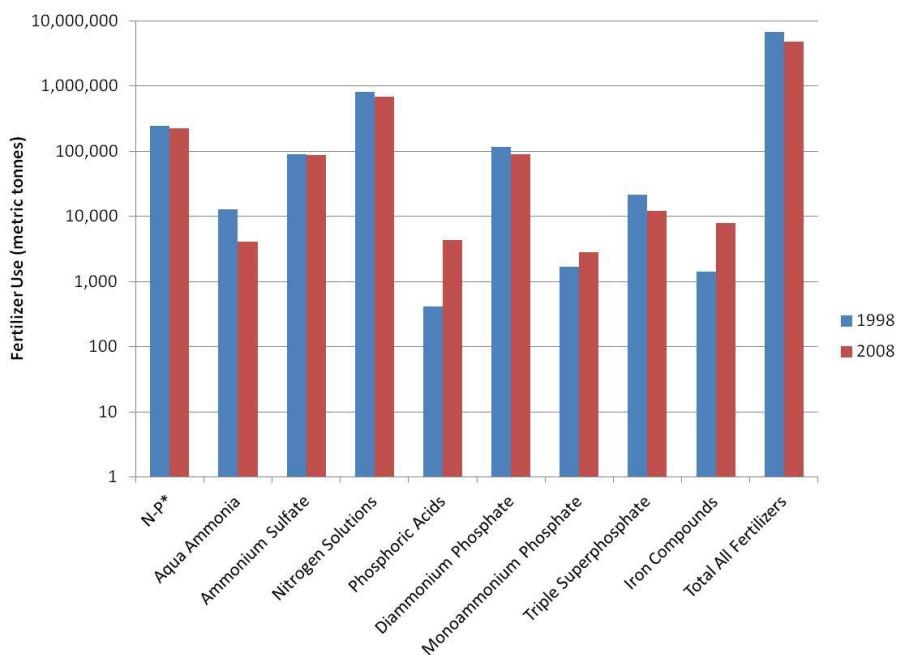


Figure 3-9. Nutrient Fertilizer Use in the South-Atlantic Region: 1998 and 2008.

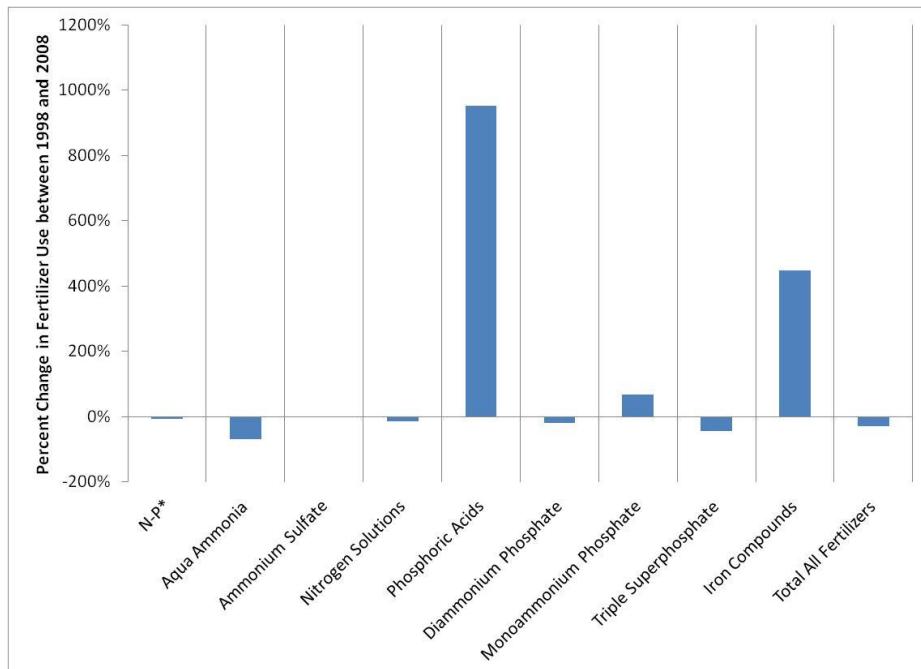


Figure 3-10. Percent Change in Nutrient Fertilizer Use in the South Atlantic Region between 1998 and 2008.

3.3.1.4 East North Central Regional Usage Trends

Historical nutrient fertilizer data for the East North Central region for 1998 and 2008 are presented in Figure 3-11. The percent change in demand for each product between 1998 and 2008 is provided in Figure 3-12.

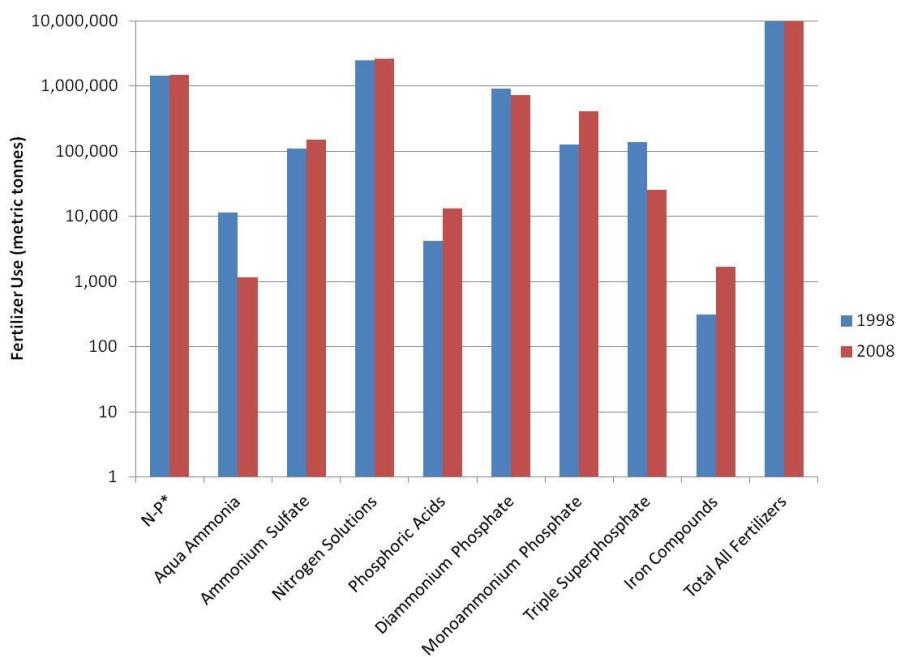


Figure 3-11. Nutrient Fertilizer Use in the East North Central Region: 1998 and 2008.

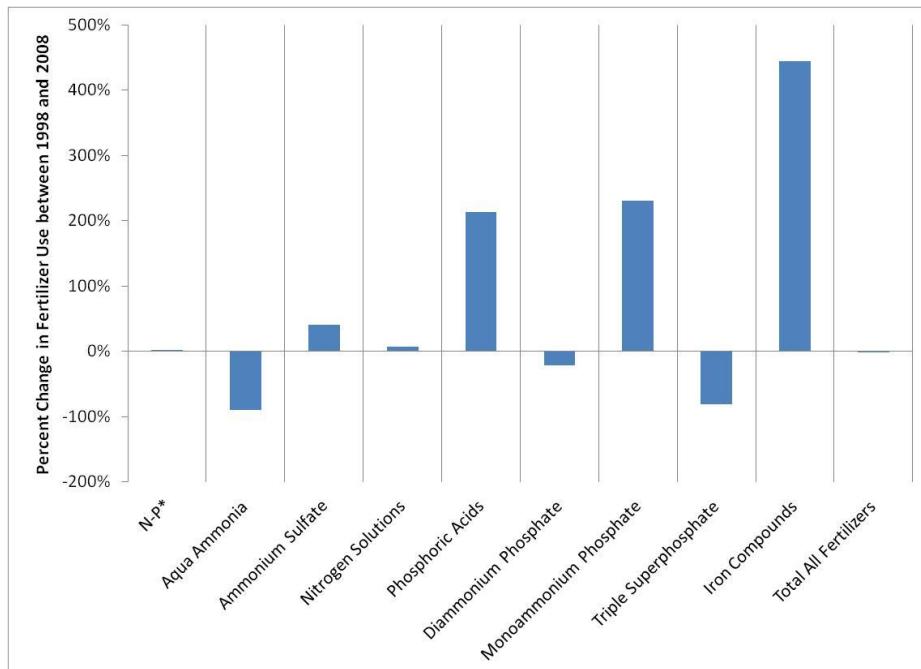


Figure 3-12. Percent Change in Nutrient Fertilizer Use in the East North Central Region between 1998 and 2008.

3.3.1.5 West North Central Regional Usage Trends

Historical nutrient fertilizer data for the West North Central region for 1998 and 2008 are presented in Figure 3-13. The percent change in demand for each product between 1998 and 2008 is provided in Figure 3-14.

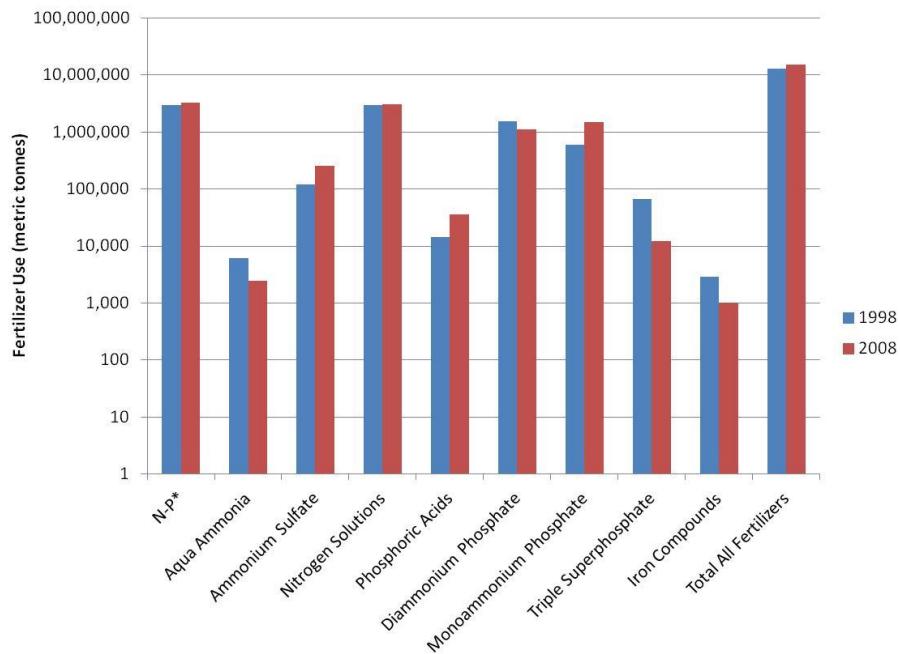


Figure 3-13. Nutrient Fertilizer Use in the West North Central Region: 1998 and 2008.

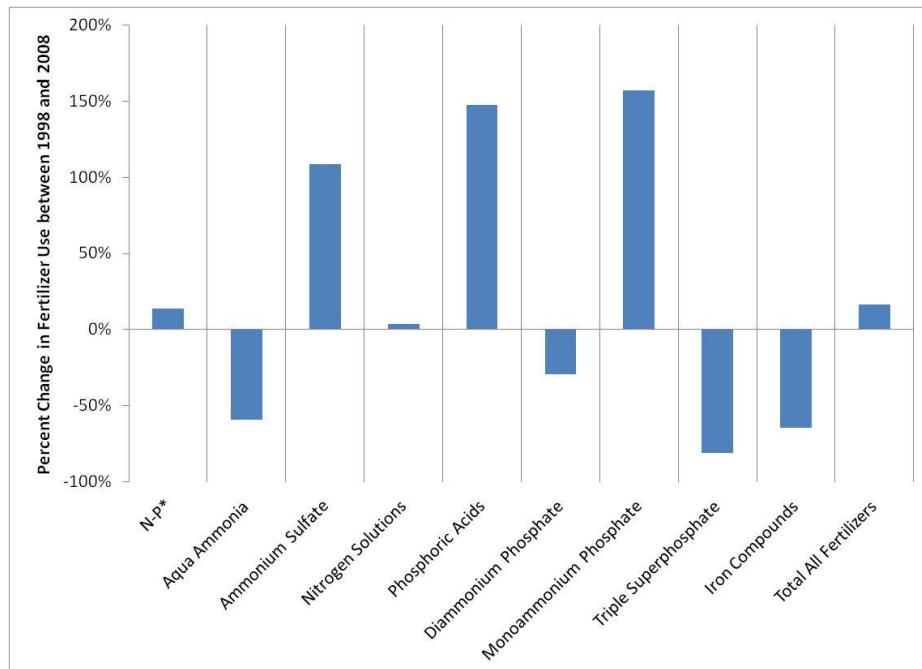


Figure 3-14. Percent Change in Nutrient Fertilizer Use in the West North Central Region between 1998 and 2008.

3.3.1.6 East South Central Regional Usage Trends

Historical nutrient fertilizer data for the East South Central region for 1998 and 2008 are presented in Figure 3-15. The percent change in demand for each product between 1998 and 2008 is provided in Figure 3-16.

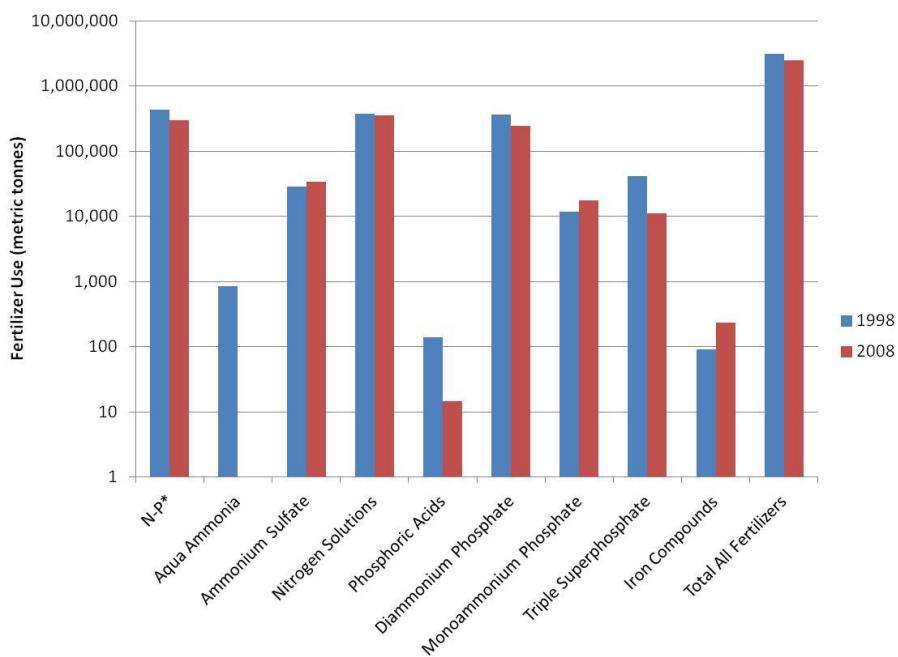


Figure 3-15. Nutrient Fertilizer Use in the East South Central Region: 1998 and 2008.

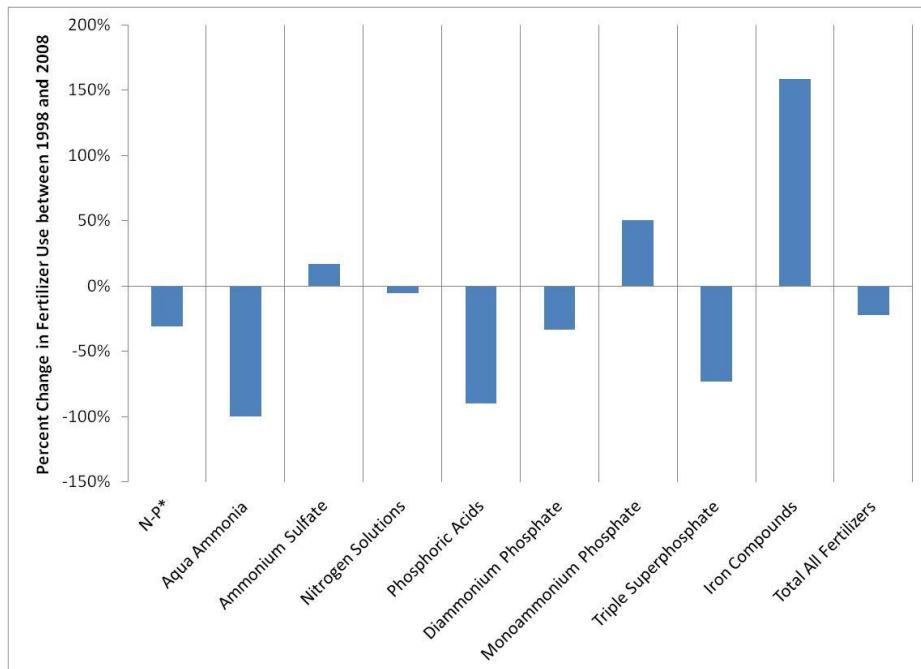


Figure 3-16. Percent Change in Nutrient Fertilizer Use in the East South Central Region between 1998 and 2008.

3.3.1.7 West South Central Regional Usage Trends

Historical nutrient fertilizer data for the West South Central region for 1998 and 2008 are presented in Figure 3-17. The percent change in demand for each product between 1998 and 2008 is provided in Figure 3-18.

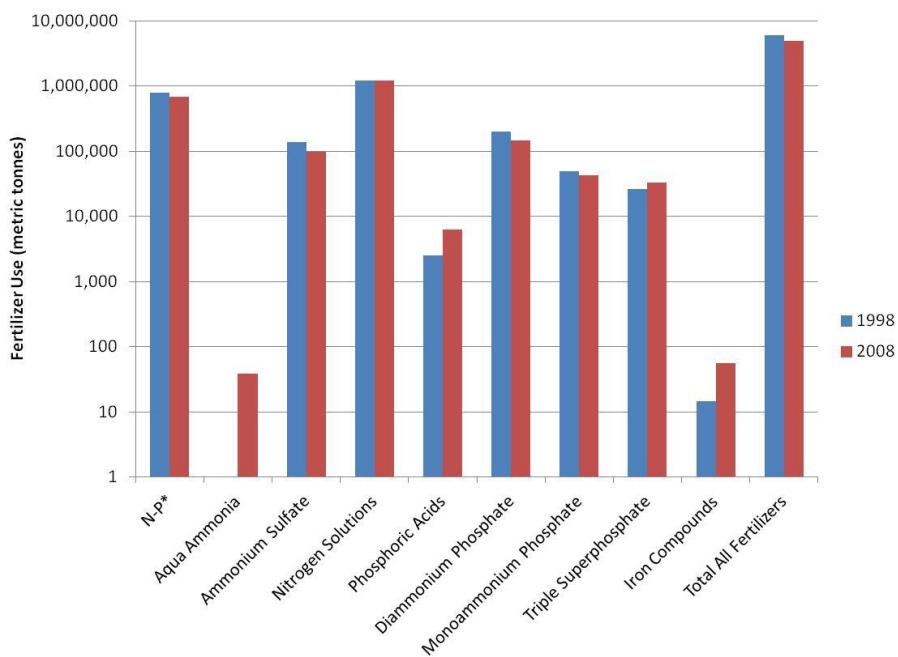


Figure 3-17. Nutrient Fertilizer Use in the West South Central Region: 1998 and 2008.

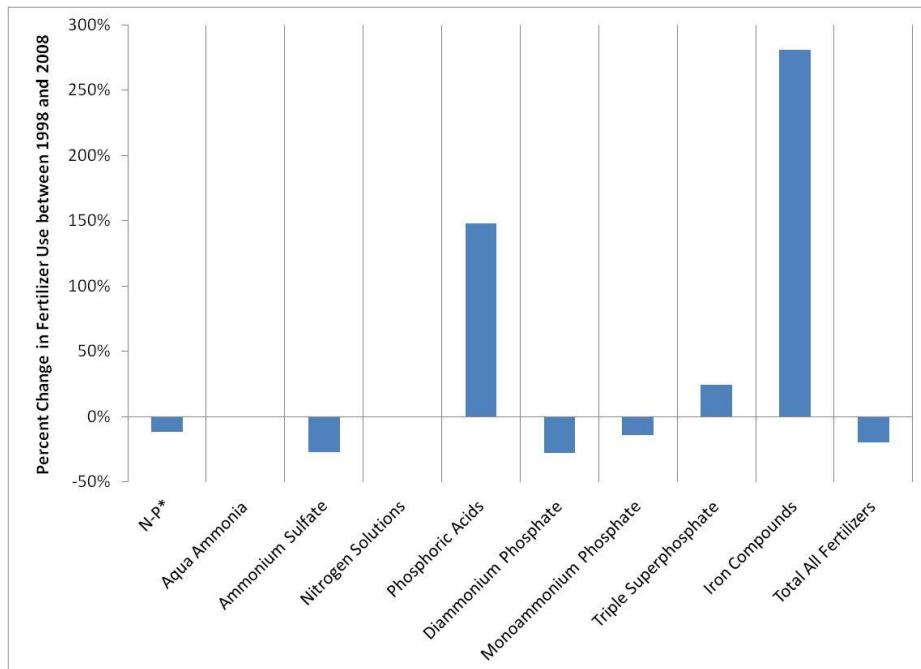


Figure 3-18. Percent Change in Nutrient Fertilizer Use in the West South Central Region between 1998 and 2008.

3.3.1.8 Mountain Regional Usage Trends

Historical nutrient fertilizer data for the Mountain region for 1998 and 2008 are presented in Figure 3-19. The percent change in demand for each product between 1998 and 2008 is provided in Figure 3-20.

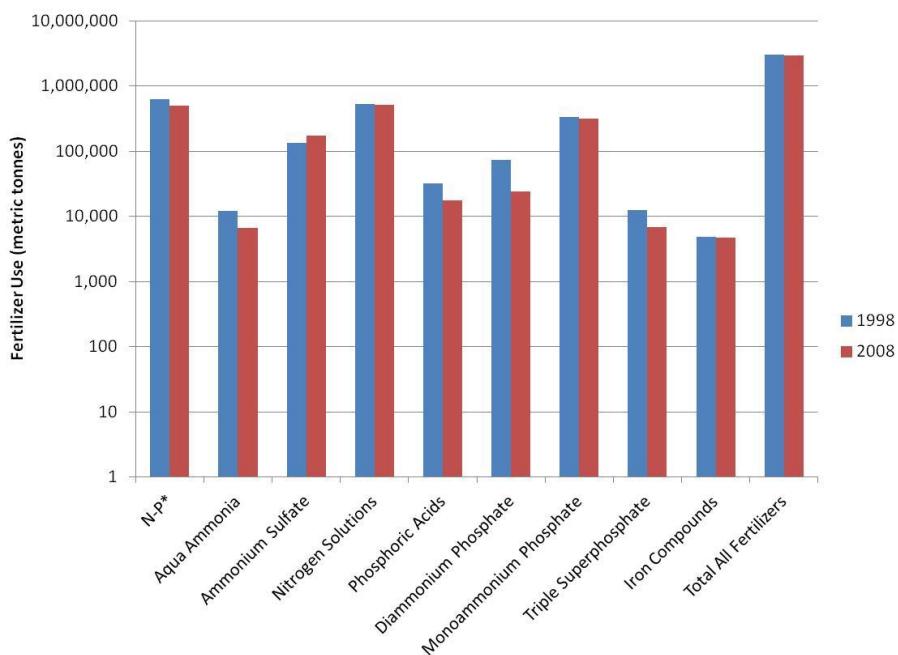


Figure 3-19. Nutrient Fertilizer Use in the Mountain Region: 1998 and 2008.

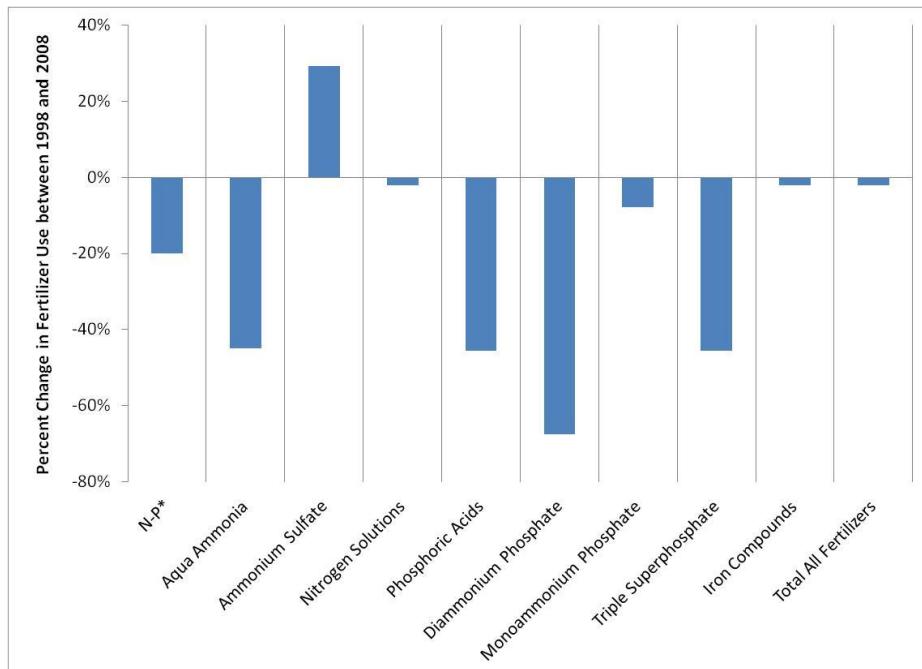


Figure 3-20. Percent Change in Nutrient Fertilizer Use in the Mountain Region between 1998 and 2008.

3.3.1.9 Pacific Regional Usage Trends

Historical nutrient fertilizer data for the Pacific region for 1998 and 2008 are presented in Figure 3-21. The percent change in demand for each product between 1998 and 2008 are provided in Figure 3-22.

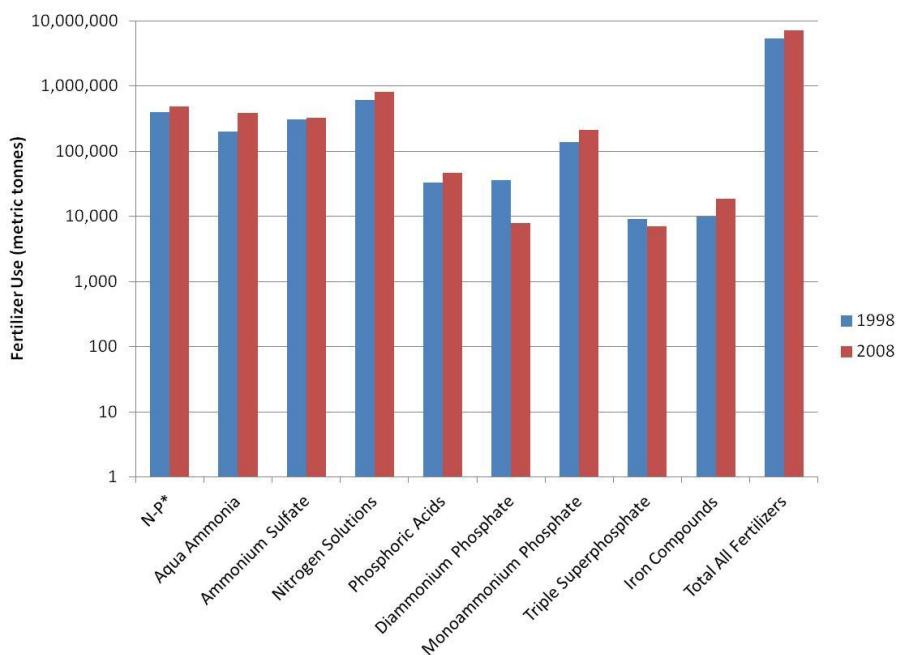


Figure 3-21. Nutrient Fertilizer Use in the Pacific Region: 1998 and 2008.

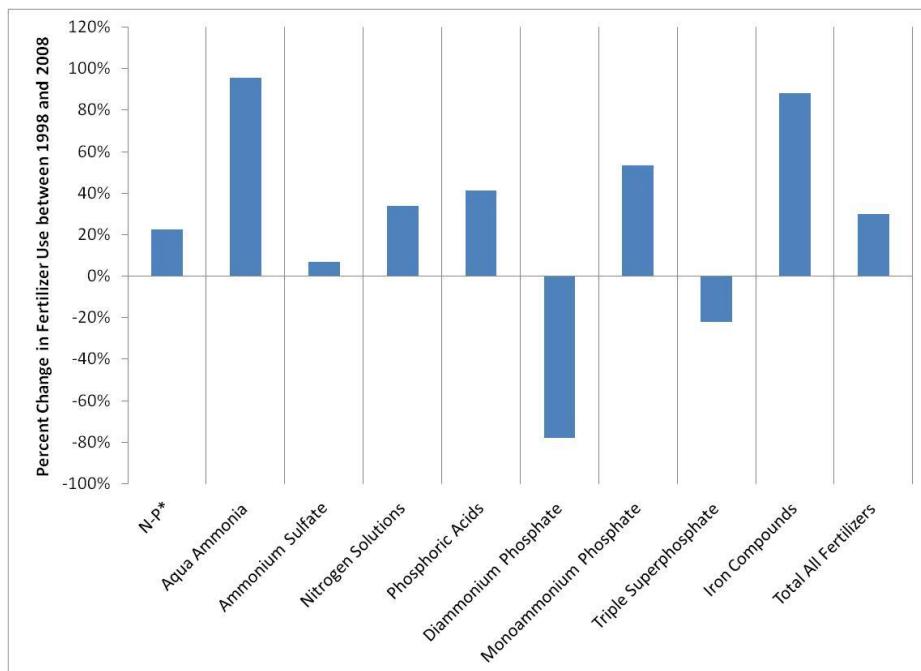


Figure 3-22. Percent Change in Nutrient Fertilizer Use in the Pacific Region between 1998 and 2008.

3.3.1.10 Alaska, Hawaii, and Puerto Rico Usage Trends

Combined historical nutrient fertilizer data for Alaska, Hawaii, and Puerto Rico for 1998 and 2008 are presented in Figure 3-23. The percent change in demand for each product between 1998 and 2008 are provided in Figure 3-24.

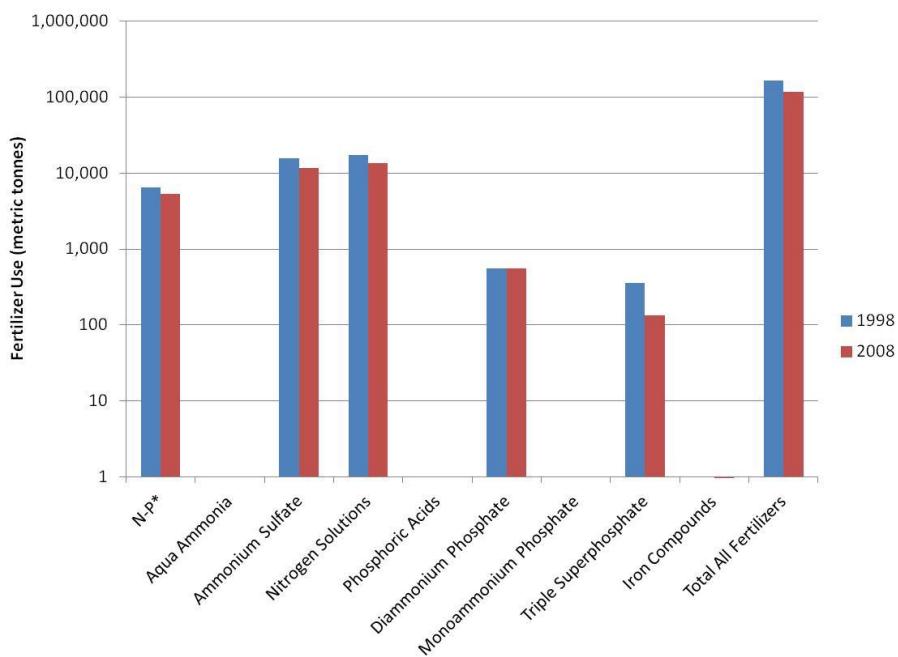


Figure 3-23. Combined Nutrient Fertilizer Use in the Alaska, Hawaii & Puerto Rico: 1998 and 2008.

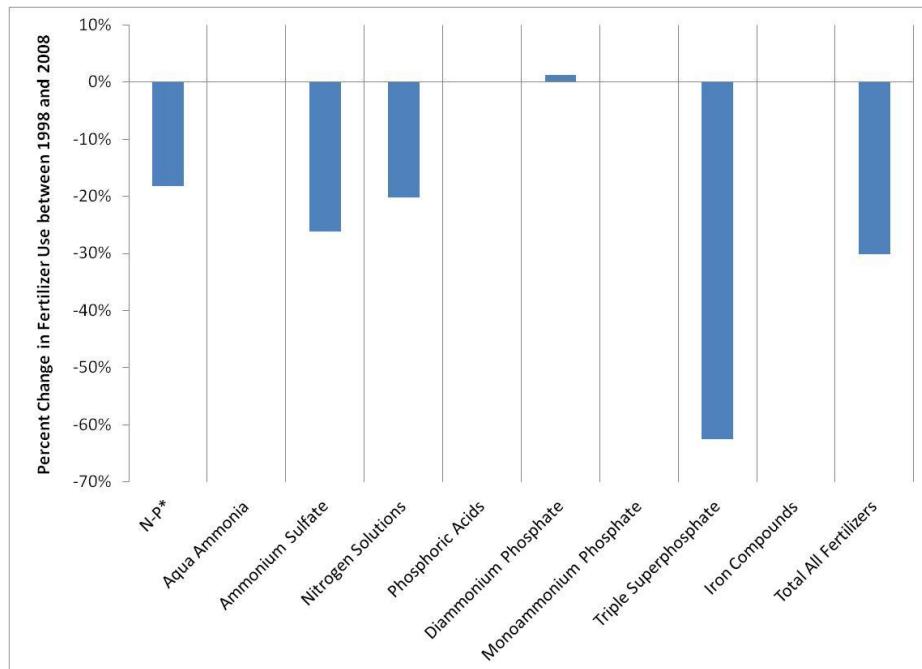


Figure 3-24. Percent Change in Nutrient Fertilizer Use in the Alaska, Hawaii and Puerto Rico between 1998 and 2008.

3.4 Potential Short-Term Markets for Sale of Recovered Nutrient Products

Within the U.S., specialty and ornamental agriculture accounts for between 5-8% of total P₂O₅ fertilizer demand and approximately 1% of total N fertilizer demand (Landels 2003). This corresponds to a market of approximately 200,000-325,000 metric tonne P₂O₅/year and approximately 110,000 metric tonne TN/year. If domestic wastewater is assumed to contain between 0.18 and 0.36 kg P per capita per year (between 0.4 and 0.8 kg P₂O₅ per capita per year) (Balmer, 2004) and the population of United States is assumed to be 311 million individuals (U.S. Census Bureau, 2011), this suggests that between 128,000 and 256,000 metric tonnes of P₂O₅/year is present in raw domestic wastewaters. Nutrient mass balances at WRRFs have suggested that up to 90% of the total phosphorus partitions to the solid fraction. If one further assumes 90% recovery of the phosphorus from this solid fraction can be achieved using existing chemical crystallization technology (Royal HaskoningDHV 2012; Ostara, 2012; Multiform Harvest Inc., 2012; NuReSys bvba, 2012; Paques, 2012; Procorp, 2012) (a very optimistic assumption), the domestic wastewater treatment industry can potentially bring between 100,000 and 210,000 metric tonnes of P₂O₅/year to the phosphorus fertilizer market (as struvite).

A similar analysis for N, assuming domestic wastewater N content of 4.1 kg N per capita per year (U.S. EPA, 2002), 20% accumulation of N in sludge (Phillips et al., 2011) and 90% recovery of N, estimates that the WRRF industry can potentially bring up to 220,000 metric tonnes N/year to the fertilizer market. While these represent optimistic projections regarding N and P recovery from WRRFs, they indicate that the industry has the potential to meet between 2 and 5% of the total domestic P₂O₅ fertilizer demand and between 30 and 100% of the domestic specialty and ornamental P₂O₅ fertilizer demand. Nitrogen recovery can potentially meet 2% of the total domestic N fertilizer demand and between 30 and 194% of the specialty and ornamental N fertilizer demand. Globally the domestic wastewater treatment industry could meet between 0.2 and 0.5 % of the global P₂O₅ demand and 0.3% of the global nitrogen demand. While the initial impact of global fertilizer markets will be small, there is potential to enter into and provide fertilizer to the smaller and ornamental markets.

As mentioned in Section 3.2, in order for these recovered chemical nutrient products to compete within the national and regional agricultural fertilizer markets, it is essential that the nutrient products possess comparable or better physical and chemical characteristics than the nutrient products currently in use. Once produced, these products can enter the market as follows (Figure 3-25):

- 1) They can be sold directly to a dealer network. The products can be blended and/or bagged and then sold to the end user.
- 2) They can be sold to a wholesaler, who will sell to a dealer network and/or the end user.
- 3) They can be sold to a broker or importer who will sell it to a dealer network.
- 4) They may be sold directly to the end user.

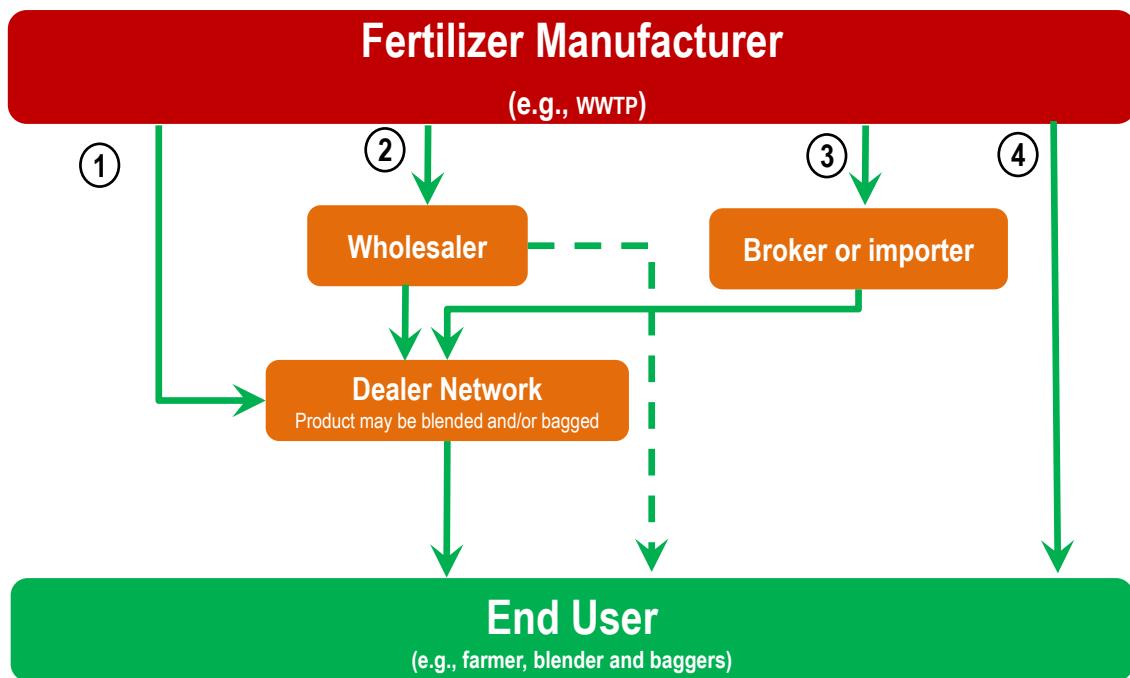


Figure 3-25. Potential Market Entry Points for Recovered Chemical Nutrient Products.

It should be noted that commercial fertilizer manufacturers do not typically sell directly to end users and may not sell to companies that bag and blend fertilizers. As the quantity of product typically recovered from a single WRRF is small compared with the mass of fertilizer produced from commercial manufacturers, it may be reasonable for individual WRRFs to sell their entire supply through a contracted wholesaler or broker. This is the strategy that is being successfully employed by commercial struvite crystallization technology providers who have targeted specialty and ornamental agricultural applications. In the ornamental and specialty fertilizer distribution chains there may be another level for the distribution of smaller volumes of packaged products. In this approach the technology provider directly or indirectly facilitates sale of the recovered nutrient product to a contracted wholesaler or broker. The advantage of this approach is that the utility does not have to become a distributor of their product; however, care must be taken to ensure that the contract price for the recovered nutrient product is truly representative of the regional market price to maximize potential revenue.

If entrepreneurial minded, direct sale to end users (defined as farmer, bagger/blender) is possible, but would expose the utility to the direct volatility of the market. Direct nutrient sales to end users (retail customers) will follow seasonal planting schedules, with spring dominating product sales (March through June). Fall would be a secondary and smaller market in most regions (September through some of November). Obviously, product sales are greatly impacted by climate and therefore the geography of where the product is to be used. In cooler parts of North America (Canada, extreme northern U.S.), a significant amount of fertilizer is used throughout the summer months, but this is not the case in the Southern regions. If selling to customers that possess onsite storage (e.g., buildings, silos, tanks), then the product(s) can be shipped over a longer period of time, and may be done so at a discounted rate or with deferred payment.

Wholesalers and retail customers can start purchasing and delivery up to two months in advance of the growing season. This product can be stored onsite in storage tanks (liquid), indoor bunkers (solid), or vertical silos (solid). It should be noted that large-scale buyers of fertilizers forward buy product, under contract, at a guaranteed price. These pricing

guaranteed contracts usually only allow forward purchasing for two to five months. Although the distribution contract may be valid for multiple years, a guaranteed price over this period is not typical.

3.5 Chemical Nutrient Product Pricing History

Historical cost data (1960 to 2011) pertaining to select fertilizer products were used to document the long term trends and variability in pricing for four comparable nutrient products (USDA, 2012). Nutrient prices have increased significantly from the year 2000 onward, although current inflation-adjusted prices have not changed as much for most products since the beginning of the historical data period (Figure 3-26). There has been significant variation in the price of N and P products used in primary production agricultural applications in recent years. This variability is likely tied to the international price of grains (food and feed commodities), such as corn, soybean, rice, as well as others. In addition, price volatility for N products can be attributed to the increasing use of natural gas, a necessary precursor to ammonia, as a transportation fuel. Marketing of recovered nutrient products to specialty agricultural markets like ornamental agriculture could help minimize exposure to extreme pricing variability associated with primary production agriculture.

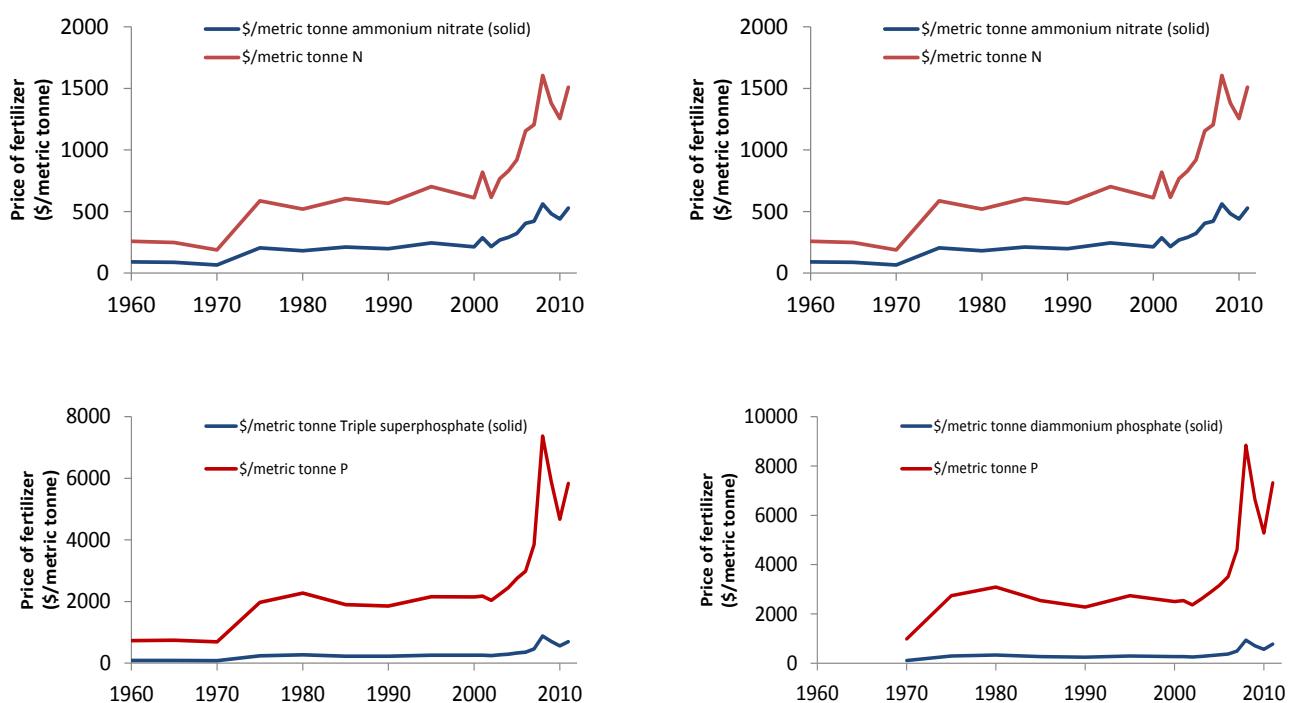


Figure 3-26. Historical Pricing of Comparable Nutrient Products in the United States (1960 to 2011).
Not adjusted for inflation.

There have been recent developments that suggest a long-term stability in supply for both P and N. While previous estimates have suggested that phosphate rock reserves would last for less than 100 years, revised estimates suggest that reserves will now last for over 300 years (Van Kauwenbergh, 2010; Jasinski, 2014). This suggests a stable long-term supply of recoverable P. Interestingly, if the supply increased greatly, the equilibrium price for phosphorus would likely decrease. However, due to the increased recovery costs of these phosphate rock reserves, prices may remain steady. Concerning the long term supply of nitrogen fertilizers, the increase in fracking will provide a long-term source of natural gas (methane) that can be used for the Haber-Bosch process. Previous research has demonstrated a correlation between the supply of natural gas and its price with the cost and production of domestic nitrogen fertilizers production (Huang, 2007). Ultimately, since the production of both nitrogen and phosphorus fertilizers is energy intensive and depends on a multitude of market factors, it is difficult to accurately forecast long-term fertilizer prices.

Based on historical data, it was estimated that the current market price for N solutions is ~U.S. \$1,300/metric tonne of N; the market price range for solid N products ranges from ~U.S. \$1,200 to 2,500 /metric tonne of N. Corresponding market price for phosphorus was estimated to range from U.S. % 5,500 to 7,500/metric tonne of P. This represents the current value of the nutrient content of the recovered chemical nutrient products without consideration of transportation costs or distribution fees. Transportation costs (e.g., U.S. \$110/metric tonne product) and distribution fees (reseller mark-ups; e.g., U.S. \$55 metric tonne product) will effectively reduce the value of the product. Regional pricing will also be affected by competing products.

This analysis provides some guidelines for the expected values of the chemical nutrient products that can be recovered from WRRFs. In the case of N and P only products (e.g., ammonium sulfate, ammonium nitrate, or phosphoric acid), it is expected that pricing will be set by the existing market for commoditized products; however, for niche products (e.g., struvite, hydroxyapatite, or vivianite), pricing will be dependent on the combination of market price of N and P and availability and supply of comparable nutrient products in a specific region.

3.6 Expected Marketability of Struvite versus Traditional Synthetic Fertilizers

Struvite was selected for an expanded market analysis because the production technology is mature. Struvite can be produced as either magnesium struvite or potassium struvite. Both magnesium struvite and potassium struvite are phosphorus fertilizers that have unique characteristics that set them apart from traditional synthetic fertilizers (Table 3-2). Specifically, they both have an extremely slow release of P, both contain magnesium, and both have a very low solubility. In the fertilizer market these two forms of struvite would most likely compete with monoammonium phosphate, diammonium phosphate, and potassium nitrate amended with a phosphate fertilizer.

The most similar commercial fertilizer analogues to magnesium struvite are monoammonium phosphate and diammonium phosphate. Magnesium struvite with an N-P-K of 5-29-0 has approximately half of the available phosphorus compared to monoammonium phosphate and diammonium phosphate with N-P-Ks of 11-52-0 and 18-46-0, respectively. Struvite has a limited solubility of 0.2 g/L compared to the 370 g/L of monoammonium phosphate (IPNI, 2015d) and 588 g/L of diammonium phosphate (IPNI 2015c). Therefore direct application of pelleted struvite may not be suitable for agricultural row and grain crops, as a more immediate effect is desired. This issue can be circumvented by dissolving the struvite in mildly acidic solutions to increase the rate of release. Nevertheless, the slow release aspect of struvite is a notable benefit for turf, horticulture, and ornamental producers.

It should be further noted, that phosphorus usage is being reduced across the U.S., especially in turf usage where regulations limiting application have been established, and therefore, a slow phosphorus releasing fertilizer may be beneficial. States that have implemented phosphorous usage restrictions include Florida, Illinois, Maine, Maryland, Michigan, Minnesota, New Jersey, New York, Vermont, Virginia, Wisconsin, and Washington. Most of the phosphorous usage restrictions are related to turf maintenance products and applications. Realistically, struvite should be seen as beneficial for use in phosphorous vulnerable areas; however, the rate of phosphorus releases has not been taken into consideration with the current regulations. Hopefully, this fact will be addressed in the future, which will increase struvite demand. Therefore, to help drive the demand and acceptance of struvite, a further understanding of the release curves for all of the nutrients in struvite is needed.

Potassium struvite has been produced to limited degree since 2008 (Graeser et al., 2008). N-P-K values are 0-27-18, which make it similar in potassium content to potassium nitrate supplemented with phosphorus, which has an N-P-K of 13-2-44. Due to its chemical composition, it is unique in the fertilizer market because it also has magnesium (9%) and is the only slow release form of magnesium and K.

Due to a lack of product knowledge, there is little knowledge on its efficacy as a fertilizer. In contrast to magnesium struvite, potassium struvite may be valued higher in the market than magnesium struvite since it contains both K and P. However, at this point, it is not clear whether a significant increase in value is warranted due to a lack of plant uptake trials.

Table 3-2. Summary of Characteristics for Struvite and Substantially Similar Fertilizers.

*Assuming 200 bu/A for P and K demand.

Characteristic	Magnesium Struvite	Monoammonium Phosphate	Diammonium Phosphate	Potassium Struvite	Potassium Nitrate with Phosphorus
Alternative names	Magnesium Ammonium Phosphate <chem>MgNH4PO4·6H2O</chem>	MAP	DAP	Potassium magnesium phosphate (KMP) <chem>KMgPO4·6H2O</chem>	Multi N-P-K, Bonus N-P-K
Chemical formula		<chem>NH4H2PO4</chem>	<chem>(NH4)2HPO4</chem>		<chem>KNO3</chem> and <chem>(NH4)2HPO4</chem>
Average price/metric tonne	\$200 - \$1,500	\$570 - \$615	\$420 - \$680	NA	\$420 - \$560
Chemical composition % (H-K-Mg-N-O-P)	6.6-0-9.9-5.7-65.2-12.6	5.2-0-0-12.2-55.6-27	6.8-0-0-21.2-48.4-23.5	4.5-14.7-9.1-0-60-11.6	0-38.6-0-13.9-47.5-0
Grade (N-P-K)	5-29-0	11-52-0	18-46-0	0-27-18	13-2-44
Feedstock materials	NA	Ammonia, phosphoric acid	Ammonia, phosphoric acid, sulfur	NA	Potassium chloride, nitrate source (sodium nitrate, nitric acid)
Physical properties (bulk density, particle sizes)	62 lb/ft ³ , multiple size grades	58 lb/ft ³ , multiple size grades	56 - 61 lb/ft ³ , multiple size grades 588 g/L	NA	65 lb/ft ³ , multiple size grades
Water solubility at 20 °C	Insoluble - 0.2 g/L	328 - 370 g/L		NA	316 g/L
Water soluble magnesium (%)	NA	0%	0%	NA	0%
Water soluble nitrogen (%)	NA	NA	NA	0%	NA
Water soluble phosphorus (%)	NA	82-90%	90%	NA	90%
Moisture content (%)	< 1%	< 1.7%	< 2.6%	NA	< 1%
Equivalent acidity	NA	0.65	0.74	NA	-0.26
Salt Index	7.7	26.7-30	29.2-34	NA	74
Storage and handling requirements	Store below 55°C, avoid oxidizing agents	Avoid alkalis, strong acids and copper alloys	Avoid alkaline metals	NA	Avoid flammable, combustible, and reducing substances
Application description	Spread on soil	Normally spread or mixed in soil	Normally spread or mixed in soil	NA	Liquid and/or solid
Typical application rates*	255 lb/A	142 lb/A	160 lb/A	300 lb/A	123 lb/A

3.7 Effects of Nutrient Recovery on Biosolids Values and Marketability

Current federal regulations limit the application of biosolids on agricultural land to the nitrogen agronomic rate, or the rate at which the plants/crops can utilize the nitrogen (U.S. EPA, 1994). A shift towards limiting biosolids applications based on the phosphorus agronomic rate is being explored by several states. Employing nutrient recovery to reduce the phosphorus content of the biosolids would be beneficial for bulk land application in these states. To date, there is limited data quantifying the magnitude of phosphorus reduction in the biosolids of WRRFs performing struvite crystallization. Generation of this data through site specific evaluations would be necessary to understand the impacts to land application costs.

Reducing the phosphorus content of the biosolids may or may not be viewed as a benefit by vendors utilizing the biosolids for soil blending. Benefits may not be observed if the blender is dependent on the biosolids phosphorus for the bulk product. In this case, reducing the phosphorus content of the biosolids will require the blender to purchase phosphorus to meet specifications. Conversely, benefits may be observed in scenarios where the distributor targets niche markets such as turf application, ornamental, or retail markets.

It is expected that reducing phosphorus content of biosolids granules would improve product versatility, but not necessarily positively impact value. This is logical since it is widely established that the physical characteristics of the biosolids product significantly impacts its perceived value. Branding and overall marketing efforts are also expected to have a higher impact on the value of the product. Further, facilities which produce high quality products and aggressively market them typically get paid more for the products. That stated, when chemical fertilizer prices increase, the perceived value and actual sales price of the granules often follows. Therefore, nutrient recovery could be one tool that WRRFs of the future utilized to institute operational flexibility to meet changing needs.

3.8 Alternative Uses for Chemical Nutrient Products

Based on discussions with officials at The Fertilizer Institute (AAPFCO and TFI), it is estimated that the U.S. industrial sector uses only 15% of the total fertilizer volume of the U.S. agricultural sector. This represents a total market of 1.7 million metric tonne N/year and 0.6 million metric tonne of P₂O₅/year. Of the seven recoverable products under consideration, hydroxyapatite, phosphoric acid, ammonium nitrate, and ammonium sulfate have the greatest potential for alternative industrial uses. While both struvite and vivianite have potential in agricultural applications, there are limited industrial uses for the compounds.

Both phosphoric acid and ammonium sulfate have the widest range uses. Phosphoric acid is commonly used in industrial and household detergents, metal treatment, food additives, water treatment and a variety of additional applications (Prayon, 2013). Due to its acidic properties and its wide range of uses, there is a strong global demand for phosphoric acid.

Ammonium sulfate has fewer uses than phosphoric acid, and is used in textile dyeing, cellulose and fiberglass insulation, fire extinguishers and a variety of biocides (IPNI, 2015b). Ammonium nitrate, is traditionally used in the industry as an explosive. Traditionally, this explosive mixture of ammonium nitrate and fuel oil is referred to as ANFO. Additional uses include instant cold packs, where the endothermic reaction of ammonium nitrate and water cool the water's temperature (IPNI, 2015a).

Hydroxyapatite has been traditionally used in medical applications. Because it is similar to the crystalline structure of bones, it has seen use in dental and bone implants due to its biocompatibility (Ferraz et al., 2004). It is also sold as a calcium supplement. Recent research has suggested that it can be used as a sorbent for heavy metals in aqueous and gaseous solutions (Constantin et al., 2012). However, the environmental applications of this hydroxyapatite remain embryonic.

Presently, it is not possible to define a specific pathway for use of chemical nutrient products in downstream industries. However, it should be noted that many biomass production facilities require nutrients to sustain productivity. In cases where site-specific conditions may make industrial reuse favorable, it is recommended that the WRRF pursue a cost-benefit analysis to determine whether production of the chemical for agricultural purposes outweigh the benefits of industrial reuse.

CHAPTER 4.0

MAKING THE CASE FOR IMPLEMENTING NUTRIENT RECOVERY AT WATER RESOURCE RECOVERY FACILITIES

4.1 Benefits of Nutrient Recovery Options

Struvite crystallization and recovery is the most mature extractive nutrient recovery technology. It has been employed at over 20 facilities throughout the world (reference Resource Recovery Technology Matrix – Nutrients). It represents a valuable tool to derive key lessons for helping accelerate the implementation of extractive nutrient recovery options.

A review of existing full-scale struvite harvesting installations has shown that adoption of extractive nutrient recovery technologies is typically favorable when the payback periods are less than 10 years and when implementation of the recovery technology provides multiple benefits to the WRRFs. These benefits can include:

- ◆ Mitigating the impact of the sidestream nutrient content on the mainstream nutrient removal process and providing a factor of safety for mainstream EBPR.
- ◆ Minimizing nuisance struvite formation and regaining infrastructure capacity.
- ◆ Reducing chemical and energy costs.
- ◆ Reducing chemical sludge production (if metal salt addition is practiced).
- ◆ Manipulating the nutrient (phosphorus and nitrogen) content of biosolids.
- ◆ Improving sludge dewaterability.

Quantifying these and other site-specific benefits (cost and non-cost) can help make the economic case for implementing nutrient recovery technologies.

4.2 Addressing Concerns With Adopting Nutrient Recovery

Results from the survey of WRRFs confirm findings outlined in Figure 4-1. They also provide insight into the different degrees of challenges associated with each barrier. These nuances as well as strategies that can be used for resolving these barriers are described in Table 4-1.

Table 4-1. List of Considerations Associated with Adopting Extractive Nutrient Recovery.

Barrier	Considerations	Resolution
Technical	<ul style="list-style-type: none"> Technologies are unknown entities. Insufficient time and staff to review available technologies and decide on path forward. 	<ul style="list-style-type: none"> Utilize existing state of science technology review summaries, e.g., WERF NTRY1R12 Resource Recovery Technology Matrix - Nutrients, to review technology fundamentals and find references to existing installations. Contact utilities that have experience with technology (see technology matrix for contact information). Engage in WERF LIFT-TEP program on nutrient recovery to acquire further knowledge and experience with technology.
	<ul style="list-style-type: none"> Insufficient data to evaluate technology performance i.e., percent removal, struvite production. 	<ul style="list-style-type: none"> Review case study guidance documents and TERRY-P to determine data needs. Perform detailed sampling in collaboration with consulting engineer.
	<ul style="list-style-type: none"> Insufficient experience in operating extractive nutrient recovery technology. 	<ul style="list-style-type: none"> Contact utilities that have experience with technology and schedule site visit (see technology matrix for contact information). Engage in WERF LIFT-TEP program on nutrient recovery to acquire further knowledge and experience with technology. If funds are available, pilot the technologies that are under consideration.
	<ul style="list-style-type: none"> Unknown maintenance requirements and long-term operational viability. 	<ul style="list-style-type: none"> Contact utilities that have experience with technology and schedule site visit (see technology matrix for contact information). Engage in WERF LIFT-TEP program on nutrient recovery to acquire further knowledge and experience with technology. Provide flexibility in design to bypass and/or upgrade facility with improved technology.
Economic	<ul style="list-style-type: none"> Insufficient and/or competing needs for funds. 	<ul style="list-style-type: none"> Utilize TERRY-P to perform a preliminary evaluation to determine whether extractive nutrient recovery process can provide benefit to facility. Perform detailed engineering evaluation in conjunction with consulting engineer. <ul style="list-style-type: none"> Consider additional benefits of implementing extractive nutrient recovery e.g., reduction in operating

Barrier	Considerations	Resolution
		<p>costs, reduction in energy costs, mitigation of nuisance struvite formation, reduction of biosolids mass, benefits to land application rates.</p> <ul style="list-style-type: none"> • Examine business models and delivery mechanisms utilized by technology providers to minimize capital and operating cost requirements. • Explore regionalization of service and importation of solids to increase scale of operation while charging tipping fees for imported solids.
	<ul style="list-style-type: none"> • Unknowns regarding cost of implementation, operating costs, etc. 	<ul style="list-style-type: none"> • Review case study guidance documents to obtain point of reference for existing installations. • Contact utilities that have experience with technology (see technology matrix for contact information). • Utilize TERRY-P to calculate order of magnitude estimates associated with capital and operating costs.
	<ul style="list-style-type: none"> • Uncertainty with respect to future demand for fertilizer product. 	<ul style="list-style-type: none"> • Utilize existing state of science technology review summaries and market analyses, e.g., WERF NTRY1R12m Resource Recovery Technology Matrix - Nutrients, to determine regional demand for different fertilizer products. • Examine business models utilized by technology providers to guarantee operating costs/reimbursement costs for struvite production.
	<ul style="list-style-type: none"> • Competition for product if many utilities adopt the technology. 	<ul style="list-style-type: none"> • Examine business models utilized by technology providers to guarantee operating costs/reimbursement costs for struvite production. • Explore alternative routes for product entry into the fertilizer market. • Explore regionalization of service and importation of solids to increase scale of operation while charging tipping fees for imported solids.
Regulatory	<ul style="list-style-type: none"> • Lack of regulatory drivers i.e., no effluent nutrient limits. 	<ul style="list-style-type: none"> • Consider and quantify other benefits of technology e.g., reduction in operating costs, reduction in energy costs, mitigation of nuisance struvite formation, reduction of biosolids mass, benefits to land application rates.
	<ul style="list-style-type: none"> • Lack of public acceptance. 	<ul style="list-style-type: none"> • Engage the public to demonstrate benefits to the environment and impact on costs. • Increase public awareness through press releases, public hearings, tours.

It should be noted that the experiences outlined in this report reflect those of systems performing struvite harvesting through chemical crystallization technologies. While the project team focused on this technology, the general approach employed can/will be translated to any alternative extractive nutrient/resource recovery technology. This is reflected in the decision tree in Figure 4-1.

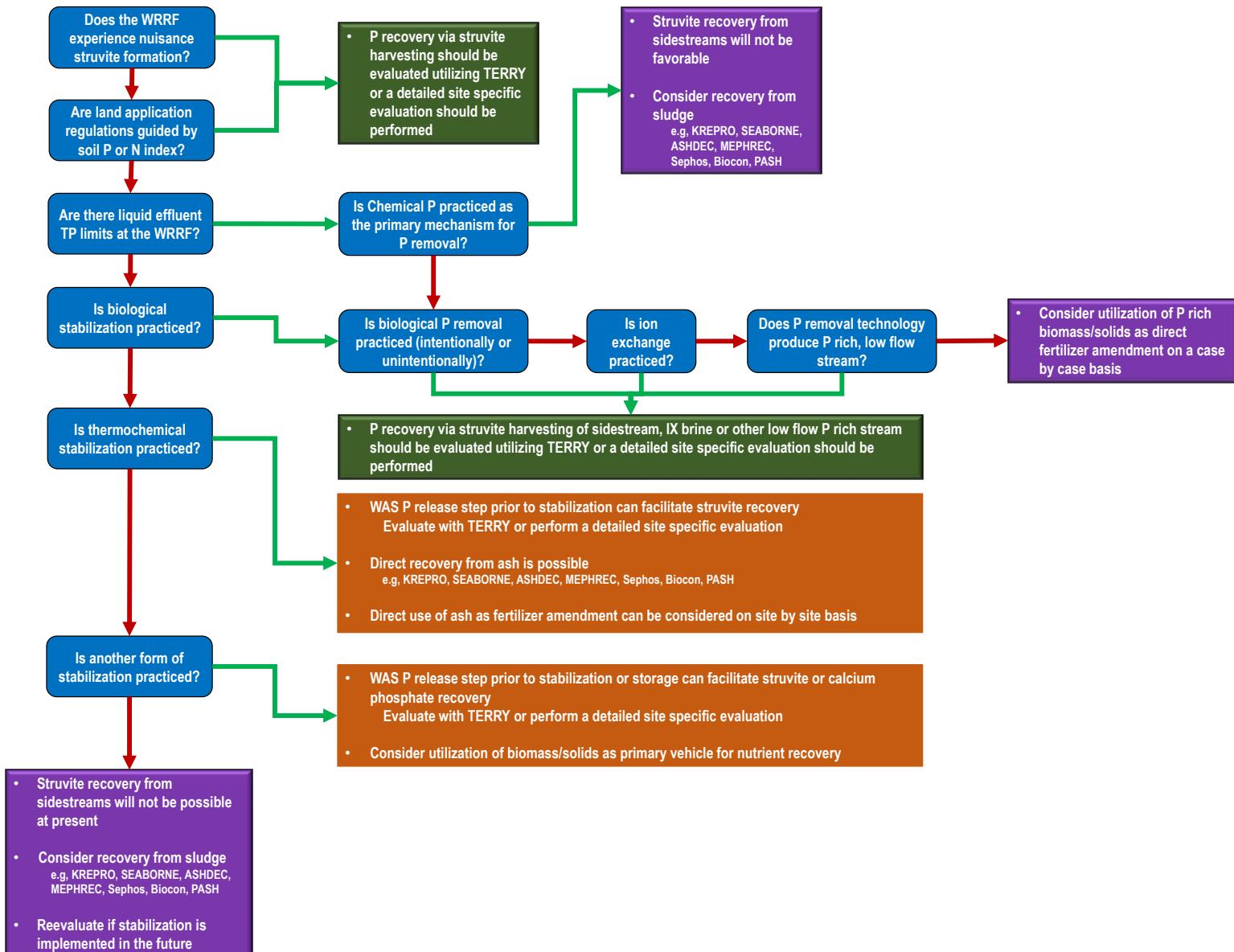


Figure 4-1. Decision Tree for Considering Extractive Nutrient Recovery.

4.3 Specific Recovery Operation Recommendations

Fundamentally, evaluating nutrient recovery must be a site specific evaluation in order to properly quantify the aforementioned benefits; however, there are a few key elements that can be distilled within a consistent methodology:

- ◆ Capital cost estimates should take into account new building requirements as well as additional tankage that can be used for equalization and/or enhanced WAS release. Costs associated with odor control should also be factored into the evaluation.
- ◆ Operating cost evaluations should take into account all chemicals required including pH adjustment, magnesium, ammonia, and phosphoric acid. A similar approach should be employed for the conventional treatment approach (assumed to be metal salt addition). As the regional cost of metals salts (e.g., ferric and alum) vary significantly, payback analyses must take these factors into account.
- ◆ Benefits analyses should quantify reductions in supplemental carbon requirements, reduction in aeration requirements, and reduction in biosolids production for nutrient recovery versus conventional alternative.
- ◆ If benefits are anticipated with respect to nuisance struvite formation, attempts should be made to quantify existing mitigation costs so that all options can be compared with a current action alternative. This includes a comparison of costs with the conventional treatment approach (assumed to be metal salt addition), whereby region specific costs of metals salts (e.g., ferric and alum) are taken into account.
- ◆ Where possible, calculations should also be undertaken to determine the benefits to N and P content of the biosolids and determine whether these changes have a favorable or non-favorable impact on land application requirements. It should be noted that manipulation of the nitrogen content of the biosolids is only relevant to scenarios where nuisance struvite formation contributes to the existing biosolids cake nitrogen content. If nitrogen containing precipitants are not predominant, the primary benefits to biosolids nutrient content will be related to the reduced phosphorus in the cake. Another important point that should be made is that these calculations and evaluations do not explicitly allow for the discrimination of plant available nutrients. Therefore, care must be taken to determine whether a benefit to plant available nitrogen and phosphorus in the biosolids cake can truly be attributed to the struvite harvesting process.

This approach can be rationalized by the underlying need for utilities to minimize capital and operating costs, particularly when considering new technologies. Individually, these benefits may not be sufficiently compelling to warrant adoption of recovery technology; however, when considered in tandem with each other, the economic and operating benefits may become sufficiently attractive to allow for implementation.

CHAPTER 5.0

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions and Future Research Directions

Design, operation, and economic assessment data for pilot or full-scale implementation is not widely published for most nutrient recovery technologies including innovative technologies such as struvite crystallization and plant accumulation. Full-scale implementation experience is lacking for the other innovative technologies such as adsorption/ion exchange, plant accumulation, and chemical extraction, whereas further pilot scale studies are required for embryonic technologies such as electrodialysis, gas permeable membrane, and magnetic methods. This lack of data constrains more widespread adoption. Consequently, future work is needed to properly quantify whole plant impacts of not only embryonic technologies but also technologies like struvite crystallization.

It should also be noted that extractive nutrient recovery has primarily focused on recovery of chemical phosphorus products, which has resulted in the development and maturation of extraction techniques like chemical crystallization. Future research should focus on implementing N and K recovery in concert with phosphorus recovery at pilot or full-scale due to the rising and variable cost of these nutrients. Phosphorus recovery is expected to become increasingly important as easily minable potash reserves are also depleted. In this regard, N and K recovery via bioaccumulation using microalgae or purple non-sulfur bacteria and electrodialysis are promising and should be investigated to allow easy integration with the established extractive nutrient recovery processes.

Diversification of the chemical nutrient products that are recovered is also needed. We expect that future product demands will require the production of chemical products that have high nutrient content, low moisture, extremely low heavy metal, and pathogens contamination. These emerging needs can potentially limit the use of manure, biosolids, and ash/char as the primary vehicle for nutrient recovery. Instead, it may be more appropriate to couple biosolids, manure, and ash/char production with extractive nutrient recovery technologies to help manage nutrient content of these bulk organic products as well as benefit from the chemical products. Identification of the most relevant chemical product will require consideration of local agricultural and industrial demands. A critical element of this work will be developing data characterizing nutrient release and plant uptake to allow for direct comparisons with more conventionally produced fertilizers.

At present, there is no single technology that is perfect for complete nutrient (N-P-K) recovery; however, this does not preclude the development of an integrated process for this purpose. It is expected that integrated technologies will increase the capital costs required by municipalities. Consequently, this dictates that O&M costs of these technologies be low. Further research into decreasing the operating costs of N-P-K technologies is needed. This may focus on finding alternative sources of chemical inputs required for the process. Alternatively, research into efforts where chemical nutrient products and non-nutrient products are recovered may

improve the economics of resource recovery. In this regard, research into electrodialysis, purple non-sulfur bacteria, microalgae, and alternate biological release technologies are warranted.

APPENDIX A

HISTORICAL FERTILIZER USE DATA FOR UNITED STATES

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Table A-1. Historical Fertilizer Use Data for United States (All States).

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	7101948	7207895	-1
Aqua Ammonia	243808	406417	-67
Ammonium Sulfate	996087	1195902	-20
Nitrogen Solutions	9310614	9622223	-3
Phosphoric Acids	88636	128298	-45
Diammonium Phosphate	3333573	2369938	29
Monoammonium Phosphate	1312258	2549214	-94
Triple Superphosphate	328656	109585	67
Iron Compounds	19803	35025	-77
Total All Fertilizers	49843309	49751725	0
States within region:	All		

Table A-2. Historical Fertilizer Use Data for New England Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	11852	27287	-130
Aqua Ammonia	n/a	n/a	n/a
Ammonium Sulfate	1144	3118	-173
Nitrogen Solutions	5493	8318	-51
Phosphoric Acids	n/a	n/a	n/a
Diammonium Phosphate	3992	9451	-137
Monoammonium Phosphate	4954	3143	37
Triple Superphosphate	741	1097	-48
Iron Compounds	73	171	-135
Total All Fertilizers	28248	52584	-86
States within region:	ME, NH, VT, MA, RI, CT		

n/a – no usage data available for this product

Table A-3. Historical Fertilizer Use Data for Mid-Atlantic Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	192733	146100	24
Aqua Ammonia	271	364	-34
Ammonium Sulfate	47637	48011	-1
Nitrogen Solutions	269850	261952	3
Phosphoric Acids	1565	4587	-193
Diammonium Phosphate	50677	21018	59
Monoammonium Phosphate	48601	23116	52
Triple Superphosphate	13269	528	96
Iron Compounds	209	538	-158
Total All Fertilizers	624811	506213	19
States within region:	NY, NJ, PA, DE, MD, WV		

n/a – no usage data available for this product

Table A-4. Historical Fertilizer Use Data for South Atlantic Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	246185	226013	8
Aqua Ammonia	12869	4061	68
Ammonium Sulfate	89395	87088	3
Nitrogen Solutions	819449	696047	15
Phosphoric Acids	412	4334	-952
Diammonium Phosphate	115447	91393	21
Monoammonium Phosphate	1671	2801	-68
Triple Superphosphate	21729	11991	45
Iron Compounds	1429	7833	-448
Total All Fertilizers	1308585	1131560	14
States within region:	VA, NC, SC, GA, FL		

n/a – no usage data available for this product

Table A-5. Historical Fertilizer Use Data for East North Central Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	1454713	1477722	-2
Aqua Ammonia	11398	1158	90
Ammonium Sulfate	109022	152749	-40
Nitrogen Solutions	2494733	2665423	-7
Phosphoric Acids	4203	13152	-213
Diammonium Phosphate	920524	723838	21
Monoammonium Phosphate	125743	416295	-231
Triple Superphosphate	137040	25645	81
Iron Compounds	312	1698	-444
Total All Fertilizers	5257689	5477680	-4

States within region: OH, IN, IL, MI, WI

n/a – no usage data available for this product

Table A-6. Historical Fertilizer Use Data for West North Central Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	2932450	3331527	-14
Aqua Ammonia	6035	2444	59
Ammonium Sulfate	122291	254846	-108
Nitrogen Solutions	2956953	3062156	-4
Phosphoric Acids	14487	35859	-148
Diammonium Phosphate	1560551	1100176	30
Monoammonium Phosphate	589444	1515166	-157
Triple Superphosphate	66106	12338	81
Iron Compounds	2846	1000	65
Total All Fertilizers	8251162	9315514	-13

States within region: MN, IA, MO, ND, SD, NE, KS

n/a – no usage data available for this product

Table A-7. Historical Fertilizer Use Data for East South Central Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	435413	301795	31
Aqua Ammonia	859	n/a	100
Ammonium Sulfate	28683	33613	-17
Nitrogen Solutions	377757	358100	5
Phosphoric Acids	141	15	90
Diammonium Phosphate	368615	244590	34
Monoammonium Phosphate	11676	17568	-50
Triple Superphosphate	41193	11016	73
Iron Compounds	91	235	-159
Total All Fertilizers	1264428	966932	24

States within region: KY, TN, AL, MS

n/a – no usage data available for this product

Table A-8. Historical Fertilizer Use Data for West South Central Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	786530	694726	12
Aqua Ammonia	n/a	39	-100
Ammonium Sulfate	137080	99657	27
Nitrogen Solutions	1220460	1209720	1
Phosphoric Acids	2521	6256	-148
Diammonium Phosphate	203430	146994	28
Monoammonium Phosphate	49627	42631	14
Triple Superphosphate	26541	32936	-24
Iron Compounds	15	55	-281
Total All Fertilizers	2426203	2233014	8

States within region: AR, LA, OK, TX

n/a – no usage data available for this product

Table A-9. Historical Fertilizer Use Data for Mountain Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	636249	508893	20
Aqua Ammonia	12073	6652	45
Ammonium Sulfate	134481	173729	-29
Nitrogen Solutions	533179	522277	2
Phosphoric Acids	32518	17716	46
Diammonium Phosphate	74042	24025	68
Monoammonium Phosphate	340461	313694	8
Triple Superphosphate	12636	6863	46
Iron Compounds	4874	4767	2
Total All Fertilizers	1780513	1578616	11

States within region: MT, ID, WY, CO, NM, AZ, UT, NV

n/a – no usage data available for this product

Table A-10. Historical Fertilizer Use Data for Pacific Region.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	399388	488569	-22
Aqua Ammonia	200302	391700	-96
Ammonium Sulfate	310771	331576	-7
Nitrogen Solutions	615704	824632	-34
Phosphoric Acids	32789	46378	-41
Diammonium Phosphate	35744	7894	78
Monoammonium Phosphate	140082	214799	-53
Triple Superphosphate	9047	7037	22
Iron Compounds	9954	18728	-88
Total All Fertilizers	1753782	2331312	-33

States within region: WA, OR, CA

n/a – no usage data available for this product

Table A-11. Historical Fertilizer Use Data for AK, HI, and PR.

Product	1998 (metric tonnes)	2008 (metric tonnes)	% change from 1998 baseline (- denotes increase)
N-P* (ammonium polyphosphate)	6435	5264	18
Aqua Ammonia	n/a	n/a	n/a
Ammonium Sulfate	15585	11514	26
Nitrogen Solutions	17036	13599	20
Phosphoric Acids	n/a	n/a	n/a
Diammonium Phosphate	552	560	-1
Monoammonium Phosphate	n/a	n/a	n/a
Triple Superphosphate	354	132	63
Iron Compounds	n/a	1	-100
Total All Fertilizers	39962	31070	22
States within region:		AK, HI, and PR	

n/a – no usage data available for this product

REFERENCES

- AAPFCO and TFI (2010). Commercial Fertilizers 2010. American Plant Food Control Officials (AAPFCO) and The Fertilizer Institute.
- Acevedo-Morantes, M., G. Colón and A. Realpe (2011). "Electrolytic removal of nitrate and potassium from wheat leachate using a four compartment electrolytic cell." *Desalination* **278** (1-3): 354-364.
- Alexander, R. (2012). Personal Archives – Topic of 'appropriate physical properties of fertilizer products'. Apex, N.C.
- Alexandratos, N. and J. Bruinsma (2006). World Agriculture: Towards 2030/2050 – Interim Report. Rome, Food and Agriculture Organization of the United Nations
- American Water Works Association. and Knovel (Firm) (2006). Fundamentals and control of nitrification in chloraminated drinking water distribution systems. *AWWA manual M56*. Denver, CO, American Water Works Association.
- Antakyali, D., Kuch, B., Preyl, V., Steinmetz, H. (2011). Effect of Micropollutants in Wastewater on Recovered Struvite. WEF Nutrient Recovery and Management 2011, WEF, pp 706-713.
- Antonini, S., M.A. Arias, T. Eichert and J. Clemens (2012). "Greenhouse evaluation and environmental impact assessment of different urine-derived struvite fertilizers as phosphorus sources for plants." *Chemosphere* **89**(10): 1202-1210.
- Balmer, P. (2004). "Phosphorus recovery: An overview of potentials and possibilities." *Water Sci Technol* **49**(10): 185-190.
- Batstone, D.J. and P.D. Jensen (2011). Anaerobic processes. *Treatise on Water Science*. P. Wilderer, IWA Publishing: 615-640.
- Battelle (2012a). Photobioreactor (PBR) for Agricultural and Municipal Wastewater Phosphorus Removal. Battelle Memorial Institute, White Paper from Battelle Memorial Institute.
- Battelle (2012b). Response to Request for Information for WERF Proposal No. NTRY1R12 Nutrient Recovery in the Global Water Industry – Anaerobic Digester Effluent Liquid-Liquid Extraction (AD-LLX): 8.
- Benemann, J.R. (1979). "Production of nitrogen fertilizer with nitrogen-fixing blue – green algae." *Enzyme and Microbial Technology* **1**(2): 83-90.
- Biswas, B.K., K. Inoue, K.N. Ghimire, H. Harada, K. Ohto and H. Kawakita (2008). "Removal and recovery of phosphorus from water by means of adsorption onto orange waste gel loaded with zirconium." *Bioresource Technology* **99**: 8685-8690.
- Blocher, C., C. Niewersch and T. Melin (2012). "Phosphorus recovery from sewage sludge with a hybrid process of low pressure wet oxidation and nanofiltration." *Water Research* **46**: 2009-2019.

- Bonmati, A. and X. Flotats (2003). "Air stripping of ammonia from pig slurry: Characterisation and feasibility as a pre- or post-treatment to mesophilic anaerobic digestion" *Waste Management* **23**: 261-272
- Bratby, J. (2006). Coagulation and Flocculation in Water and wastewater Treatment. London, IWA Publishing.
- Brummer, J.R., J.A. Keely and T.F. Munday (2005). Phosphorus. *Kirk-Othmer Encyclopedia of Chemical Technology*.
- Camus, O., S. Perera, B. Crittenden, Y.C. van Delft, D.F. Meyer, P. Pex, I. Kumakiri, S. Miachon, J. Dalmon, S. Tennison, P. Chanaud, E. Groensmit and W. Nobel (2006). "Ceramic membranes for ammonia recovery." *AICHE J.* **52**: 2055-2065.
- Castilho, L.R., D.A. Mitchell and D.M. Freire (2009). "Production of polyhydroxyalkanoates (PHAs) from waste materials and by-products by submerged and solid-state fermentation." *Bioresour Technol* **100**(23): 5996-6009.
- Environmental Technology Evaluation Center (2000). Environmental Technology Verification Report for Ammonia Recovery Process. Civil Engineering Research Foundation.
- Cheng, S. and B.E. Logan (2007). "Sustainable and efficient biohydrogen production via electrohydrogenesis." *Proc Natl Acad Sci U S A* **104**(47): 18871-18873.
- Choi, J.I. and S.Y. Lee (1997). "Process analysis and economic evaluation for poly (3-hydroxybutyrate) production by fermentation." *Bioprocess Eng* **17**(6): 335-342.
- Clarens, A.F., H. Nassau, E.P. Resurreccion, M.A. White and L.M. Colosi (2011). "Environmental Impacts of Algae-Derived Biodiesel and Bioelectricity for Transportation." *Environmental Science & Technology* **45**: 7554-7660.
- Collivignarelli, C., G. Bertanza, M. Baldi and F. Avezzù (1998). "Ammonia stripping from MSW landfill leachate in bubble reactors: process modeling and optimization." *Waste Management and Research* **16**(5): 455-466.
- Constantin, L.V., S. Iconaru and C.S. Ciobanu (2012). "Europium Doped Hydroxyapatite for Applications n Environmental Field." *Romanian Reports in Physics* **64**(3): 788-794.
- Couillard, D. and G. Mercier (1993). "Removal of metals and fate of N and P in the bacterial leaching of aerobically digested sewage sludge." *Water Research* **27**(7): 1227-1235.
- Cox, A.E., J.J. Camberato and B.R. Smith (1997). "Phosphate availability and inorganic transformation in an alum sludge- affected soil." *Journal of Environmental Quality* **26**(5): 1393-1398.
- De Haas, D.W., M.C. Wentzel and G.A. Ekama (2000). "The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological excess phosphate removal Part 1: Literature review." *Water SA* **26**(4): 439-452.
- Decloux, M., A. Bories, R. Lewandowski, C. Fargues, A. Mersad, M.L. Lameloise, F. Bonnet, B. Dherbecourt and L.N. Osuna (2002). "Interest of electrodialysis to reduce potassium level in vinasses. Preliminary experiments." *Desalination* **146**(1-3): 393-398.

- Decrey, L., K.M. Udet, E. Tilley, B.M. Pecson, T. Kohn and A. Rosenthal (2011). "Fate of the pathogen indicators phage FX174 and *Ascaris suum* eggs during the production of struvite fertilizer from source-separated urine." *Water Research* **45**: 4960-4972.
- Demirbas, A. (2001). "Biomass resource facilities and biomass conversion processing for fuels and chemicals." *Energy Conversion and Management* **42**(11): 1357-1378.
- Di Iaconi, C., S. Rossetti, A. Lopez and A. Ried (2011). "Effective treatment of stabilized municipal landfill leachates." *Chemical Engineering Journal* **168**(3): 1085-1092.
- Donatello, S., D. Tong and C.R. Cheeseman (2010). "Production of technical grade phosphoric acid from incinerator sewage sludge ash (ISSA)." *Waste Management* **30**(8-9): 1634-1642.
- Donnert, D. and M. Salecker (1999). "Elimination of phosphorus from municipal and industrial waste water." *Environmental Technology* **20**(7): 735-742
- EL-Bourawi, M.S., M. Khayet, R. Maa, Z. Ding, Z. Lia and X. Zhang (2007). "Application of vacuum membrane distillation for ammonia removal." *Journal of Membrane Science* **301**: 200-209.
- Evans, T.D. (2007). Recovering ammonium and struvite fertilisers from digested sludge dewatering liquors, Moncton, NB, Canada.
- Fenton, O. and D. Ó hUallacháin (2012). "Agricultural nutrient surpluses as potential input sources to grow third generation biomass (microalgae): A review." *Algal Research* **1**(1): 49-56.
- Fernandez-Salvador, L.O.M.R.I. (2012). Personal Communication - Topic of 'acceptable products for certified organic farm usage'. R. Alexander.
- Ferraz, M.P., F.J. Monteiro and C.M. Manuel (2004). "Hydroxyapatite nanoparticles: A review of preparation methodologies." *J Appl Biomater Biomech* **2**(2): 74-80.
- Forrest, A.L., K.P. Fattah, D.S. Mavinic and F.A. Koch (2008). "Optimizing Struvite Production for Phosphate Recovery in WWTP." *Journal of Environmental Engineering* **134**(5).
- Ganrot, Z. (2005). Urine processing for efficient nutrient recovery and reuse in agriculture. Ph.D., Göteborg University
- Gell, K., F.J. de Ruijter, P. Kuntke, M. de Graff and A.L. Smit (2011). "Safety and effectiveness of struvite from black water and urine as a phosphorus fertilizer." *Journal of Agricultural Science* **3**(3): 67-80.
- Giotta, L., A. Agostiano, F. Italiano, F. Milano and M. Trotta (2006). "Heavy metal ion influence on the photosynthetic growth of Rhodobacter sphaeroides." *Chemosphere* **62**(9): 1490-1499.
- Gonzalez, C., J. Marciniak, S. Villaverde, C. Leon, P.A. Garcia and R. Munoz (2008). "Efficient nutrient removal from swine manure in a tubular biofilm photo-bioreactor using algae-bacteria consortia." *Water Sci Technol* **58**(1): 95-102.
- Grady, C.P.L.J., G.T. Daigger and H.C. Lim (1999). Biological Wastewater Treatment, 2nd Edition, Marcel Dekker, Inc., New York.
- Graeser, S., W. Postl, H.P. Bojar, P. Berlepsch, T. Armbruster, T. Raber, K. Ettinger and F. Walter (2008). "Struvite-(K), KMgPO_{4.6H₂O}, the potassium equivalent of struvite – A new mineral." *European Journal of Mineralogy* **20**(4): 629-633.

Guest, J.S., S.J. Skerlos, J.L. Barnard, M.B. Beck, G.T. Daigger, H. Hilger, S.J. Jackson, K. Karvazy, L. Kelly, L. Macpherson, J.R. Mihelcic, A. Pramanik, L. Raskin, M.C.M. Van Loosdrecht, D. Yeh and N.G. Love (2009). "A new planning and design paradigm to achieve sustainable resource recovery from wastewater." *Environmental Science and Technology* **43**(16): 6126-6130.

Güngör, K. and K.G. Karthikeyan (2008). "Phosphorus forms and extractability in dairy manure: A case study for Wisconsin on-farm anaerobic digesters." *Bioresource Technology* **99**(2): 425-436.

Gunnarsson, C.C. and C.M. Petersen (2007). "Water hyacinths as a resource in agriculture and energy production: A literature review." *Waste Management* **27**(1): 117-129.

Gutierrez, M.J.F., D. Baxter, C. Hunter and K. Svoboda (2005). "Nitrous oxide (N₂O) emissions from waste and biomass to energy plants." *Waste Management and Research* **23**(2): 133-147.

Heliae (2013). Heliae Starts Up Next-Generation Commercial Algae Facility in Arizona. Gilbert, AZ.

Hermann, L. (2009). P-Recovery from sewage sludge ash – Technology transfer from prototype to industrial manufacturing facilities. International Conference on Nutrient Recovery from Wastewater Streams, Vancouver, Canada.

Higgins, C.P. (2010). Trace Organic Chemicals in Biosolids-Amended Soils: State of the Science Review (SRSK5T09). Water Environment Research Federation: 212.

Huang, W. (2007). Impact of Rising Natural Gas Prices on U.S. Ammonia Supply WRS-0702, USDA.

IFA (2012). IFA database - Historical production, trade and consumption statistics of nitrogen, phosphate and potash fertilizers. <http://www.fertilizer.org/ifa/ifadata/search>, International Fertilizer Industry Association.

IPNI (2015a). Nutrient Source Specifics - Ammonium Nitrate.

IPNI (2015b). Nutrient Source Specifics - Ammonium Sulfate.

IPNI (2015c). Nutrient Source Specifics - Diammonium Phosphate.

IPNI (2015d). Nutrient Source Specifics - Monoammonium Phosphate.

Ippersiel, D., M. Mondor, F. Lamarche, F. Tremblay, J. Dubreuil and L. Masse (2011).

"Nitrogen potential recovery and concentration of ammonia from swine manure using electrodialysis coupled with air stripping." *Journal of Environmental Management*.

Ishiwata, T., O. Miura, K. Hosomi, K. Shimizu, D. Ito and Y. Yoda (2010). "Removal and recovery of phosphorus in wastewater by superconducting high gradient magnetic separation with ferromagnetic adsorbent." *Physica C* **470**: 1818-1821.

Ito, D., K. Nishimura and O. Miura (2009). "Removal and recycle of phosphate from treated water of sewage plants with zirconium ferrite adsorbent by high gradient magnetic separation." *Journal of Physics: Conference Series* **156**.

Jagadeeswaran, R., V. Murugappan and M. Govindaswamy (2005). "Effect of slow release NPK fertilizer sources on the nutrient use efficiency in turmeric (*Curcuma longa* L.)." *World Journal of Agricultural Sciences* **1**(1): 65-69.

- Jasinski, S.M. (2014). Mineral Commodity Summaries – Phosphate Rock, United States Geological Survey.
- Jasinski, S.M. (2012). Phosphate rock. U.S. Geological Survey, Mineral Commodity Summaries, Available: http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/.
- Johnston, A.E. and I.R. Richards (2004). "Effectiveness of different precipitated phosphates as phosphorus sources for plants." *Phosphorus Research Bulletin* **15**: 52-59.
- Jung, J.Y., Y.C. Chung, H.S. Shin and D.H. Son (2004). "Enhanced ammonia nitrogen removal using consistent biological regeneration and ammonium exchange of zeolite in modified SBR process." *Water Research* **38**(2): 347-354.
- King, S.J.N.O.P.U. (2012). Personal Communication – Topic of 'acceptable products for certified organic farm usage'. R. Alexander.
- Landels, S.P. (2003). Global Update on Slow-Release Fertilizers. 53rd Annual Meeting of The Fertilizer Industry Round Table, Winston-Salem, North Carolina, pp 13.
- Larsdotter, K., J. La Cour Jansen and G. Dalhammar (2007). "Biologically mediated phosphorus precipitation in wastewater treatment with microalgae." *Environ Technol* **28**(9): 953-960.
- Latimer, R., W.O. Khunjar, S. Jeyanayagam, C. Mehta, D. Batstone and R. Alexander (2012). Towards a Renewable Future: Assessing Resource Recovery as a Viable Treatment Alternative – Biannual Report 1. *Nutrient Recovery Challenge*, WERF.
- Le Corre, K.S., E. Valsami-Jones, P. Hobbs and S.A. Parsons (2009). "Phosphorus recovery from wastewater by struvite crystallization: A review." *Critical Reviews in Environmental Science and Technology* **39**(6): 433-477.
- Lehmann, J., M.C. Rillig, J. Thies, C.A. Masiello, W.C. Hockaday and D. Crowley (2011). "Biochar effects on soil biota – A review." *Soil Biology and Biochemistry* **43**(9): 1812-1836.
- Li, N., X. Wang, N. Ren, K. Zhang, H. Kang and S. You (2008). "Effects of solid retention time (SRT) on sludge characteristics in enhanced biological phosphorus removal (EBPR) reactor." *Chemical and Biochemical Engineering Quarterly* **22**(4): 453-458.
- Li, X.Z. and Q.L. Zhao (2003). "Recovery of ammonium-nitrogen from landfill leachate as a multi-nutrient fertilizer." *Ecological Engineering* **20**(2): 171-181.
- Liao, P.H., A. Chen and K.V. Lo (1995). "Removal of nitrogen from swine manure wastewaters by ammonia stripping." *Bioresource Technology* **54**: 17-20.
- Lisitsin, D., D. Hasson and R. Semiat (2008). "The potential of CO₂ stripping for pretreating brackish and wastewater desalination feeds." *Desalination* **222**: 50-58.
- Liu, W.T., K. Nakamura, T. Matsuo and T. Mino (1997). "Internal energy-based competition between polyphosphate- and glycogen-accumulating bacteria in biological phosphorus removal reactors--effect of P/C feeding ratio." *Water Research* **31**(6): 1430-1438.
- Liu, Y., J.H. Kwag, J.H. Kim and C. Ra (2011). "Recovery of nitrogen and phosphorus by struvite crystallization from swine wastewater." *Desalination* **277**(1-3): 364-369.
- Logan, B.E. and K. Rabaey (2012). "Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies." *Science* **337**(6095): 686-690.

- Lu, H., F. Nuruzzaman, J. Ravindhar and K. Chandran (2011). "Alcohol dehydrogenase expression as a biomarker of denitrification activity in activated sludge using methanol and glycerol as electron donors." *Environmental Microbiology* **13**(11): 2930-2938.
- Lü, Z., H. Guan, L. Li and W. Jia (2011). "Isolation and identification of acidithiobacillus thiooxidans with strong phosphorous ore bioleaching ability." *Chinese Journal of Applied and Environmental Biology* **17**(3): 326-329.
- Lundquist, T., I. Woertz, N. Quinn and J. Benemann (2010). A Realistic Technology and Engineering Assessment of Algae Biofuel Production. *Energy Biosciences Institute Report*, <http://www.energybiosciencesinstitute.org/sites/default/files/media/AlgaeReportFINAL.pdf>, Energy Biosciences Institute, University of California.
- Maier, A. (2011). Gathering Unpublished Data for Compounds Detected in Biosolids (TOBI1T11). Water Environment Research Foundation: 154.
- Malik, A. (2007). "Environmental challenge vis a vis opportunity: The case of water hyacinth." *Environment International* **33**(1): 122-138.
- Mamo, M., C. Wortmann and C. Brubaker (2007). "Manure phosphorus fractions: Development of analytical methods and variation with manure types." *Communications in Soil Science and Plant Analysis* **38**(7-8): 935-947.
- Manning, D.A.C. (2010). "Mineral Sources of Potassium for Plant Nutrition." *Agronomy Sustainable Development* **2**: 188-201.
- Markou, G. and D. Georgakakis (2011). "Cultivation of filamentous cyanobacteria (blue-green algae) in agro-industrial wastes and wastewaters: A review." *Applied Energy* **88**(10): 3389-3401.
- Martin Jr., J.H., R.C. Loehr and T.E. Pilbeam (1983). "Animal manures as feedstuffs: Nutrient characteristics." *Agricultural Wastes* **6**(3): 131-166.
- Massey, M., J. Davis, J. Ippolito and R. Sheffield (2009). "Effectiveness of recovered magnesium phosphates as fertilizers in neutral and slightly alkaline soils." *Agronomy Journal* **101**(2): 323-329.
- Mata, T.M., A.A. Martins and N.S. Caetano (2010). "Microalgae for biodiesel production and other applications: A review." *Renewable and Sustainable Energy Reviews* **14**: 217-232.
- McLaughlin, M. (2007). Fluid Fertilisers: A South Australian Manual. B. Holloway, T. Mcbeath, D. Brace and J. Kelly. Adelaide, School of Earth and Environmental Sciences, CSIRO Land and Water and University of Adelaide.
- Mehta, C.M. and B.J. Damien (2012). "Nutrient solubilization and its availability post anaerobic digestion." *Water Science & Technology Accepted*.
- Menetrez, M.Y. (2012). "An overview of algae biofuel production and potential environmental impact." *Environ Sci Technol* **46**(13): 7073-7085.
- Mercier, G., P. Drogui, J.F. Blais and M. Chartier (2006). "Pilot-plant study of wastewater sludge decontamination using a ferrous sulfate bioleaching process." *Water Environment Research* **78**(8): 872-879.

- Merino-Martos, A., J. de Vicente, L. Cruz-Pizarro and I. de Vicente (2011). "Setting up High Gradient Magnetic Separation for combating eutrophication of inland waters." *Journal of Hazardous Materials* **186**: 2068-2074.
- Metcalf and Eddy, I., G. Tchobanoglou, F. Burton and H.D. Stensel (2002). *Wastewater Engineering: Treatment and Reuse*, McGraw-Hill Science Engineering.
- Meunier, N., P. Drogui, C. Gourvenec, G. Mercier, R. Hausler and J.F. Blais (2004). "Removal of metals in leachate from sewage sludge using electrochemical technology." *Environmental Technology* **25**(2): 235-245.
- Meyer, V., E. Redente, K. Barbarick, R. Brobst, M. Paschke and A. Miller (2004). "Plant and soil responses to biosolids application following forest fire." *Journal of Environmental Quality* **33**: 873-881.
- Mihelcic, J.R., L.M. Fry and R. Shaw (2011). "Global potential of phosphorus recovery from human urine and feces." *Chemosphere* **84**: 832-839.
- Mohedano, R.A., V.F. Velho, R.H.R. Costa, S.M. Hofmann and P. Belli Filho (2012). "Nutrient recovery from swine waste and protein biomass production using duckweed ponds (*Landoltia punctata*): Southern Brazil." *Water Science and Technology* **65**(11): 2042-2048.
- Moita, R. and P.C. Lemos (2012). "Biopolymers production from mixed cultures and pyrolysis by-products." *J Biotechnol* **157**(4): 578-583.
- Molinos-Senante, M., F. Hernandez-Sancho, R. Sala-Garrido and M. Garrido-Baserba (2011). "Economic feasibility study for phosphorus recovery processes." *Ambio* **40**(4): 408-416.
- Mondor, M., D. Ippersiel, F. Lamarche and L. Masse (2009). "Fouling characterization of electrodialysis membranes used for the recovery and concentration of ammonia from swine manure." *Bioresource Technology* **100**(2): 566-571.
- Mondor, M., L. Masse, D. Ippersiel, F. Lamarche and D.I. Massé (2008). "Use of electrodialysis and reverse osmosis for the recovery and concentration of ammonia from swine manure." *Bioresource Technology* **99**(15): 7363-7368.
- Moralejo-Garate, H., E. Mar'atusalihat, R. Kleerebezem and M.C. van Loosdrecht (2011). "Microbial community engineering for biopolymer production from glycerol." *Appl Microbiol Biotechnol* **92**(3): 631-639.
- Mulder, A. (2003). "The quest for sustainable nitrogen removal technologies." *Water Sci Technol* **48**(1): 67-75.
- Multiform Harvest (2012). Response to Request for Information for WERF Proposal No. NTRY1R12 Nutrient Recovery in the Global Water Industry: 9.
- Munch, E.V. and K. Barr (2001). "Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams." *Water Research* **35**(1): 151-159.
- Mwabonje, O.N. and J.Q. Jiang, (2010). "A Trial of Using Solvent Extraction for Phosphorus Recovery." *Journal of Water Resource and Protection* **2**: 830-838.
- Neethling, J.B. (2008) "Tertiary Phosphorus Removal." 19.

- Neethling, J.B., D. Clark, A. Pramanik, H.D. Stensel, J. Sandino and R. Tsuchihashi (2010). "WERF Nutrient Challenge investigates limits of nutrient removal technologies." *Water Sci Technol* **61**(4): 945-953.
- Norddahl, A., V.G. Horn, M. Larsson, J.H. Preez and K. Christensen (2006). "A membrane contactor for ammonia stripping, pilot scale experience and modeling." *Desalination* **199**: 172-174.
- NuReSys (2012). "Response to Request for Information for WERF Proposal No. NTRY1R12 Nutrient Recovery in the Global Water Industry": 15.
- Oron, G., L.R. Wildschut and D. Porath (1985). "Waste water recycling by duckweed for protein production and effluent renovation." *Water Science and Technology* **17**(4-5 -5 pt 2): 803-817.
- Ostara (2012). Response to Request for Information for WERF Proposal No. NTRY1R12 Nutrient Recovery in the Global Water Industry H. a. Sawyer: 41.
- Paques (2012). "Response to Request for Information for WERF Proposal No. NTRY1R12 Nutrient Recovery in the Global Water Industry." 6.
- Park, J.H., G.K. Choppala, N.S. Bolan, J.W. Chung and T. Chuasavathi (2011). "Biochar reduces the bioavailability and phytotoxicity of heavy metals." *Plant and Soil* **348**(1-2): 439-451.
- Parsons, S.A. and J.A. Smith (2008). "Phosphorus removal and recovery from municipal wastewaters." *Elements* **4**(2): 109-112.
- Pastor, L., N. Marti, A. Bouzas and A. Seco (2008). "Sewage sludge management for phosphorus recovery as struvite in EBPR wastewater treatment plants." *Bioresource Technology* **99**(11): 4817-4824.
- Pathak, A., M.G. Dastidar and T.R. Sreekrishnan (2009). "Bioleaching of heavy metals from sewage sludge by indigenous iron-oxidizing microorganisms using ammonium ferrous sulfate and ferrous sulfate as energy sources: A comparative study." *Journal of Hazardous materials* **171**(1-3): 273-278.
- Pueluelas, J., J. Sardans, A. Rivas-Ubach, and I.A. Janssens, (2012). "The human-induced imbalance between C, N and P in Earth's life system." *Global Change Biology* **18**: 3-6.
- Phillips, H., C. deBarbadillo, B. Wimmer, J. Barnard and M. Steichen (2011). Perspectives on Nitrogen and Phosphorus Recovery from Wastewater: The State of the Industry. Nutrient Recovery and Management 2011, Water Environment Federation, pp 426-436.
- Powell, N., A.N. Shilton, S. Pratt and Y. Chisti (2008). "Factors influencing luxury uptake of phosphorus by microalgae in waste stabilization ponds." *Environmental Science and Technology* **42**(16): 5958-5962.
- Prayon (2013). Phosphoric Acid – Product Range.
- Pritchard, D., N. Penney, M. McLaughlin, H. Rigby and K. Schwarz (2010). "Land application of sewage sludge (biosolids) in Australia: Risks to the environment and food crops." *Water Science and Technology* **62**(1): 48-57.
- Procorp (2012). "Response to Request for Information for WERF Proposal No. NTRY1R12 Nutrient Recovery in the Global Water Industry." 11.

- Pronk, W., M. Biebow and M. Boller (2006). "Electrodialysis for Recovering Salts from a Urine Solution Containing Micropollutants." *Environmental Science & Technology* **40**(7): 2414-2420.
- Punrattanasin, W. (2001). The Utilization of Activated Sludge Polyhydroxyalkanoates for the Production of Biodegradable Plastics. Ph.D., Virginia Polytechnic Institute and State University.
- Rothrock Jr, M.J., A.A. Szögi and M.B. Vanotti (2010). "Recovery of ammonia from poultry litter using gas-permeable membranes." *Transactions of the ASABE* **53**(4): 1267-1275.
- Royal Haskoning, DHV. (2012). "Response to Request for Information for WERF Proposal No. NTRY1R12 Nutrient Recovery in the Global Water Industry." (8).
- Ryu, H.D., C.S. Lim, Y.K. Kim, K.Y. Kim and S.I. Lee (2012). "Recovery of struvite obtained from semiconductor wastewater and reuse as a slow-release fertilizer." *Environmental Engineering Science* **29**(6): 540-548.
- Saber, L. S., Safferman, S.I., Helperich, R. (2011). Onsite Wastewater Phosphorus Removal Using Nano Enhanced Reactive Iron Media. The 2011 Borchardt Conference: A Seminar on Advancements in Water and Wastewater, Ann Arbor MI.
- Saeed, T. and G. Sun (2012). "A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: Dependency on environmental parameters, operating conditions and supporting media." *Journal of Environmental Management* **112**: 429-448.
- Salehizadeh, H. and M.C. Van Loosdrecht (2004). "Production of polyhydroxyalkanoates by mixed culture: recent trends and biotechnological importance." *Biotechnol Adv* **22**(3): 261-279.
- Sartorius, C., J. Von Horn and F. Tettenborn (2012). "Phosphorus recovery from wastewater-expert survey on present use and future potential." *Water Environment Research* **84**(4): 313-322.
- Schuiling, R.D. and A. Andrade (1999). "Recovery of struvite from calf manure." *Environmental Technology* **20**(7): 765-768.
- Sengupta, S. and A. Pandit (2011). "Selective removal of phosphorus from wastewater combined with its recovery as a solid-phase fertilizer." *Water Research* **45**(11): 3318-3330.
- Shaikh, A.M.H. and S.G. Dixit (1992). "Removal of phosphate from waters by precipitation and high gradient magnetic separation." *Water Research* **26**(6): 815-852.
- Shilton, A., N. Powell and B. Guieysse (2012). "Plant based phosphorus recovery from wastewater via algae and macrophytes." *Current Opinion in Biotechnology*: In Press, <http://dx.doi.org/10.1016/j.copbio.2012.1007.1002>.
- Shu, L., P. Schneider, V. Jegatheesan and J. Johnson (2006). "An economic evaluation of phosphorus recovery as struvite from digester supernatant." *Bioresour Technol* **97**(17): 2211-2216.
- Smith, V.H. and D.W. Schindler (2009). "Eutrophication science: where do we go from here?" *Trends in Ecology and Evolution* **24**(4): 201-207.
- Solatube (2013). Project: Algae to Omega - Building Type: Indoor Agriculture. Vista, CA.
- Sprynskyy, M., M. Lebedynets, R. Zbytniewski, J. Namieśnik and B. Buszewski (2005). "Ammonium removal from aqueous solution by natural zeolite, Transcarpathian mordenite, kinetics, equilibrium and column tests." *Separation and Purification Technology* **46**(3): 155-160.

- Stendahl, K. and S. Jäfverström (2003). "Phosphate recovery from sewage sludge in combination with supercritical water oxidation." *Water Science and Technology* **48**(1): 185-191.
- Sturm, B. and S. Lamer (2011). "An energy evaluation of coupling nutrient removal from wastewater with algal biomass production." *Applied Energy* **88**(10): 3499-3506.
- Tan, X., S.P. Tan, W.K. Teo and K. Lia (2006). "Polyvinylidene fluoride (PVDF) hollow fibre membranes for ammonia removal from water." *Journal of Membrane Science* **271**: 59-68.
- Tchobanoglous, G., F. Burton, H. Stensel and M.A. Eddy (2003). *Wastewater Engineering, Treatment and Reuse*. New York, NY (US), McGraw-Hill.
- Tenkorang, F. and J. Lowenberg-DeBoer (2009). "Forecasting long-term global fertilizer demand." *Nutrient Cycling in Agroecosystems* **83**(3): 233-247.
- Teoh, M., W. Chu and S. Phang (2010). "Effect of temperature change on the physiology and biochemistry of algae: a review." *Malaysian Journal of Science* **29**(2): 82-97.
- Thygesen, A.M., O. Wernberg, E. Skou and S.G. Sommer (2011). "Effect of incineration temperature on phosphorus availability in bio-ash from manure." *Environmental Technology* **32**(6): 633-638.
- Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor and S. Polasky (2002). "Agricultural sustainability and intensive production practices." *Nature* **418**(6898): 671-677.
- Trent, J., P. Wiley, S. Tozzi, B. McKuin and S. Reinsch (2012). "Research Spotlight: The future of biofuels: Is it in the bag?" *Biofuels* **3**(5): 521-524.
- U.S. Census Bureau (2011). State & County Quickfacts.
<http://quickfacts.census.gov/qfd/states/00000.html>.
- USDA (2012). National Agricultural Statistics Service – Agricultural Prices, .
<http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1002>.
- U.S. EPA (1994a). *A Plain English Guide to the EPA Part 503 Biosolids Rule*. Washington, D.C.
- U.S. EPA (2002b). *Onsite Wastewater Treatment Systems Manual*. O. o. R. a. D. Office of Water. Washington, D.C.
- U.S. EPA (2003c). *Environmental Regulations and Technology Control of Pathogens and Vector Attraction in Sewage Sludge*. N. R. M. R. L. Office of Research and Development.
- Van Kauwenbergh, S. (2010). *World Phosphate Rock Reserves and Resources*. Muscle Shoals, Alabama, International Fertilizer Development Center.
- Van Velsen, A., G. van der Vos, R. Boersma and J. de Reuver (1991). "High grade magnetic separation technique for wastewater treatment." *Water Sci Technol* **24**(10): 195-203.
- Vanotti, M.B., J.M. Rice, A.Q. Ellison, P.G. Hunt, F.J. Humenik and C.L. Baird (2005). "Solid-liquid separation of swine manure with polymer treatment and sand filtration." *Transactions of the ASAE* **48**(4): 1567-1574.
- Vanotti, M.B. and A.A. Szogi (2010). Removal and recovery of ammonia from liquid manure using gas-permeable membranes. American Society of Agricultural and Biological Engineers Annual International Meeting, Pittsburgh, Pennsylvania.

- Veeken, A.H.M. and H.V.M. Hamelers (1999). "Removal of heavy metals from sewage sludge by extraction with organic acids." *Water Science & Technology* **40**(1): 129-136.
- Vieira, J.G., A.G.S. Manetti, E. Jacob-Lopes and M.I. Queiroz (2012). "Uptake of phosphorus from dairy wastewater by heterotrophic cultures of cyanobacteria." *Desalination and Water Treatment* **40**(1-6): 224-230.
- Vitousek, P.M., R. Naylor, T. Crews, M.B. David, L.E. Drinkwater, E. Holland, P.J. Johnes, J. Katzenberger, L.A. Martinelli, P.A. Matson, G. Nziguheba, D. Ojima, C.A. Palm, G.P. Robertson, P.A. Sanchez, A.R. Townsend and F.S. Zhang (2009). "Agriculture. Nutrient imbalances in agricultural development." *Science* **324**(5934): 1519-1520.
- Vymazal, J. (2007). "Removal of nutrients in various types of constructed wetlands." *Science of the Total Environment* **380**(1-3): 48-65.
- Vymazal, J. (2011). "Constructed wetlands for wastewater treatment: five decades of experience." *Environ Sci Technol* **45**(1): 61-69.
- Waller, P., R. Ryan, M. Kacira and P. Li (2012). "The algae raceway integrated design for optimal temperature management." *Biomass and Bioenergy* **46**: 702-709.
- Wang, H., S.L. Brown, G. Magesan, S.A., M. Quintern, P. Clinton and T. Payn (2008). "Technological options for the management of biosolids." *Environ Sci Pollut Res* **15**: 308-317.
- Wang, Y., M. Pelkonen and M. Kotro (2010). "Treatment of high ammonium-nitrogen wastewater from composting facilities by air stripping and catalytic oxidation." *Water, Air, and Soil Pollution* **208**(1-4): 259-273.
- Wei, Y.X., Z.F. Ye, Y.L. Wang, M.G. Ma and Y.F. Li (2011). "Enhanced ammonia nitrogen removal using consistent ammonium exchange of modified zeolite and biological regeneration in a sequencing batch reactor process." *Environmental Technology* **32**(12): 1337-1343.
- Wilkinson, K.G. (2011). "A comparison of the drivers influencing adoption of on-farm anaerobic digestion in Germany and Australia." *Biomass & Bioenergy* **35**(5): 1613-1622.
- Wilsenach, J.A., M. Maurer, T.A. Larsen and M.C.M. Van Loosdrecht (2003). From waste treatment to integrated resource management. **48**: 1-9.
- Wilsenach, J. A., C. A. H. Schuurbiers and M. C. M. van Loosdrecht (2007). "Phosphate and potassium recovery from source separated urine through struvite precipitation." *Water Research* **41**(2): 458-466.
- Wise, J., D. Vietor, T. Provin, S. Capareda, C. Munster and A. Boateng (2012). "Mineral nutrient recovery from pyrolysis systems." *Environmental Progress and Sustainable Energy* **31**(2): 251-255.
- Wong, J.W.C., L. Xiang and L.C. Chan (2002). "pH requirement for the bioleaching of heavy metals from anaerobically digested wastewater sludge." *Water, Air, and Soil Pollution* **138**(1-4): 25-35.
- Wong, J.W. C., L. Xiang, X.Y. Gu and L.X. Zhou (2004). "Bioleaching of heavy metals from anaerobically digested sewage sludge using FeS₂ as an energy source." *Chemosphere* **55**(1): 101-107.

Woods, J., A. Williams, J.K. Hughes, M. Black and R. Murphy (2010). "Energy and the food system." *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**(1554): 2991-3006.

Yetilmezsoy, K. and Z. Sapsi-Zengin (2009). "Recovery of ammonium nitrogen from the effluent of UASB treating poultry manure wastewater by MAP precipitation as a slow release fertilizer." *Journal of Hazardous materials* **166**(1): 260-269.

Yuan, Z., S. Pratt and D.J. Batstone (2012). "Phosphorus recovery from wastewater through microbial processes." *Current Opinion in Biotechnology*: In Press,
<http://dx.doi.org/10.1016/j.copbio.2012.1008.1001>.

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