water e-journal
Online Journal of the Australian Water Association
ISSN 2206-1991
Volume 1 No 2 2016
http://dx.doi.org/10.21139/wej.2016.010

ACCELERATING THE IMPLEMENTATION OF EXTRACTIVE NUTRIENT RECOVERY AS AN INTEGRAL COMPONENT OF SUSTAINABLE NUTRIENT MANAGEMENT

FINDINGS OF THE RECENTLY COMPLETED WATER ENVIRONMENT RESEARCH FOUNDATION STUDY

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ABSTRACT

Resource management strategies that support the water-energy-nutrient nexus are pivotal components of the Basins of the Future initiative. In this paper, we present information generated as part of a Water Environment Research Foundation (WERF) study that focuses on closing the gap between innovation and practice, thereby accelerating wider adoption of extractive nutrient recovery.

Extractive nutrient recovery, defined as the production of chemical nutrient products devoid of significant organic matter, represents a disruptive technology. It often entails a three-step framework to include accumulation, release and extraction of a chemical nutrient product that is marketable and could potentially offset operating costs and synthetic fertiliser use.

While several approaches are being explored for nutrient extraction, intentional struvite formation is currently the technology of choice. Using case studies the paper reviews drivers for, and barriers against, extractive nutrient recovery, implementation challenges, cost, lessons learned, and design and operational guidance. This paper also reviews experimental evaluation of emerging strategies for maximising nutrient extraction.

Keywords: Extractive nutrient recovery, nutrient recovery, resource recovery, struvite, sustainable nutrient management.

INTRODUCTION

Nitrogen (N) and phosphorus (P) are life-essential macronutrients that are extensively used in agricultural applications. Production of synthetic fertilisers containing N and P is an energy-intensive process that uses non-renewable resources. For example, ammonia (NH_3) is produced via the Haber-Bosch process with a high energy demand (12 kWh/kg NH_3 produced). With respect to P, experts believe that economically extractable reserves are being consumed faster than the geologic cycle can replenish it.

To minimise the accumulation of these nutrients in the environment, the current approach is to remove N and P before discharge to a water body. In this scenario, energy and other non-renewable resources are supplied to replenish nutrient supply for agricultural uses and again to remove these nutrients from wastewater before discharge to the environment. This linear approach, which assumes an unlimited and cheap supply of energy and resources, is unsustainable and not aligned with the Basins of the Future (BoF) initiative. Disruptive approaches and transformational changes are needed in how we manage and capture resources (water, nutrients and others) and energy from wastewater streams.

While nutrient recovery is being practised via land application of biosolids and effluent reuse, extraction of a chemical nutrient product with low organic matter content, defined here as extractive nutrient recovery, has not been widely applied within the wastewater treatment industry.

Table 1. Benefits of extractive nutrient recovery.

- Manage recycle loads and enhance P removal process reliability.
- Achieve chemical and energy savings by reducing/eliminating chemicals for P removal.
- Reduce solids production by minimising/eliminating dependence on chemicals.
- Achieve lower biosolids P content and potentially increase land application rates.
- Minimise struvite nuisance scaling and reduce maintenance requirements and cost.
- Generate an environmentally friendly product (slow-release fertiliser).
- Create a potential revenue stream from a highly desirable fertiliser product.
- Enhance sludge dewaterability by achieving favourable mono to divalent cation ratio.
- Achieve overall sustainability benefits.

It remains a disruptive technology and a necessary component of any sustainable decision paradigm that strives to optimise the water-energy-nutrient nexus. Disruptive technology has a potential to create a new market and value network, and eventually it disrupts an existing market and value network. In wastewater management, it describes a paradigm shift that views wastewater not as a waste that requires treatment, but as a conglomeration of valuable resources that could be recovered and reused. Benefits of nutrient recovery are listed in Table 1.

This paper presents technical information generated as part of a global study funded by the Water Environment Research Federation (WERF) aimed at filling the knowledge gap and enabling the advancement of extractive nutrient recovery (Latimer *et al*., 2015a, 2015b, 2015t; Mehta *et al*., 2015). The material presented includes performance data, lessons learned, plant-wide impacts and integration issues. The overarching objective is to empower the industry to adopt sustainable nutrient management practices.

APPROACH

The nutrient concentration in municipal wastewater typically ranges from 10 to 50 mg N/L and from 1 to 10 mg P/L. Since the efficiency of extractive nutrient recovery is lower at these concentrations, a three-step framework, shown in Figure 1, is often needed to make it viable:

- Accumulation of nutrients to high concentrations (>1000 mgN/L and > 100 mg P/L);
- Release of nutrients to a small liquid flow with low COD;
- Extraction of nutrients as a marketable chemical product.

Figure 1 also lists some of the technologies organised by process step. Accumulation and release technologies are already commonplace at many nutrient removal facilities that utilise enhanced biological phosphorus removal and anaerobic sludge digestion. Consequently, achieving nutrient recovery at these plants entails incorporating the last extraction step, which could make extractive nutrient recovery a financially viable proposition.

RESULTS AND DISCUSSION

Technology Review

The various disruptive technologies available to accomplish the three steps outlined above may be further characterised as embryonic (early stage of development, bench/pilot scale experience); innovative (limited full-scale application); or established (mature with proven track record). Key information regarding selected technologies is summarised in Table 2. A more detailed review of all available alternatives is contained in the WERF report (Latimer *et al*., 2015a).

With respect to proven approaches, intentional struvite formation is

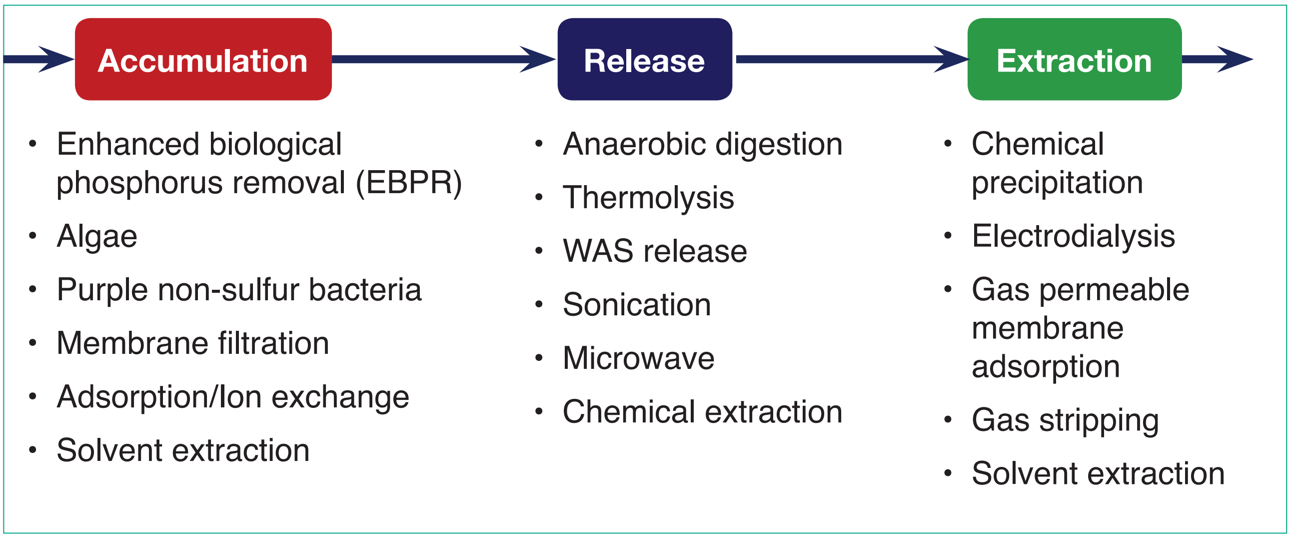

Figure 1. Components and candidate technologies for extractive nutrient recovery.

Table 2. Summary of selected nutrient accumulation, release and recovery technologies.

Technology		Operating Conditions Temp. (°C)	pH	Pre-treatment required	Chemical Input	Commercial process	Nutrients Accumulated
Accumulation Technologies							
Embryonic	Microalgae	15–30	7.5–8.5	-		Lemna Technologies	N and P
	Cyanobacteria	5–40	6.5–8	-	Carbon source	-	N and P
Innovative	Adsorption/Ion exchange	NA	<8.0	Solid-liquid separation	Adsorbent, Regeneration solution	P-ROC, RECYPHOS, PHOSIEDI, RIM NUT, BIOCON	N and P
Established	EBPR	5–40	6.5–8	-	Carbon	-	P only
	Chemical	25–40	6.5–10	-	Metal salts (Al or Fe)	-	P only
Release Technologies							
Innovative	Chemical extraction	25–200	1–3	-	Leaching solution (sulfuric acid, hydrochloric acid, nitric acid, citric acid, oxalic acid, EDTA)	SEABORNE, STUTTGARTER VERFAHREN, LOPROX/PHOXAN, CAMBI, KREPCO, BIOCON, SEPHOS, AQUARECI, SESAL-PHOS, PASCH	N and P
	Thermochemical	150 – 1100	All	Temperature adjustment	-	MEPHREC, ASHDEC, THERMPHOS	P only
	Enhanced P release from WAS	5–40	6.5–8	-	Carbon (volatile fatty acids)	WASStrip, PRISA	P only
Established	Anaerobic digestion	35–60	6.5–7.5	-	-	-	N and P
Extraction Technologies							
Embryonic	Electrodialysis	10–40	< 8.0	Solid-liquid separation	Electricity	GE Water	N and P
Innovative	Liquid-gas stripping	>80°C	> 9.5	pH and temperature adjustment	Caustic	ThermoEnergy Castion™	N only
Established	Struvite crystallisation	25–40	8–9	Solid-liquid separation	Caustic, Magnesium or Calcium	PHOSTRIP, PRISA, DHV CRYSTALACTOR, CSIR, KURITA, PHONIX, OSTARA, BERLINER VERFAHEN, FIX-PHOS	N and P

Table 3. Comparison of proven nutrient recovery processes.

	Ostara	Multiform Harvest	NuReSys	Phospaq	Royal HaskoningDHV	Airprex™
Type of reactor	Fluidised Bed Reactor (FBR)		Completely Stirred Tank Reactor (CSTR)		FBR	CSTR
Name of product recovered	Crystal Green® (struvite)	Struvite	BioStru® (struvite)	Struvite	Struvite, Ca phosphate	Struvite
Recovered from	Dewatering filtrate/centrate		Filtrate/centrate & digested sludge	Filtrate/centrate		Digested sludge
Recovery efficiency	80–90% P 10–50% N	80–90% P	45% P	80% P	85–95% P	80–90% P 10–40% N
Full-scale installations	8	3	7	2	5	3

currently the technology of choice. Table 3 compares salient features of six mature struvite crystallisation technologies. The overall phosphorus removal that can be achieved by adopting these technologies is about 30% to 40% of influent total phosphorus.

Case Studies

This section presents information gathered from 20 collaborating utilities as part of the Water Environment Research Federation (WERF) project on extractive nutrient recovery (Latimer *et al.*, 2015b). The data provide valuable guidance for enabling the implementation of nutrient removal. The 20 case studies covered are at various stages of implementing nutrient recovery, as follows:

- Five with operating nutrient recovery systems;
- Eight had completed desktop and/or pilot evaluation;
- Seven had completed a high-level evaluation using the Tool for Evaluation Resource Recovery (TERRY), which was developed as part the WERF study.

Drivers And Barriers

A survey of the 20 wastewater treatment plants revealed the key drivers for, and barriers against, incorporating extractive nutrient recovery. The following are the main drivers:

- Stringent nutrient limits;
- Nuisance struvite scaling;
- Unstable bio-P performance due to high sidestream P load;
- Aeration energy savings through reduced sidestream ammonia load;
- Higher biosolids land application rates due to reduced P content;
- Mainstream bio-P process upgrade can be delayed;
- Impending phosphorus discharge standard;
- Enhanced public perception.

Despite the benefits, there remain technical, social and economic barriers to a wider adoption of nutrient recovery. The review also provided further insight into the challenges associated with each barrier. Based on this information, strategies were developed for overcoming the barriers, as shown in Table 4.

Plants With Nutrient Recovery

Salient features of the five plants using nutrient recovery are summarised in Table 5. The reported ortho-P and ammonia-N removals at these plants ranged between 80–90% and 7–19%, respectively. There was no discernible performance difference between Ostara and Multiform Harvest installations.

Lessons Learnt From Facilities Using Struvite Recovery

Based on feedback from utilities operating struvite recovery systems, several lessons learnt were identified and summarised below. Treatment plants planning on implementing a full-scale extractive nutrient recovery should consider the following during design, construction and operation.

- <u>Plant-wide impacts:</u> Inclusion of struvite recovery impacts the mainstream bio-P process, anaerobic digestion and dewatering operations, due to the reduced phosphorus loadings. One of the reported benefits of struvite recovery is reduced foaming in bioreactors and digesters, and enhanced dissolved air flotation thickening of WAS. These experiences suggest that plants will need to optimise their mainstream process after the start-up of struvite recovery. Some process improvements may be expected due to reduced phosphorus loading in the plant.
- <u>General design considerations:</u> Struvite crystallisation requires a high concentration of nutrients in the feed, which can result in unintentional struvite formation in the conveyance system. In order to mitigate this, the recovery facility should be located as close as possible to the dewatering facilities and equalisation tanks. In addition, the use of traps, check valves, small tubing and short radius elbows should be avoided. Flush connections, large tubing and long radius turns should be considered to facilitate cleaning during maintenance. Installing a second reactor, duplicate piping and additional pumps will minimise downtime during maintenance and ensure that recycle P load to the mainstream is controlled.
- <u>Start-up considerations</u>: The start-up process should be implemented in stages to facilitate operator training and learning. Struvite reactor start-up and operation should be followed by harvesting and then bagging. Training staff on non-functional equipment often results in a poor understanding of optimising the nutrient recovery system. Extra care should be taken during initial start-up, as operational variations during this sensitive stage can cause ‘washout’ of fine struvite particles, which serve as seed material for the growth of struvite prill. Uniform struvite prill size is critical for marketing the end product. Producing the desired prill size requires iteration and optimisation of the recovery process.
- <u>Operations and maintenance considerations:</u> Regular acid flushing as part of a routine maintenance plan controls and removes nuisance struvite. For example, the weekly use of Struv-Free (a proprietary chemical) has been reported to minimise struvite scaling at one plant. During dewatering, the addition of carbon dioxide depresses the pH and inhibits struvite formation. Before stopping feed pumps, operators recommend closing the inlet valves to minimise struvite formation in the piping. During the winter one treatment plant in Canada struggled to optimise the WASSTRIP™ process, which suggests that extremely cold weather negatively affects the WAS P release process; however, none of the plants in the US reported problems with colder weather. At one facility, digested sludge thickening declined after struvite recovery

Table 4. Strategies for overcoming key barriers to a wider adoption of extractive nutrient recovery.

Barrier	Challenges	Resolution
Technical	• Insufficient time and staff to review available technologies and decide on path forward.	• Review technology factsheets and references to existing installations in WERF report. • Contact utilities that have experience with technology. • Review WERF Leaders Innovation Forum for Technology (LIFT) initiative on nutrient recovery.
	• Insufficient data to evaluate technology performance. • Lack of manufacturers' independent performance information.	• Review WERF report to determine data needs. • Perform detailed sampling.
	• Insufficient experience in operating nutrient recovery technology. • Lack of access to intellectual property created in trials with technology providers.	• Visit facilities that have implemented nutrient recovery. • Participate in WERF LIFT program to acquire further knowledge. • If funds are available, pilot-test candidate technologies.
	• Unknown maintenance requirements and long-term operational viability.	• Contact utilities that have implemented nutrient recovery for lessons learnt. • Participate in WERF LIFT program. • Provide flexibility in design to bypass and/or upgrade facility with improved technology.
Economic	• Insufficient and/or competing needs for funds. • Costs (cash and in-kind) associated with running technology trials at utilities.	• Utilise WERF report and the Toll for Evaluating Resource Recovery (TERRY) to determine site-specific viability of nutrient recovery. • Examine vendor-business models and delivery mechanisms to minimise capital and operating costs. • Explore regionalisation of service to increase scale of operation while charging tipping fees for imported solids.
	• Unknowns regarding cost of implementation, operating costs, etc.	• Review WERF report to obtain point of reference for existing installations. • Contact utilities that have experience with technology. • Use TERRY to calculate order of magnitude costs.
	• Uncertainty with respect to future demand for fertiliser product.	• Review market analysis in the WERF report to determine regional demand for different fertiliser products. • Examine business models utilised by technology providers to guarantee revenue from marketing struvite.
	• Competition for product if many utilities adopt the technology.	• Examine business models utilised by technology providers to guarantee revenue. • Explore alternative routes for product entry into the fertiliser market. • Explore regionalisation of service and importation of solids to increase scale of operation while charging tipping fees for imported solids.
Regulatory	• Lack of regulatory drivers – i.e., no effluent nutrient limits.	• Consider and quantify other benefits such as reduction in operating and energy costs, mitigation of nuisance struvite formation, reduction of biosolids mass, higher land application rates, potentially improved dewaterability, etc.
	• Lack of public acceptance due to increase in utility bills and concerns with the safety of the final product.	• Engage the public to demonstrate benefits to the environment and impact on costs. • Increase public awareness through press releases, public hearings and tours.

Table 5. Summary of facilities with nutrient recovery.				
Location	Plant Configuration	Current Nutrient Limits	Size (ML/d)	Nutrient Recovery System
Virginia, USA	Liquid: 5-Stage BNR Solids: Mesophilic Anaerobic Digestion Digested Sludge Dewatering: Centrifuge	8.0 mg/L TN; 2.0 mg/L TP (annual average)	113.5	Ostara
Washington, USA	Liquid: 3-Stage BNR Solids: Mesophilic Anaerobic Digestion Digested Sludge Dewatering: Centrifuge	No limits. Proactive in reducing TP < 1 mg/L	83.3	Multiform Harvest
Wisconsin, USA	Liquid: 3-Stage BNR and UCT process in parallel Solids: Acid Gas Mesophilic Anaerobic Digestion Digested Sludge Dewatering: Gravity Belt Thickeners	None	215.7	Ostara
Saskatchewan, Canada	Liquid: Modified UCT process Solids: Mesophilic Anaerobic Digestion Digested Sludge Dewatering: Sludge Storage Cells	1.0 mg/L TP	120	Ostara
Idaho, USA	Liquid: MLE, Johannesburg. Conversion to West Bank underway Solids: Mesophilic Anaerobic Digestion Digested Sludge Dewatering: Belt Filter Press	0.07 mg/L TP (monthly average) 0.084 mg/L TP (weekly average; (May 1 – Sept 30)	90.8	Multiform Harvest

Table 6. Cost summary.					
Location	Size (ML/d)	Nutrient Recovery System Design Criteria	No. of Reactors	Construction Cost	Annual O&M Cost
Virginia, USA	113.5	378.5 m³/d 600 mg/L TP 60% TP removal	3 – Ostara 500 reactors	$5,600,000	$88,800
Washington, USA	83.3	1.1 ML/d 381 mg/L TP 75% Ortho-P removal	2 – Multiform Harvest reactors	$735,000	$28,300
Wisconsin, USA	215.7	4.4 ML/d 126 mg/L Ortho P 175 mg/L NH3-N 80% Ortho P removal 15% NH3-N removal	2 – Ostara 500 reactors	$9,021,000	N/A
Saskatchewan, Canada	120	2.8 ML/d 78% Ortho-P 250 mg/L NH³-N 68% Ortho-P removal 10% NH3-N removal	1 – Ostara 2000 reactor	$4,450,000	$100,000
Idaho, USA	90.8	2.1 ML/d 390 mg/L Ortho-P 1,100 mg/L NH3-N 75% Ortho-P removal	5 – Multiform Harvest reactors	$3,681,695	$322,584

Table 7. Business case evaluation factors.
Wastewater treatment plant performance factors
• Reduce nuisance precipitate formation
• Improve phosphorus removal capacity
• Improve reliability for meeting effluent total phosphorus limits
Environmental/Health/Social/Economic Factors
• Perform nutrient recovery
• Reduce amount of chemical sludge produced and disposed
• Reduce supplemental carbon demand
• Alternative is more acceptable to the public than the baseline
Financial Factors
• Net present value
• Payback period
Risk Assessment Factors
• Technological track record
• Sufficient information for proper assessment
• Additional building footprint required
• Manpower and skill required

was implemented. A low ferric chloride dose was initiated to the gravity belt thickener to improve thickening. When ferric dosing was discontinued, the hydrogen sulfide concentration in the digester gas increased from <300 to >500 ppm by volume. The hydrogen sulfide and siloxane treatment system was unable to handle the increased loading, necessitating the resumption of low ferric dose.

Implementation Costs

Construction and operating costs, where available, for the five facilities that use nutrient recovery are presented in Table 6. These costs are influenced by many site-specific factors. Hence a direct comparison is not possible. All costs are expressed in US$.

Evaluation Tool

A value-added deliverable of the WERF project is the Excel™ based tool called the Tool for the Evaluating Resource Recovery (TERRY), which allows users to perform a site-specific business case evaluation and payback scenario of the treatment options by considering 13 factors listed in Table 7 (Latimer *et al*., 2015t). Fact sheets describing an array of struvite harvesting technologies are also available within the tool so that users can compare and contrast competing options.

Experimental Evaluations Of Emerging Concepts

During anaerobic digestion, the nutrients that are released tend to form inorganic compounds that precipitate. This unintentional precipitation not only causes scale formation, but also results in less than 10% of the released nutrient remaining soluble and available for extraction. This lack of nutrient availability can limit the effectiveness of recovery processes that utilise crystallisation.

One alternative that has been implemented involves the use of waste-activated sludge phosphorus release preceding anaerobic digestion. However, not all plants have the capability to include a dedicated mixing tank and separate dewatering facility. A more attractive option for these plants would be the suppression of P precipitation until the stream enters the struvite crystallisation reactor. Two anaerobic digester operating strategies were tested by the University of Queensland, a project partner, to enhance phosphorus solubility: (1) depressed pH; and (2) use of complexing/chelating agents. The outcome of this research, which was co-funded by Grain Research Development Corporation (GRDC), Australia, is summarised below. Details may be found in Mehta *et al.* (2015).

Impact of pH depression on phosphorus solubility

Laboratory-scale experiments were conducted to determine the impact of depressed pH on P availability for struvite crystallisation. Results confirmed that P solubility under acidic conditions (pH < 5.7) was 3.6 times higher than under neutral conditions. However, methane production under acidic conditions was approximately 65% per cent lower compared to that at pH 7. *Methanosaeta* dominated the microbial population and was not influenced by pH. However, the reduction in pH caused a shift and narrowing in bacterial diversity towards *Clostridium* within the hydrogen utilising methanogens.

Impact of chelating agents and ion exchange resins on phosphorus solubility

Batch assessments of adding chelating agents and cation exchange resins on P availability revealed that, in general, chelating agents were more effective than ion exchange resins in increasing the amount of P solubilised during testing. In addition, chelating agents have the potential to enhance sludge dewaterability, which can result in operating cost savings. In a hypothetical scenario where benefits to P recovery and sludge dewaterability (through offset of polymer addition) are considered, an operating cost offset between 16% and 20% will be needed to make the addition of chelating agents economically viable (assuming polymer cost of $1.00/kg and polymer dose of 9 kg/dry tonne).

The laboratory assessment was extended to include MIEX resin, a magnetically charged complexing agent. The results suggest that P was bound to the resin, most likely due to the presence of iron (magnetic) in the resin. This implies that MIEX could be used to recover P directly from the digester contents, followed by regeneration of the resin.

On-going research

Crystallisation is the only mature P extraction technology that is currently available for implementation. In an effort to identify other viable recovery mechanisms, research is being conducted at the University of Queensland to evaluate electrodialysis. In this process, an electric current is used to separate anions and cations across an ion exchange membrane, making it possible to recover multiple ionic products (e.g. nitrogen, potassium, etc.) downstream of struvite recovery. Recovery of potassium is of particular interest, since its presence is known to cause poor sludge dewaterability by blocking negative sites in a floc, thereby stabilising the colloidal suspension. This could result in a substantial increase in polymer use and decrease in sludge dewaterability and cake solids content. Results of this on-going evaluation were to be reported in the final WERF report, scheduled to be released in 2015 (Latimer *et al*., 2015c).

CONCLUSION

Population explosion and rapid urbanisation are forcing us to go from a comfortable position of abundant resources to a stressful position of scarcity. Wastewater treatment plants of the future will continue to remain true to their core objectives of public health and environmental protection. However, in order to be sustainable, current practices must evolve drastically to cope with the practical realities of the 21st century and beyond, and transformational changes are needed in how we manage our wastewater. Disruptive technologies such as extractive nutrient recovery are essential for the paradigm shift to occur and to align with the Basins of the Future, which strives to optimise the linkages between water, food and energy. The WERF study reported in this paper disseminates seminal practical information that bridges the knowledge gap and enables the advancement of extractive nutrient recovery.

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