Transforming Biosolids

Nutrient recovery from wastewater and biosolids in Australia

Potential, challenges and way forward

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About the report

The ARC Training Centre for the Transformation of Australia's Biosolids Resource has a primary goal of delivering world-class and innovative technological solutions and knowledge, to train the next generation of biosolids practitioners in cutting-edge, transformational approaches, and to guide best practice in the biosolids sector. A key project delivered by the Centre was ensuring sustainability in biosolids management by exploring the role of Biosolids Management in preserving Earth's resilience (Project 3B). The project used tailored sustainability assessment frameworks to quantify the environmental, economic and social impacts of key biosolids treatment alternatives. The assessments included carbon, water, energy and nutrient management, life cycle assessments. This report presents the results pertaining to nutrient recovery studies. For further information visit: www.transformingbiosolids.com.au

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Executive summary

Global food demand is expected to rise by up to 60% between 2019 and 2050, [12,13] significantly increasing the need for nutrients in agriculture. Recovering nutrients from municipal wastewater for fertiliser offers a promising solution because it can reduce dependence on synthetic fertilisers, minimise environmental pollution by nutrients, and support a circular nutrient economy. This research evaluated Australia's current nutrient recovery efforts from wastewater and biosolids using a literature review and a survey of the water industry. It highlights; 1) Where Australia currently stands, 2) What are the challenges for nutrient recovery, 3) How Australia can advance its wastewater nutrient recovery. By applying the insights from this report, utilities can better plan for enhanced nutrient recovery, and policymakers can develop strategies to support national-level improvements

Key results

1) Why the Australian wastewater industry needs to care about nutrient recovery is two facetted:
   i. We need the nutrients for agricultural production. Australian soils are nutrient-deficient, and recovering phosphorus from wastewater can contribute to the 450 kt of phosphorus fertiliser used in the country.
   ii. Recovery of nutrients from the side stream can reduce phosphorus loading to the plant headworks by up to 50%, generating significant economic savings.

2) Where does Australia stand in nutrient recovery
   i. Nutrient recovery from wastewater is not yet a priority in Australia
   ii. Despite the clear potential, transitioning wastewater systems from a focus solely on pollutant removal to integrated resource recovery remains a major challenge in Australia.
   iii. Wastewater utilities often operate in silos, relying heavily on technological solutions without feeling the need to address broader socioeconomic, sustainability and policy factors beyond their immediate scope.
   iv. Although technologies for nutrient recovery are generally well established, their adoption remains limited.

3) Opportunities for improving nutrient recovery in Australia
   i. Increasing nutrient recovery during wastewater treatment using:
      - Enhanced Biological Phosphorus Removal (EBPR) for phosphorus recovery
      - Nitrogen assimilating heterotrophs for nitrogen recovery in high chemical oxygen demand (COD) wastewater
      - Nitrogen assimilating autotrophs for nitrogen recovery from low-COD wastewater
   ii. Recovering nutrients from the sidestream
      - Controlled struvite crystallisation can recover 71–96% of sidestream phosphorus, equating to approximately 491 ± 64 tonnes per year and generating up to $150,000 in annual revenue from a single WWTP[2].
      - Sidestream nitrogen recovery can be economically viable in streams with high ammonia concentrations. Technologies like struvite precipitation, air stripping, steam stripping, ion exchange and hollow fibre membrane contactors can be used.
   iii. Recovering nutrients from stockpiled biosolids
      Australian biosolids stockpiles contain an estimated 65,000 tonnes of phosphorus and 117,000 tonnes of nitrogen, a substantial nutrient reserve.

4) Way forward for enhancing wastewater nutrient recovery in Australia

The way forward for Australia to increase nutrient recovery from wastewater involves three interrelated aspects, including:

i. Shifting Mindsets to prioritise nutrient recovery for a sustainable future

As Australia's wastewater sector evolves, a fundamental shift in mindset is needed to one that positions nutrient recovery as a central pillar of sustainable wastewater and biosolids management.

In shifting mindsets about nutrient recovery, the cost-benefit analysis needs to go beyond financial costs and benefits to include the carbon intensity of raw fertiliser production compared to nutrient recovery from wastewater and biosolids. Generally, nutrient recovery from wastewater sidestreams can reduce carbon intensity by 70–95% for nitrogen and 50–80% for phosphorus compared to conventional manufacturing, which is highly carbon-intensive.

ii. The role of policy in driving change

The responsibility for increasing nutrient recovery should not rest solely with individual wastewater utilities. Instead, it requires coordinated action at the state and national levels. Policymakers have a critical role to play in creating the right incentives and regulatory frameworks.

iii. Learning from global Leaders

Countries that have successfully integrated nutrient recovery into mainstream wastewater treatment have done so through strong policy support, market development for recovered products, and cross-sector collaboration.

1. Introduction

Global food demand is expected to rise by up to 60% between 2019 and 2050, [12,13] significantly increasing the need for nutrients in agriculture. However, due to growing environmental and climate challenges, it is essential to supply these nutrients sustainably to maintain both food security and ecological resilience. Recovering nutrients from municipal wastewater for fertiliser offers a promising solution. It can:

1. Reduce dependence on synthetic fertilisers,
2. Minimise environmental pollution by nutrients, and
3. Support a circular nutrient economy.

Compared to solid waste, municipal wastewater is easier to collect, transport, and treat, making it a more efficient source for recovering nitrogen and phosphorus [14]. Additionally, municipal wastewater typically has higher nutrient concentrations than solid waste; three times more N and four times more phosphorus have been reported[15]. Individual wastewater treatment plants (WWTPs) have reported high nutrient loads, 103-264 tonnes of phosphorus [2,3,14] and 204-1161 tonnes of nitrogen per year [3,16,17]. Additionally, municipal wastewater carries significant amounts of carbon, ranging from 2,000 to 8,600 tonnes/yr [16,18,19], which can be recovered for agricultural use or energy production [20]. Recovering carbon also helps reduce greenhouse gas emissions.

Because of its high nutrient content and ease of collection, wastewater treatment is a key area for nutrient recovery for enhance of agricultural production. In fact, nutrient recovery can also be beneficial to the WWT plants as it has been shown to lower treatment costs [21]. For example, recovering phosphorus instead of removing it can save approximately USD 2.22–3.33 per kgP [22]and reduce energy use by about 27% [23]. As a result, there is a growing movement to transform WWTPs from basic treatment facilities into resource recovery centres. This shift involves moving from nutrient removal to nutrient recovery [24,25]. However, achieving this goal requires balancing multiple, sometimes conflicting, factors. The focus should be on recovering nitrogen, phosphorus and carbon efficiently and sustainably. Economic, social, policy, and technological considerations must also be addressed at plant, regional, and national levels.

This research evaluated Australia’s current nutrient recovery efforts from wastewater and biosolids and explored:

1. Where Australia currently stands,
2. What are the challenges for nutrient recovery,
3. How Australia can advance its wastewater nutrient recovery.

By applying the insights from this report, utilities can better plan for enhanced nutrient recovery, and policymakers can develop strategies to support national-level improvements

1.1. Our approach

This section presents findings from a combination of methods, including a literature review and a survey of water utilities (Box 1).

The literature review evaluated the effectiveness of various municipal wastewater treatment (WWT) systems and biosolids management approaches for integrated recovery of nitrogen (N), phosphorus (P), and carbon (C).

The review provided recommendations for energy-efficient treatment configurations and examined nutrient flow pathways, identifying opportunities and challenges for improving recovery based on recent studies.

The industry survey, conducted between July and September 2024, aimed to understand current nutrient recovery practices and priorities within the Australian wastewater sector.

Invitations were sent to industry partners, the training centre, and professional groups including IWN, ANZBP, WIOA, WaterRA, and the Queensland Water Directorate.

Of the 34 responses received, 16 contained sufficient data for inclusion in the results.

Box 1: The approach used for this study

The report also incorporates insights and conclusions drawn from nutrient recovery conferences attended by the research team.

2. Why care about nutrient recovery?

2.1. We need the nutrients in the wastewater

Phosphorus is a **non-renewable resource** with no known substitute, making its recovery critically important[26]. Current estimates suggest that global phosphate rock reserves could be depleted within 61 to 131 years if extraction continues at current rates [27], but this estimate varies greatly in literature. Recovering phosphorus from wastewater, at both local and national levels, can help reduce dependence on mined phosphate, buffer against supply disruptions caused by geopolitical instability, and mitigate the impact of rising fertiliser prices [28,29].

Recovering phosphorus from wastewater can make a significant contribution to meeting the global demand of 15.1 million tonnes of phosphorus required for food production [30]. This not only supports agricultural productivity but also enhances environmental sustainability and the planet's resilience. Assessment of phosphorus supply from biosolids and other organic sources has shown promising results for different countries (Box 2).

In Austria, it was estimated that phosphorus in biosolids could potentially replace about 70% of the mineral phosphorus fertiliser used annually [5].

In Norway, it was shown that that with improved distribution, the phosphorus contained in biosolids and animal manure could fully meet the country's fertiliser need [6].

In Denmark, up to 35% of mineral phosphorus fertiliser imports could be replaced by the combined amounts of phosphorus in the country's biosolids and organic household waste

Box 2: Phosphorus supply from biosolids and other organic sources in Austria, Norway and Denmark

Australian soils are typically low in phosphorus, making fertiliser application essential for maintaining high agricultural output. Around 450 kt of P fertiliser are used annually to for agriculture production to ensure food security [29]. Therefore, efficient use and recovery of phosphorus are vital for improving farm profitability and managing future fertiliser costs.

Recovering phosphorus from wastewater in Australia could play a key role in stabilising supply, reducing import dependence, and supporting sustainable agriculture in the face of global uncertainties [28]. The wastewater phosphorus is even greater when the system boundary is expanded from just biosolids to include the WWT stage.

Similarly, recovering nitrogen from wastewater offers significant benefits. It reduces reliance on synthetic nitrogen fertilisers produced via the energy-intensive Haber-Bosch process, which consumes about 2.5% of global fossil energy [31]. In fact, if all the nitrogen in municipal wastewater worldwide were recovered, it could supply up to half of the global nitrogen fertiliser demand [32].

2.2. To reduce treatment costs

Recycled sidestreams contribute 25–50% phosphorus to influent

The recycling of sidestreams in WWT plants presents a significant operational challenge due to the release of nutrients from biosolids back to the soluble phases during biosolids digestion. This process can effectively reintroduce nutrients that were previously removed, thereby increasing the influent nutrient load.

Studies have shown that recycled sidestreams can contribute between 25% and 50% of the total phosphorus load entering the headworks of WWT plants. [1-4]. If not properly managed, these elevated nutrient levels can lead to process instability, including reactor shock and upset conditions [8].

To mitigate these risks, phosphorus recovery from sidestreams has emerged as a viable strategy. By recovering phosphorus before recycling, WWT plants can reduce influent phosphorus loads by up to 50%, resulting in significant economic savings and improved process stability[1]. As a result, there is a growing research interest and technological developments to reduce the sidestream nutrient loads[11].

"By recovering phosphorus from the sidestream, the phosphorus load in the influent of WWTP may be reduced by up to 50% where the sidestream is recycled, representing a significant economic saving."

3. Where does Australia stand in nutrient recovery?

Globally, the recovery of phosphorus from wastewater for agricultural use remains limited. Although wastewater contains approximately 3 million Mt P per annum globally, which could supply up to 20% of global agricultural demand, most of this valuable resource is lost. In Australia, for instance, wastewater holds around 18,000 t P per year, yet only 4% (720 tonnes) of the national phosphorus demand is met through recovery. Unfortunately, about 9 kt P are discharged into the ocean annually, representing a significant loss [33].

Despite the clear potential, transitioning wastewater systems from a focus solely on pollutant removal to integrated resource recovery remains a major challenge in Australia [34]. While research increasingly highlights the importance of nutrient recovery, particularly from side streams, implementation across the industry is still limited. This is probably due to the high costs of retrofitting infrastructure and the complexity of integrating new technologies into existing systems, which were not originally designed for multifunctional outcomes like wastewater treatment, nutrient recycling, and energy generation.

Moreover, wastewater utilities often operate in silos, relying heavily on technological solutions without feeling the need to address broader socioeconomic, sustainability and policy factors beyond their immediate influence [34]. This disconnect hinders the practical application of innovative research. To bridge this gap, stronger collaboration between researchers and industry stakeholders is essential. Research must be aligned with the operational realities and policy environments of utilities, ensuring that innovations are both practical and scalable.

Hence, although technologies for nutrient recovery are generally well established, their adoption remains limited. This suggests that the primary barrier is not technical feasibility, but rather institutional, regulatory, and economic challenges. Wastewater and biosolids management involve complex and sometimes conflicting objectives, making it difficult for utilities to prioritise nutrient recovery without broader systemic support.

1.1 Decision-making about nutrient recovery

The insights presented in this section are derived from an industry-wide survey of Australian water utilities. The findings reflect current operational practices, decision-making frameworks, and the level of priority given to nutrient recovery within wastewater treatment and biosolids management.

Survey results indicate that **nutrient recovery is not yet a strategic priority** for most utilities in Australia. This may be attributed to the prevailing view that the primary role of wastewater utilities is to ensure effective treatment and safe discharge, with resource recovery considered a secondary objective.

To paraphrase a participant at the 2024 Nutrient Removal and Recovery conference in Brisbane, Australia "**The primary objective of the wastewater industry is to ensure that wastewater is safe to return to the environment and hence their main mandate is to protect the health of humans and the environment from the contaminants and nutrients in the wastewater. This is a duty that only the utilities can serve and they cannot afford to take the focus off that onto other functions, especially with specified budgets that they have to work within**."

This phrase highlights the mindset of utilities regarding nutrient recovery, showing a roadblock to increasing recovery efficiency, but also points to a way of increasing nutrient recovery. To move toward more sustainable wastewater management, decision-making must evolve to incorporate environmental, economic, and social impacts across spatial and temporal scales[35].

This includes evaluating the fertiliser value of recovered nutrients, their market price, and availability in the agricultural sector.

A shift in focus is needed to one that integrates nutrient recovery into core utility operations and planning. This will require not only technological innovation but also policy support, economic incentives, and cross-sector collaboration to align recovery efforts with broader sustainability goals

Review of the nutrient recovery efficiency of the water treatment processes.	Plans to enhance nutrient recovery water treatment processes.
Seven utilities occasionally (when the need arises) but what constitutes or informs the need for review was not specified. 4 utilities review annually (2) or in 3-5 years. 3 utilities have never had a review of the nutrient recovery efficiency, 18 utilities gave no responses.	1 utility- Within the next 3 years (Upgrade an older setup to improve aeration control) 3 utilities- within the next 6 years -Examining biochar-based options to improve recovery of most nutrients. Retrofit of bioreactor to include internal walls and replacement of surface aeration with diffused air and also introduction of bio-phosphorus removal 2 utilities- within the next 9 years (Struvite recovery & no clear plan, other than circular economy focus) 1 Utility in more than 10 years 8 utilities have no immediate plans to improve nutrient recovery 18 utilities gave no response

Table 1: Results of the industry survey showing the decision-making processes for enhancing nutrient recovery

4 Opportunities for increasing nutrient recovery in Australia

4.1 Recovery during wastewater treatment

All 16 utilities that provided valid responses during the industry survey selected agricultural applications as the main end use of biosolids targeted. Four utilities selected it as the sole target, highlighting the importance of retaining nutrients in biosolids while treating wastewater.

4.1.1 Phosphorus recovery

Biosolids offer multiple reuse pathways, but their application as soil amendments and fertilisers remains the most cost-effective and sustainable method for reclaiming their carbon and nutrient content[36]. To maximise fertiliser value, it is essential to retain as much phosphorus as possible during both WWT and biosolids processing.

Research has shown that combining chemical precipitation with biological processes yields the highest phosphorus recovery rates, up to 99% from the effluent [2,37,38]. Among these, Enhanced Biological Phosphorus Removal (EBPR) is gaining traction due to its high efficiency, lower operational costs, and reduced sludge production compared to chemical methods [39]. EBPR also has a significantly lower greenhouse gas footprint, with global warming potentials reported at 3,609 kg CO_2-e per 37,854 m^3 of treated wastewater, compared to 5,622 kg CO_2-e for chemical recovery [40].

EBPR can remove up to 90% of phosphorus, which is 20–50% more than conventional activated sludge systems. Importantly, all phosphorus removed via EBPR is retained in the biosolids, resulting in concentrations that are 2–5 times higher than those from chemical precipitation. EBPR biosolids typically contain 5–7% phosphorus by dry weight, compared to 1–2% in conventional sludge [41]. Moreover, the phosphorus in EBPR biosolids has been shown to be as effective as mineral fertilisers for plant growth [42], whereas phosphorus bound to aluminium or iron in chemically precipitated biosolids is less bioavailable [37,43].

Despite these advantages, EBPR adoption in Australia remains low, highlighting a disconnect between the potential of phosphorus recovery technologies and their actual implementation. One contributing factor is that downstream sludge management operations heavily influence the effectiveness of phosphorus recovery. While EBPR technology is well established, further development is needed in post-treatment processes that release and recover phosphorus from microbial biomass [42]. To unlock the full potential of phosphorus recovery, the industry needs to address this gap through targeted research, infrastructure investment, and integrated system design.

4.1.2 Nitrogen recovery

Current Biological Nutrient Removal (BNR) technologies primarily focus on removing nitrogen by converting ammonia into nitrogen gas (N_2), which is then released into the atmosphere. While effective for pollution control, this approach results in the loss of reactive nitrogen, which could otherwise be recovered and reused as a fertiliser substitute, a more sustainable and economically beneficial outcome [44].

Recovering nitrogen, particularly in a reactive form, supports circular economy goals by reducing reliance on synthetic fertilisers. However, nitrogen recovery from the main wastewater stream is technically challenging due to its low concentration, which requires high energy input for extraction and concentration [25,45]. As a result, most WWT plants are optimised for nitrogen removal rather than recovery, leading to significant nitrogen losses and missed opportunities for agricultural reuse.

Among BNR technologies, anaerobic ammonium oxidation (anammox) stands out for its energy efficiency. It removes reactive nitrogen autotrophically, without adding carbon or oxygen [46], and can eliminate over 80% of total nitrogen from wastewater [47]. However, like other removal-based methods, anammox ultimately returns nitrogen to the atmosphere, rather than capturing it for reuse.

To enhance sustainability, the industry must shift focus from nitrogen removal to nitrogen recovery, supported by innovations in downstream processing and energy-efficient recovery technologies. For more energy-efficient nitrogen recovery, WWT could move towards the use of nitrogen-assimilating organisms, which provide a promising alternative to improve mainstream nitrogen recovery [48,49]. Additionally, utilities can focus on nitrogen recovery from the sidestream as a start.

"Although, anammox is effective for energy-efficient nitrogen removal, it serves a contradictory role in nitrogen recovery. Therefore, a critical question is posed: In the strive to transform WWTPs into resource recovery centres, what is the role of anammox? Despite the long way that WWTPs in most countries have to go to achieve the transformations, it is a question worth considering now to make the necessary adjustments as the redesign of already established infrastructure can take many years and considerable capital. Other key areas for improving the sustainability of BNR processes are energy neutrality, cost-effectiveness and low carbon footprint[9]. Hence, further development and research of nitrogen recovery technologies ought to pay attention to these aspects."[10]

Box 3: Role of anammox in nitrogen recovery

4.1.3 Integrated recovery of nitrogen and phosphorus

An integration of enhanced biological phosphorus removal with nitrogen-assimilating heterotrophs is proposed for energy-efficient recovery of the three nutrients from wastewater with high chemical oxygen demand (>550 mg/L), with potential average recovery rates of 90%, 79% and 67% for phosphorus, nitrogen and carbon, respectively [10]. In low chemical oxygen demand (<350 mg/L) systems, the sequential or combined application of chemical precipitation and phototrophic nitrogen-assimilation offers a viable approach to enhance integrated nutrient recovery.

For the integrated recovery of phosphorus, nitrogen and carbon, the complexity of nutrient interactions during WWT is the most critical hindrance to achieving it, and trade-offs may be necessary. However, prioritising which nutrients to recover can be complex because of the interrelationships among nutrients and the benefits of recovered nutrients. Generally, phosphorus has been highlighted as the most valuable nutrient in biosolids, and hence its recovery should be prioritised when resources are limited for nutrient recovery.

4.2 Recovering nutrients from the sidestream

Sidestreams in WWT plants offer a highly efficient pathway for nutrient recovery, thanks to their high nutrient concentrations and low volumes. This makes them particularly suitable for targeted recovery of nitrogen and phosphorus, with lower energy and operational costs compared to mainstream treatment. Phosphorus can be recovered from sidestreams using chemical precipitation. Coagulation with aluminium or iron salts enables complete recovery of phosphorus from the liquid phase and also helps control hydrogen sulphide (H_2S) levels during anaerobic digestion [50]. However, iron-based precipitation can bind phosphorus in forms that are less bioavailable, limiting its agricultural reuse [28].

Struvite is widely regarded as the most effective compound for phosphorus recovery due to its low chemical binding, high fertiliser value, and low contaminant levels [51,52]. It is a slow-release fertiliser mostly applied for turf production, speciality horticulture and plant nurseries and can be blended with other inorganic fertilisers for sale [53]. Struvite recovery technologies are already commercially available and have been successfully implemented in countries like the Netherlands and Japan [54,55]. Controlled struvite crystallisation can recover 71–96% of sidestream phosphorus, equating to approximately 491 ± 64 tonnes per year and generating up to $150,000 in annual revenue from a single WWTP[2].

Sidestream nitrogen recovery is also economically viable, especially in streams with high ammonia concentrations (≥ 200–1,000 mg NH_4^+/L). Technologies such as struvite precipitation, air stripping, steam stripping, ion exchange, hollow fibre membrane contactors and microbial electrochemical cells can be used to recover pure or concentrated ammonia, suitable for reuse as fertiliser or industrial feedstock [4,25,56].

4.3 Recovering nutrients from stockpiled biosolids

Australia's wastewater sector holds a largely untapped resource in the form of stockpiled biosolids, which have accumulated over decades of treatment operations. These biosolids are rich in phosphorus and nitrogen, which are essential for agricultural productivity. In 2023, it was reported that approximately 2.6 million tonnes of biosolids were historically stockpiled across the country, with significant proportions in states like Victoria (32%) and Western Australia and the Northern Territory (14.8%) [57].

These stockpiles contain an estimated 65,000 tonnes of phosphorus and 117,000 tonnes of nitrogen, a substantial nutrient reserve. If recovered and reused, these nutrients could significantly reduce

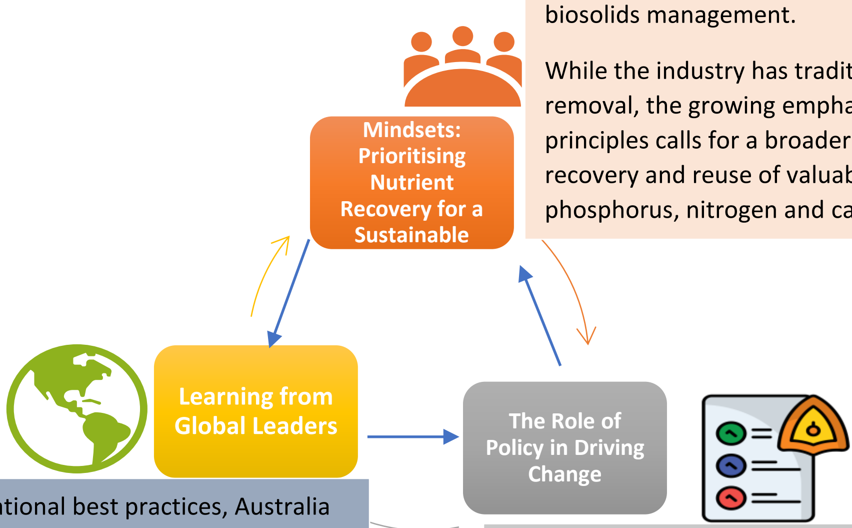
reliance on synthetic fertilisers and support circular-economy goals in the wastewater and agricultural sectors. Based on recent market prices [58], for example, monoammonium phosphate (MAP) and diammonium phosphate (DAP) trading around AUD $1,300–$1,360 per tonne and nitrogen fertilisers such as urea around AUD $880–$900 per tonne in Australia (2025-26), this nutrient reserve represents hundreds of millions of dollars in potential fertiliser value(AUD $400–$600 million for phosphorus and $150–$300 million for nitrogen) if transformed into saleable products rather than lost as waste inputs. This underscores the need for investment in nutrient recovery technologies, particularly those that can be integrated with biosolids management strategies, including pre- and post-treatment processes for thermal systems.

5 Way forward for Australia

The way forward for Australia increasing nutrient recovery from wastewater involves three interrelated aspects including: Shifting Mindsets to prioritising nutrient recovery, the role of policy in driving change and learning from global Leaders.

As Australia's wastewater sector evolves, a fundamental shift in mindset is needed to one that positions nutrient recovery as a central pillar of sustainable wastewater and biosolids management.

While the industry has traditionally focused on pollutant removal, the growing emphasis on circular economy principles calls for a broader approach that includes the recovery and reuse of valuable resources such as phosphorus, nitrogen and carbon.



Examining international best practices, Australia can benchmark its progress and identify effective strategies for scaling up nutrient recovery. Countries that have successfully integrated nutrient recovery into mainstream wastewater treatment have done so through strong policy support, market development for recovered products, and cross-sector collaboration.

Embracing these lessons will be key to unlocking the full environmental and economic potential of nutrient recovery in Australia. Adopting international practices that are locally relevant needs industry involvement.

The responsibility for increasing nutrient recovery should not rest solely with individual wastewater utilities. Instead, it requires coordinated action at the state and national levels. Policymakers have a critical role to play in creating the right incentives and regulatory frameworks.

A recommended approach is to introduce nutrient recovery credits, where utilities earn financial or regulatory benefits for each unit of phosphorus or nitrogen recovered and reused. Such mechanisms would shift the economic equation in favour of recovery over removal, aligning utility operations with national sustainability goals. On the other side punitive measures for noncompliance are also needed.

In shifting mindsets about nutrient recovery, the cost-benefit analysis needs to go beyond financial costs and benefits to include the carbon intensity of raw fertiliser production compared to nutrient recovery from wastewater and biosolids. Generally, nutrient recovery from wastewater sidestreams can reduce carbon intensity by **70–95% for nitrogen** and **50–80% for phosphorus** compared to conventional manufacturing, which is highly carbon-intensive. Nitrogen fertilisers manufactured via the Haber–Bosch process typically emit 2.5–5.5 t CO_2-e per tonne of ammonia (depending on the natural gas or coal feedstock). When converted into urea, emissions remain high at approximately 1.5–3.0 t CO_2-e per tonne of urea. These emissions arise from both the large energy demand of ammonia synthesis and the direct release of CO_2 during fossil-fuel reforming [59]. Similarly, phosphorus fertilisers derived from mined phosphate rock incur substantial embodied emissions from extraction, beneficiation, sulphuric acid production, and granulation. Life-cycle assessments generally estimate 0.3–0.6 t CO_2-e per tonne of MAP/DAP (mono-/diammonium phosphate), with higher values when long-distance transport is included [60].

In comparison, recovering nitrogen and phosphorus from wastewater treatment plant sidestreams, such as through struvite precipitation, air/steam stripping, ion exchange, or membrane contactors, typically exhibits much lower carbon intensity. Most recovery pathways fall within **0.05–0.20 t CO_2-e per tonne of recovered fertiliser product**, largely because the nutrients already exist in concentrated form and recovery offsets both (1) upstream fertiliser manufacturing and (2) downstream treatment burdens such as nitrification–denitrification energy demand.

In learning from global leaders, a good example is the Amersfoort WWT plant in the Amsterdam, owned and operated by the Dutch water board and run as an energy and nutrient factory using innovative approaches to recover nutrients after upgrades to their existing wastewater and sludge processing facilities [61]. This facility is a great example of combining shifting mindsets about the role of WWTPs and different entities working together to take responsibility for enhancing nutrient recovery at a regional level.

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