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# Platforms for energy and nutrient recovery from domestic wastewater: A review

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## HIGHLIGHTS

- The increasing cost of energy and essential plant nutrients require a shift towards resource recovery.
- Options are low energy mainline (LEM) and partitioning to a solid phase through biological growth.
- LEM generates energy, while partitioning is energy consuming, but can recover nitrogen.
- LEM is more mature, and is likely to see increased application in the short term.

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## ABSTRACT

Alternative domestic wastewater treatment processes that recover energy and nutrients while achieving acceptable nutrient limits ($<5\ \mathrm{mg\ N\ L^{-1}}$) are a key challenge. Major drivers are value and availability of phosphorous, nitrogen, and potassium, and increasing energy costs. The two major platforms that can achieve this are (a) low energy mainline (LEM), with low strength anaerobic treatment, followed by mainline anaerobic nitrogen removal and chemical or adsorptive phosphorous removal and (b) partition–release–recover (PRR), in which carbon and nutrients are partitioned to solids through either heterotrophic or phototrophic microbes, followed by anaerobic digestion of these solids and recovery from the digestate. This paper reviews practical application of these processes, with a focus on energy costs. Compared to conventional processes which require $0.5\ \mathrm{kW\ h\ kL^{-1}}$ electricity ($500\ \mathrm{mg\ COD\ L^{-1}}$ influent concentration), PRR requires only $0.05\ \mathrm{kW\ h\ kL^{-1}}$ electricity. LEM offers the possibility to recover $0.1\ \mathrm{kW\ h\ kL^{-1}}$ as electricity with net energy generation above $400\ \mathrm{mg\ COD\ L^{-1}}$ influent, while PRR becomes energy generating at $>650\ \mathrm{mg\ COD\ L^{-1}}$. PRR offers the possibility for recovery of nitrogen and other nutrients (including potassium) through assimilative recovery. However, the energetic overhead of this is substantial, requiring $5\ \mathrm{kW\ h\ kg\ N^{-1}}$ as electricity, which compares to ammonia fixation costs. The lower energy costs, and near to market status of LEM treatment make it likely as a recovery platform in the shorter term, while ability to recover other elements such as nitrogen and potassium, as well as enhance favourability on concentrated wastewaters may enhance the desirability of partitioning in the longer term.

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## 1. Introduction

Domestic wastewater treatment is now an extremely mature technology from the point of view of human health, and environmental impact. This is because wastewater can be treated to a sanitised, low or zero impact waste for $<0.6\ \mathrm{kW\ h\ kL^{-1}}$ ($N<5\ \mathrm{mg\ N\ L^{-1}}$, $P<1\ \mathrm{mg\ P\ L^{-1}}$) (Foley et al., 2010), with potable recycled water being produced from domestic wastewater for $<2\ \mathrm{kW\ h\ kL^{-1}}$ (Pearce, 2008). Overall, given the volumes, range of contaminants, and stringent goals involved in wastewater treatment processes, it is a remarkable success that society is able to manage its liquid wastes so effectively. Over the past 20 years though, a number of major drivers have emerged that emphasize the need to improve recovery of the resources available in wastewater. These are water itself, energy, and nutrients. The current activated sludge paradigm for wastewater treatment requires a substantial amount of energy (approximately 50% (Foley et al., 2010)) for aeration. This is a limit

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imposed by the longer sludge ages necessary to retain nitrification and denitrification capacity (Tchobanoglous et al., 2003). Organic nitrogen is effectively destroyed (converted to nitrogen gas) by nitrification and denitrification, and chemical energy is required by the denitrification process. Phosphorous can be recovered in the sludge, but this is bulky and contaminated with organics, and occasionally metals (Yuan et al., 2012), and if aluminium sulfate is used for phosphate trimming or clarification, it can have restricted plant availability (Pritchard et al., 2010).

While electricity costs have not changed substantially in the last 10 years, there have been a number of pricing and management changes that have decreased the favourability of constant loads such as wastewater treatment and there is a high degree of uncertainty in future pricing (to 2035) due to changes in energy generation methods that may need load-generator balancing (DOE/EIA-0484, 2010). There is also likely to be a high degree of international variation in energy pricing, particularly where there is a transition in energy sources such as in Japan (DOE/EIA-0484, 2010), or where supply is constrained, but growth is not. As an example, Australian Energy Market Commission forecasts an increase in residential electricity prices of around 22% or 8.34 cents per kW h in the period from 2010–2011 to 2013–2014 (AEMC, 2011) The high degree of uncertainty, as well as various drivers at the national level mean that there is an urgent need for alternative low energy wastewater treatment options.

Natural gas pricing in particular is highly variable, has doubled in the last 10 years, and is expected to double again to 2025 (DOE/EIA-0484, 2010). This is directly driving an increase in commercial nitrogen pricing, as ammonia is manufactured using the Haber–Bosch process using electrons derived from natural gas (Appl, 2000). 60% of the cost of ammonia is natural gas costs, and nitrogen manufacturing utilises 1–2% of the world's energy supply (Smil, 2001) (dwarfing the energy costs of wastewater treatment). Natural gas price increases, as well as an increase in demand have driven ammonia prices from a low of \$150 tonne$^{-1}$ in 1998–2000 to its current pricing of approximately \$600 per tonne (DiFrancesco et al., 2010; Fertecon, 2013a).

As a reference, current world fertilizer consumption (2013 projection) is 111 MT nitrogen as N, 19 MT phosphorous as P, and 26 MT potassium as K (FAO, 2008). Depletion and availability of phosphates, as well as market fluctuation have been recently addressed extensively in the public arena and scientific literature (Cordell et al., 2009), with peak phosphorous likely to occur within the next 50 years, and as early as 2035 (Cordell et al., 2009). Pricing has also fluctuated strongly in the past 10 years, rising to \$4000 tonne$^{-1}$ P in 2009, and currently sitting at \$2000 tonne$^{-1}$ P (calculated from DAP pricing in Fertecon (2013b)). Pricing increases, as well as a focus on reducing wastewater treatment costs have driven a substantial increase in research in, and commercial application of phosphorous recovery from concentrate streams, mainly through magnesium ammonium phosphate (struvite) crystallization in dewatering reject streams (Le Corre et al., 2009; Yuan et al., 2012).

There has been almost no discussion of potassium as a macronutrient target for recovery in the literature. This is perhaps at current consumption rates, there are some 330 years of reserves (Jasinski, 2011), and pricing has historically been <\$500 tonne$^{-1}$ K (Fertecon, 2013c), which given its moderate consumption level, has not effected a substantial economic impact on farming compared with phosphorous. However, long-term pricing has doubled over the last 10 years to \$1000 tonne$^{-1}$ K (Fertecon, 2013c), and is projected to substantially rise in the next 10 years. This does not account for the accelerated depletion being seen in intensive grain areas, or its accelerated use to make potassium depleted soils viable (Peverill et al., 1999). There are concerns for developing countries for long term availability and self-reliance on potash based conventional fertilizers (Manning, 2010). This is because potash ores have a limited geological distribution, with the bulk of the world's potash mined in Canada and Europe (Jasinski, 2012).

The amount of nutrients available in wastewater are substantial. Phosphorous inventories have been best quantified, and globally, (Cordell et al., 2009) estimated that 20% of the mineral phosphorous consumed is excreted by humans (and hence recoverable). Including domestic animals, the mineral phosphorous market could technically be fully supplied from excreta streams, though much of the waste is currently recycled as manure from grazing animals and is hence not practically or beneficially recoverable. Long-term, additional environmental or geological input is required, though this could be on a much lower level. On a national level, waste derived phosphorous availability depends heavily on agricultural fertilizer consumption and food exports. An extreme case is Australia, where some 5% of the phosphorous can be recovered from domestic effluent, and a total of 20% from humans and domestic animals (Tucker et al., 2010). This is reversed in food sink nations with large domestic animal populations, such as the Netherlands, where manure must be exported to maintain national mineral balances (Henkens and Van Keulen, 2001). Availability of nitrogen and potassium have not been assessed in the same level of detail, but nitrogen:phosphorous mass ratio in wastewaters are on the order of 3:1–5:1 (Tchobanoglous et al., 2003; Tucker et al., 2010), indicating that a far higher proportion of applied and naturally assimilated nitrogen is lost during consumption and treatment. There are generally large amounts of potassium available in specific wastes such as sugar cane processing, spent grains, yeast, and manure and processing byproducts from animals fed with grains and legumes (Tucker et al., 2010). As a global picture, phosphorous (Cordell et al., 2009, 2011) can be largely serviced from waste streams, with likely moderate environmental, and minimum geological input, potassium fully serviced from waste, while approximately 50% of the nitrogen market could be serviced from waste streams (assuming 4:1 N:P average concentration).

### 1.1. Towards resource recovery from wastewater treatment

Addressing global nutrient needs, as well as recovering energy and water from wastewater streams are powerful drivers for change in the wastewater industry. This has led to two major position papers for novel domestic wastewater processes that are low energy or energy generating, designed to produce wastewater fit for reuse (given specific purposes), and designed to allow recovery of nutrients. In particular, Verstraete et al. (2009) proposed separation of streams into major and minor (M&M) concentrated and dilute streams. The default sets of technologies identified were filtration based treatment (gravity–microfiltration–reverse osmosis), with treatment of solids and concentrate by anaerobic digestion, and recovery of the nutrients from digestate though Verstraete also identified alternatives, including biological concentration. The key limitation of filtration based technology is that if MF/RO is used in the mainline, it imposes a minimum energy requirement of approximately 3 kW h kL$^{-1}$ (Pearce, 2008). Given that the chemical energy in domestic wastewater is approximately 3 kW h kL$^{-1}$ (1000 mg COD L$^{-1}$), and electrical generation efficiency is normally on the order of 35%, this process will always require electrical input (though it could be very favourable where potable recycled water is required anyway).

As an alternative, McCarty et al. (2011) proposed a low energy mainline (LEM) process, in which domestic wastewater is primary settled, and treated through low strength anaerobic treatment (anaerobic membrane bioreactor (AnMBR), or anaerobic filter membrane bioreactor), which would remove solids and dissolved organics, and generate methane gas, but not remove substantial amounts of nitrogen or phosphorous. McCarty et al. (2011) proposed

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