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# INDUSTRIAL ECOLOGY TOOLS AS DECISION – MAKING AIDS FOR SUSTAINABLE PHOSPHORUS RECOVERY – A METHODOLOGY PAPER

# INDUSTRIELL-EKOLOGIVERKTYG SOM BESLUTSSTÖD FÖR HÅLLBAR FOSFORÅTERVINNING – EN METODARTIKEL

*G Venkatesh*[1], *Arun Kansal*[2]

[1] *Department of Engineering and Chemical Sciences, Karlstad University, 651 88 Karlstad, Sweden. Venkatesh.govindarajan@kau.se*
[2] *Dean Research and Relationships, Coca-Cola Department of Regional Water Studies, TERI School of Advanced Studies, New Delhi, India. akansal@terisas.ac.in*

## Summary

India, being the second largest importer, and the largest consumer of phosphate fertilisers in the world, needs to focus on securing its supplies not merely by providing subsidies to importers but also focusing on recovery and recycling of phosphorus from waste streams. In the process, the country can avail of concomitant benefits like wastewater reclamation and bio-energy generation, and improve the lot of the millions of farmers in the country. In this paper the authors have outlined a methodology based on industrial ecology tools – MFA (SFA), E-LCA, LCC and S-LCA – which they intend to adopt in the near-term to study, analyse and model the status quo and proposed interventions, from a sustainability perspective, which will become indispensable in the not-too-distant future for the country. The literature review which has been segmented on the basis of the application of the different tools to the study and analysis of resource recovery from wastewater, provides insights into what has been done thus far, and prepares the bedrock for a more detailed analysis.

## Sammanfattning

Indien, som är den näst största importören, och den största konsumenten av fosfatgödsel i världen, måste inrikta sig på att säkra sina leveranser, inte bara genom att ge stöd till importörer utan också med fokus på återvinning av fosfor från avloppsvatten. I processen kan landet utnyttja samtidiga fördelar som avloppsvatten återvinning och bio-energi generationen, och förbättra välståndet av de miljontals bönder i landet. I detta dokument, har författarna skisserat en metod som bygger på industriell ekologi verktyg-MFA (SFA), E-LCA, LCC och S-LCA-som de avser att anta på kort sikt för att studera, analysera och modellera status quo och föreslagna insatser, från en hållbarhet perspektiv, som kommer att bli oumbärlig i framtiden för landet. Den litteraturöversikt som har segmenterats på grundval av tillämpningen av de olika verktygen för att studera och analysera resursåtervinning från avloppsvatten, ger insikter i vad har gjorts hittills och förbereder berggrunden för en mer detaljerad analys.

*Keywords:* E-LCA (Environmental Life Cycle Analysis), India, Industrial Ecology, LCC (Life-Cycle Costing), MFA (Material Flow Analysis), Phosphorus recovery, S-LCA (Social Life-Cycle Analysis), Sustainability analysis, Wastewater

## Introduction and background

India is the second largest importer, and the largest consumer of phosphate fertilisers in the world, accounting for close to 50% of the global annual phosphoric acid imports (Farcy et al, 2015; Keil et al, 2017). Phosphate reserves – in concentrations that are economically feasible to extract - are dwindling and even though the phosphorus biogeochemical cycle is a closed one, the dissipation of phosphorus (P) to the hydrosphere and pedosphere pushes more and more of it 'out of reach' from us. As the population increases – which will happen at a much faster rate in India vis-à-vis many other parts of the world – and the purchasing power of the middle class in the country rises, the quantities of food that will have to make the journey 'from field to fork' will swell. Consequently, the amount of P discharged through urine and faeces, will also rise, resulting in, if the status quo of wastewater treatment in India continues, dissipation of more and more P into the water bodies. On the one hand, this would be a great loss of an eminently-recoverable resource and also at the same time, lead to marine and aquatic eutrophication, having deleterious effects on the hydrosphere-ecosystems and associated anthropospheric processes (fishing for instance). Of course, depletion of mineable phosphate reserves has got nothing to do with climate change – directly or indirectly. Neither does it contribute to nor it is caused by it. But there is a very strong interlinkage here – the so-called water-food-energy nexus – which if appreciated in the planning process, will, while helping one combat the unavoidable impacts of climate change in the future, also uncover wonderfully, the possibilities for wide-ranging benefits, contributing to sustainable development – not just the environmental dimension of it, but also socio-economic, in keeping with the spirit of the triple bottom line. (see Figure 2, which is an original work by the authors of this paper).

A key consequence of climate change of course is changes in precipitation patterns. This means that there would be regions which may receive very heavy rainfall causing floods and soil erosion and thereby losses of nutrients from the soil to water bodies, while there will also be regions which have to face droughts and water scarcity. In other words, the existing systems may not be robust enough to handle these changes. To cope and be resilient in the face of climate-change-induced challenges, stress must be laid on increasing wastewater collection and treatment (Ratna Reddy et al., 2018). Whether it is municipal wastewater or storm-water run-off from agricultural land or forests, decentralised wastewater treatment facilities to collect, treat and reuse wastewater (cascade applications), generate biogas from the organic matter separated from it, and divert the sludge to farmers who would use it in lieu of synthetic phosphate fertilisers which are bound to get costlier over time, will solve several problems at once. Another spin-off benefit is that P recovery will make such treatment process more financially viable and incentivise utilities for their appropriate operation and maintenance, currently a problem where significant number of treatment plants are not being able to meet discharge standards in India.

Industrial ecology tools like substance flow analysis or SFA (a form of material flow analysis or MFA) will enable one to track P (or phosphate) through the Indian economy into the environmental bodies in and around it. An MFA of water and wastewater linked to the SFA referred to above, will yield useful information which can be communicated to decision-makers and planners in municipal, state and national governments. Environmental life-cycle analysis (E-LCA) can be conducted to show potential (possible) net environmental benefits by recovering phosphorus, avoiding the production of synthetic fertilisers, recovering biogas and using it to replace fossil-fuel-sourced energy, and recycling the treated wastewater. In addition, social life-cycle analysis (S-LCA) can also be conducted to estimate the benefits associated with increasing the number of hours for which biogas-sourced electricity can be supplied. The increase in the degree of self-sufficiency of the farmers who subsist on meagre incomes obtained by the sale of small quantities of vegetables or other food crops on the marketplace, with recourse to sludge rich in phosphorus (and nitrogen), is also a social benefit. If farmers are able to sustain themselves better, it will lead to a positive impact on the health and education of their children. This will have positive spill-over effects on governance in a multi-party democracy like India, where trendsetters in a region, motivate others to follow suit, especially when benefits are conspicuous and vote-banks are to be secured.

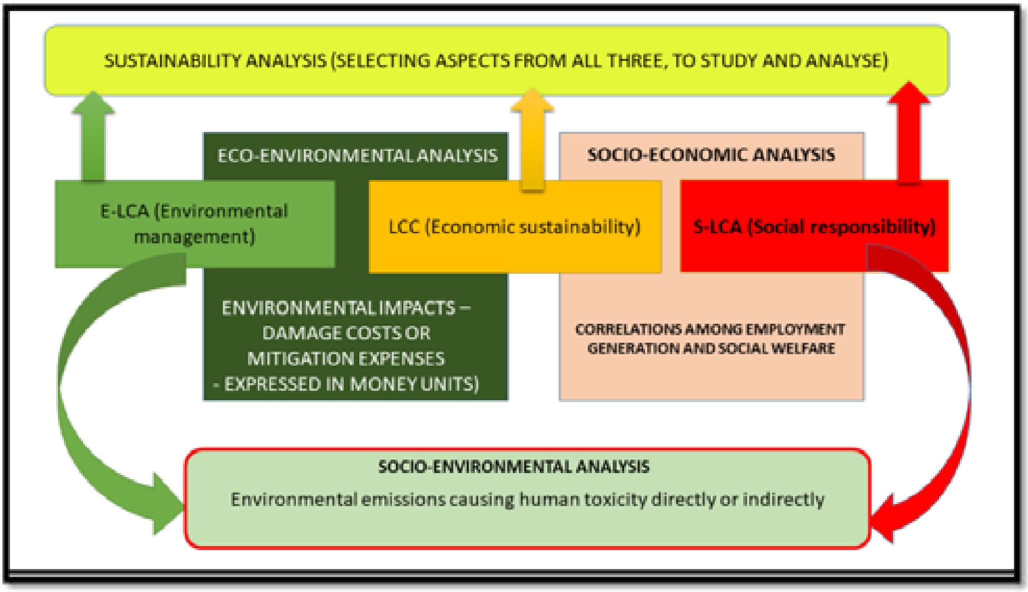
Sustainability has three main dimensions – social, economic and environmental – and these can be analysed and understood using industrial ecology tools. The fourth one, which overrides these three is governance. As Keil et al. (2017) have observed, an effective national P governance is indispensable for countries like India which rely entirely on imports of a dwindling resource like phosphates. The Government of India reduced the customs duty on phosphoric acid (a precursor to fertiliser P) not very long ago – a move which cannot be labelled as very sustainable, while the Nutrient Based Subsidy Policy of 2010 grants subsidies now on domestic phosphorus fertilisers (Government of India, 2013). However, there is no explicit reference in this government document to recovery and recycling of P from waste streams and so, 'domestic phosphorus fertiliser production' does not obviously refer to recovered/recycled P. Talking of governance, Nedelciu et al. (2018) have identified the policymakers at both local and national levels are key stakeholders who can, by utilising the influence they can wield, with political will, promote phosphorus recycling.

Recovery of different types of resources from wastewater – energy (heat, electricity and transport fuel), nutrients, materials and reclaimed wastewater - has been studied by many researchers, using one or more of the aforesaid industrial ecology tools over the years. A comprehensive review of publications focusing on resource recovery from wastewater in general was done by Venkatesh et al. (2018). In the current paper, the brief literature review is narrowed down to some of the more-recent peer-reviewed publications studying recovery with the aid of the industrial ecology (or sustainability analysis) tools referred to earlier. Thereafter, the authors propose a methodology which avails of MFA, LCA (both environmental and social) and LCC to study the status quo of the phosphorus flows in India and on the basis of the analysis, recommend strategies which may become indispensable in the not-too-distant future for the country.

## Literature review

Industrial ecology, as defined by Robert White (Ehrenfeld, 2002) is 'The study of flows of materials and energy in industrial and consumer activities, of the effect of these flows on the environment, and of the influence of the economic, political, regulatory and social factors on the flow, use and transformation of resources. The objective of industrial ecology is to understand better how we can integrate environmental concerns into our economic activities. This integration, an ongoing process, is necessary if we are to address current and future environmental concerns.' This systems approach of industrial ecology advocates thinking not merely of all the sub-systems as an integrated whole, but also of different aspects of the sub-systems. White's stress on the study of materials and energy and the effect of such flows on the environment, brings in Material Flow Analysis (MFA), Embodied Energy Analysis (EEA), Environmental Life-Cycle Assessment (LCA), Life-Cycle Costing (LCC) and Social Life-Cycle Assessment (SLCA) as relevant and handy tools to be employed in

**Figure 1.** *Sustainability analysis using the Industrial Ecology toolkit.*



sustainability studies (Refer Figure 1). However, the study of flows and their impacts on the environment, and thereby environmental planning and management, cannot be totally understood without factoring in several external factors (social, political, regulatory and economic as suggested by White in the definition above). Assessments which use all the aforementioned tools are bracketed under Life-Cycle Sustainability Assessments (LCSA).

In this article, the literatures (articles and reviews) which have been reviewed and discussed are from the period 2008–2018. The previous decade has been considered as 'recent' in this paper. Only Scopus was availed of as the repository of publications. The reason for this is the known fact that Scopus accounts for 14,000 journal titles from 4000 publishers around the world and that makes it the largest and the most comprehensive database.

'Resource recovery AND wastewater' ; 'Nutrient recovery AND wastewater'; 'Phosphorus recovery AND wastewater' were chosen as search-phrases to be located in the article title and/or abstract and/or keywords, realizing that resource and nutrient are terms which may refer to phosphorus. Searches with combinations of each of these with 'LCA', 'LCC' and 'MFA' were also attempted. All articles and reviews written in English – open access and otherwise – with overlaps among the different sets, were filtered out of the system into CSV files. Evidently, while one would expect the umbrella term 'resource recovery' to yield more matches than the subsets 'nutrient recovery' and 'phosphorus recovery', it was not so, owing to the fact that the term 'resource recovery' per se, need not have been adopted by all the researchers. The authors then carefully perused the abstracts of the papers to shortlist those which had adopted industrial ecology tools like E-LCA, LCC, S-LCA or sustainability analysis with any two or all three dimensions of the triple bottom-line. Browsing through the references in the publications selected for review also yielded some more, which were subsequently added to the filtered list. Needless to state, there certainly are many more relevant publications in literature which this Literature Review section does not refer to – a key limitation here.

### Environmental -LCA

Van der Hoek (2012), adopting E-LCA as a tool, calculated the reduction in greenhouse gas (GHG) emissions by recovering energy from the water cycle in and around Amsterdam in the Netherlands, as 148 000 tons of $CO_2$-eq/year and posited this as one of the many interventions needed to combat climate change. This result must be understood in the context of the fossil-heaviness of the Dutch energy mix (81% of the electricity is produced from coal and natural gas). This means any effort made to recover renewable energy from the wastewater streams, is strongly motivated by the fact that it will contribute significantly to truncating the carbon footprint of the Dutch capital's water cycle. In Latin America as a whole, fossil fuels account for the biggest share of the energy mix and thereby, as observed by Meneses-Jácome et al. (2016), there exists a good potential for recovery of clean and renewable energy from the region's agro-industrial wastewaters, which is not being harnessed to the extent it should and can be. They believe that methodologies based on E-LCA will enable researchers to drive home both the necessity and the possibility to decision-makers on that continent.

Miller-Robbie (2017), using E-LCA as a tool, have estimated a 33% reduction in life-cycle GHG emissions associated with treatment-plus-reuse of municipal wastewater from the city of Hyderabad in India, in urban agriculture. In Theregowda et al. (2015), a comparative E-LCA has been carried out to find out the most environmentally-favourable option among six treatment alternatives for municipal wastewater to be reused as a cooling medium in a thermal power plant. The recommendation of the authors was to dispense with tertiary treatment and reuse secondary-treated wastewater for the defined purpose, in order to minimize environmental impacts.

In an attributional E-LCA carried out to compare the life-cycle GHG emissions of two nutrient recovery systems in Sweden, Kjerstadius et al. (2017) have concluded that a system for the source separation of urine would increase the annual nutrient recovery by 0.30-0.38 kg P per capita and 3.1-3.28 kg N per capita, while decreasing the carbon footprint by 24 to 58 kg $CO_2$-eq per capita, vis-à-vis the status quo. Separation of urine at source for nutrient recovery has made inroads into Sweden of late, and this explains the interest among researchers in academia here, in this particular field. McConville (2017), in another paper from Sweden, while observing that small-scale and decentralized wastewater systems have been in vogue in the country for a quarter of a century now, have advocated the importance of new perspectives focusing on holism and sustainability – here is where industrial ecology can play a key role - including nutrients other than merely P, global issues like planetary boundaries and the consequences of climate change (water scarcity for instance). Entrenchment is fine, according to them, but there is a need now to sustain and widen the reach for source-separation and resource recovery technologies within Sweden and elsewhere in the world also. Algal-based systems for nutrient recovery have been studied widely over the last few years. By focusing on these, researchers at once straddle wastewater treatment and reuse, nutrient recovery and energy recovery as well – industrial symbiosis which is a domain of industrial ecology.

Bradford-Hartke et al. (2015), using E-LCA, have compared the environmental benefits of different methods of P recovery from wastewater – struvite production, chemical-based recovery, decentralized recovery from urine. According to them, while eutrophication may be reduced in all these instances, there are burdens associated with other environmental impact categories which must not be neglected. This being an Australian case study, the use of electricity (the mix being dominated by fossil fuels) in the recovery processes contributes to global warming.

Kleerebezem et al. (2015) encourage utilities to look at alternatives to generating biogas from anaerobic digestion of sewage sludge by contending that higher-value end-products can be recovered. Zhang, et al. (2010), by availing of process-based E-LCA and input-output LCA as tools, and using life-cycle energy consumption as the sole criterion for comparison, and considering the decrease of secondary effluent discharge and water saving as benefits, have proven that there are environmental benefits to be availed of by reusing treated wastewater vis-à-vis extracting and treating raw water for consumption. A comparative E-LCA of conventional raw water treatment, treatment of wastewater for reuse, and desalination was carried out by Meneses et al. (2010), and this led to the conclusion that non-potable uses (both agricultural and urban uses) of reclaimed wastewater have both environmental and economic advantages and the recommendation that use of treated wastewater must be promoted for non-potable uses, to counter challenges associated with scarcity of freshwater in the future. Pasqualino et al. (2011) calculated the carbon footprint of reclaiming wastewater to be 0.16 kg $CO_2$-eq/$m^3$, vis-à-vis 0.83 kg $CO_2$-eq / $m^3$ for wastewater treatment prior to discharge to sinks. If freshwater is substituted with reclaimed wastewater, for every $m^3$ (cubic meter) of wastewater reclaimed, 1.1 $m^3$ of freshwater is not extracted, while substituting for desalinated water (which is a source of water supply in some countries in the Middle East) accomplishes substantial energy use reduction.

### Life-cycle costing / Economic analysis

Posados et al. (2017), adopting a detailed economic analysis, posit high-rate algal ponds utilizing solar drying as an economical and energy-efficient wastewater treatment and nutrient recovery alternative, costing about 24.4 Euros per person equivalent per year. Molinos-Senante et al. (2011) suggest that for P-recovery projects to be economically viable in the years to come, one must also internalize the positive environmental externalities – the wider benefits which accrue by reducing the discharge of P to water bodies and controlling eutrophication and concomitant eco-system damages. These positive externalities can be quantified using E-LCA (endpoint indicators) as a starting point, and extending the results to study the socio-economic benefits by adopting suitable IE tools.

Indonesia faces challenges quite similar to Bangladesh, when it comes to population pressures, and stress on resources. Kerstens et al. (2016), to foster a circular economy thinking-based sustainable municipal wastewater management in Indonesia, carried out a P and compost demand analysis based on fertiliser requirements of 68 crops for the period 2016–2035, and estimated, inter alia, that if such recovery would be instituted in the system, about 15% of the P demands could be easily met, reducing the phosphate-based fertiliser import bill for the country. This, considering Indonesia's population growth and its dependence on fertiliser and phosphorus rock imports, is a finding which ought to be taken seriously by the Indonesian government.

Pricing of potable water is a decisive factor when it comes to the economic feasibility of decentralized wastewater treatment for reuse, as shown by Pan et al. (2010) in a case study of a large public building in Shanghai. Life-cycle costing enabled them to show that the water tariff had to increase to about 6.10 yuan per ton (as determined in the year 2010), for the payback period for the investment in a decentralized wastewater recycling unit to be attractive enough (4–5 years). Al-Jasser (2011) comes to a similar conclusion as regards pricing of potable water, in a case study conducted in Saudi Arabia. Using pilot and full-scale data for current technologies from a German wastewater-sludge treatment train, Nättorp et al. (2017) concluded that precipitation (a maximum of 0.23 Euro per population equivalent per year), sludge leaching (2.5 Euros) and use of dry sludge and mono-incineration ash (3.13 Euros), raise the specific costs of P recovery from WWTPs to a maximum of about 10 Euros per kg P (which is about 6 times greater than the cost of conventional fertiliser production). However, they commented in favour of implementing full-fledged recovery processes, by stating that the costs would account for less than 3% of the total costs for wastewater disposal.

### Social LCA

Teah et al. (2017) have used S-LCA to encourage P recycling within Japan by highlighting the human rights violation in the Western Sahara region (one of the major exporters of phosphate rock to the world) and communicating the semi-quantitative results to decision-makers in the country. Nedelciu et al. (2018) may not have performed an S-LCA per se, but they have performed a stakeholder analysis, and with the aid of a causal loop diagram and an interest-influence matrix, discussed how one could move forward to entrench phosphorus recycling from solid wastes and wastewater in the socio-politico-economic fabric of any country.

### Material Flow Analysis

Ott et al. (2012) presented and discussed an SFA for P in Europe; they also recommended a regional-level focus for several similar SFAs of P in the future, while bearing in mind the imminent phosphate rock resource depletion which we are looking at in the years to come, and also the indisputable fact that several big economies are totally dependent on a handful of rock phosphate exporters to sustain their respective agricultural sectors. India, as referred to earlier, is one such economy, which needs to feed an ever-increasing populace in the future, and sustain the livelihoods of its farmers. The proposed methodology based on an industrial ecologist's toolkit, is thus not just relevant and useful but quite indispensable if the challenges that loom large need to be systematically understood, analysed and tackled. In a recent publication, Keil et al. (2017) have carried out a dynamic ('time-continuous' in their words) historical SFA of P in India for the time period 1988-2011, and have concluded that India could substitute up to 19% of the presently applied mineral P if manure used as household fuel can be recycled (presently one third of the manure is used as fuel), and an additional 21% of the P can be fully recovered from wastewater and household wastes. They have reported a conspicuous rise in the P losses through waste streams and by way of soil erosion over the studied time-period. While Ott et al. (2012) consider the whole of the EU, Villalba et al. (2008) and Chen et al. (2016) have expanded the system boundary to encompass the whole world, Theobald et al. (2016) focus only on the Berlin-Brandenburg region in northern Germany, Schmid-Nesset et al. (2008) on the city of Linköping in Sweden, Wu et al. (2012) on Feixi in Central China, Do-Thu et al. on a selected rural area in Vietnam, and Senthilkumar et al. (2012), Bateman et al. (2011) and Pathak et al. (2010) have focused on the agricultural sector in France, England and India respectively. Thus, 'regional' can imply continental or multinational, national, provincial, urban, rural, or for that matter even sectoral. Mishima et al. (2009) have studied the phosphorus flows for Japan, both on a national aggregated level and on multi-regional levels.

### Double bottom-line analysis

In Venkatesh et al. (2013), a systematic double bottomline (economic, using LCC and environmental, using partial E-LCA) analysis of realistic and realizable options for recovering and utilizing energy from biogas produced in sewage sludge digesters, as heat and/or electricity and/or transport fuel, in WWTPs was carried out and applied subsequently to a WWTP in Oslo, Norway. The findings are dependent on the assumptions made and the conditions prevailing in Oslo at the time the paper was written. Mulchandani et al. (2016) have suggested new thermo-chemical and liquid extraction processes (hydrothermal liquefaction) for wastewater treatment, which would yield a 50% reduction in sludge mass, and conversion of about one-third of the liquefaction products to bio-oil (source of energy) and sequestering of heavy metals within a small mass of biochar (which can be used for soil amendment). Such sequestration prevents the availability of heavy metals to the plants for uptake and also leaching from the soil to the ground water. The authors agree that the introduction of these new processes may augment the cost, but the benefits in terms of environmental upkeep and resource recovery would more than justify the increase in expenditure. Here, while LCC and E-LCA would be handy tools, interpretation of environmental benefits in monetary units may be necessary.

Greywater reclamation and reuse in households, is technically possible and economically and environmentally favourable too, if the government subsidies on freshwater can be scrapped or substantially reduced, to shift public perception towards greywater reuse. A study similar to Pan et al. (2010) was carried out by Zeng et al. (2013)

for Beijing in which the authors estimated that greywater recycling in households could conserve 28.5% of freshwater resources for the city. Though it would have cost 1.2% more than the system which was prevalent at the time of writing, the pollution load, according to the authors could be decreased by 10%.

Kumar et al. (2015) have assessed the economic feasibility of treating sewage to be subsequently reused in aquaculture and agriculture by farmers in a region of north India, using LCC as a tool. Among the benefits which accrued to the farmers (and to the economy and environment) were the reduction in the annual consumption of synthetic fertilisers equivalent to about 26–41 tons of nitrogen, 10–18 tons of P and 38–58 tons of potassium, and a cost reduction per acre of crop of approximately USD 133 (INR 9440 at current exchange rates) annually. This shows clearly that reuse of treated municipal wastewater provides concomitant benefits related to nutrient recycling.

Longo et al. (2017), using a method which they call Shortcut Enhanced Nutrient Abatement, have concluded that considering the actual P availability (as fertilisers to crops and plants) from the biosolids tides over the overestimation one usually does by assuming a fixed P replacement ratio (from the total P content in the biosolids). As a result, it emerges that chemical precipitation of P does not provide environmental benefits through synthetic fertiliser replacement. This makes them recommend, using E-LCA and LCC as the analysis tools, the shifting of the P recovery from chemical precipitation in the main line to biologically enhanced uptake in the side stream and thereby accomplish a reduction in chemicals consumption, a decrease in the operation cost and also an increase in the environmental benefits by improving the P availability in the biosolids added to the soil.

### Holistic sustainability assessment

Holistic assessment includes the social, economic and environmental, and also, in some cases the political or geopolitical/governance aspects of sustainability. Zhou et al. (2009) is a review of papers published between 2006 and 2008, focusing on different aspects of sustainability of wastewater treatment and case studies from around the world.

Verstraete et al. (2016) is a concept-based paper which provides solutions based on nutrient recovery in general from both municipal and industrial wastewaters, and recommends that these solutions need a much broader implementation than the prevailing status quo, along with ingrained life-cycle thinking – which entails the use of E-LCA, LCC and even S-LCA as tools - to minimize losses along the entire chain from phosphate mining to consumption of food and feed. Papa et al. (2016), while admitting that wastewater reuse is advisable and necessary, have discussed the technical and economic sustainability of the same, using a novel tool that rates the three stakeholders (or agents) in the reclamation process – the WWTP which discharges the treated effluent, the hydraulic system which transports it, and the final user whose 'social acceptance' is necessary for recycling wastewater.

Woltersdorf et al. (2018) have focused on Namibia for their case study and compared four different alternatives for wastewater reuse and nutrient recovery using ecological, economic, societal, institutional, political, and technical criteria. Quite understandably, a holistic assessment like this one will depend on how decision-makers in Namibia wish to prioritise the different criteria. This article, well and truly, positions the issue of resource recovery from wastewater as a sustainability issue, with no one-size-fits-all solution. The developing world nations, which are experiencing rapid population growth, are the ones that must take resource recovery from wastewater much more seriously, as the stress on food and water supply and challenges associated with energy scarcity are only going to be exacerbated in the years to come (Ahmed et al, 2016).

Murray et al. (2011), in a multinational study involving India, Ghana and China, found out seven years ago that there is some momentum witnessed in these developing countries for expanding access to sanitation at household and community levels, and also a rise in awareness about the need to ensure safe end-of-life management of human faeces. Governments of these countries have been engaging the private sector but more solid public-private partnerships have to be created in order to accomplish these objectives. In Johansson et al. (2017), the authors have concluded that as the countries in the developing world are striving towards the living standards of those in the developed world, even as they combat population pressure, it is imperative that they learn from the experiences (the mistakes which occurred during the 'learning-by-doing' process) of the developed world. Inhabitants of the developing world need to be educated about the socio-economic and environmental benefits of wastewater treatment in the first place, and nutrient and energy recovery therefrom on the other. As abiotic metallic reserves keep getting depleted, the recovery of metals from wastewaters needs to be assigned due importance. The economic value of these recoveries is also certain to increase with time, making investments in such technologies all the more attractive. In two similar papers, Opher et al. (2017; 2018) performed an LCSA of urban wastewater reuse in Israel using the AHP method. In one of then, the authors compared centralised treatment with and without water reuse, on-site rotating biological contactors (RBCs) and cluster RBCs. The weightage assigned to the social dimension was 22% (water saving 8.6%, urban landscaping 3.2%, community involvement in decision-making 3%, expenses to consumer 2.8%, level of contact of the utility with the consumer 4.5%); and the reuse alternatives scored much higher on overall sustainability, vis-à-vis the lone linear option.

**Table 1.** *Snapshot of the literature review (arranged in alphabetical order of first-author surnames for each block).*

| **Tools /Type of Analysis** | **Publication/s** |
|---|---|
| *E-LCA* | Bradford-Hartke et al. (2015), Kjerstadius et al. (2017), Kleerebezem et al. (2015), McConville (2017), Meneses et al. (2010), Meneses-Jacome et al. (2016), Miller-Robbie (2017), Pasqualino et al. (2011), Theregowda et al. (2015), Van der Hoek (2012), Zhang, Q.H. et al. (2010) |
| S-LCA | Teah et al. (2017) |
| LCC | Al-Jasser (2011), Kerstens et al. (2016), Molinos-Senante et al. (2011), Nättorp et al. (2017), Pan et al. (2010), Posados et al. (2017) |
| MFA / SFA | Bateman et al. (2011), Chen et al. (2016), Do-Thu et al. (2011), Keil et al. (2017), Mishima et al. (2009), Ott et al. (2012), Pathak et al. (2010), Schmid-Nesset et al. (2008), Senthilkumar et al. (2012), Theobald et al. (2016), Villalba et al. (2008), Wu et al. (2012), Chen et al. (2016), Pathak et al. (2010). |
| Double bottomline analysis | Kumar et al. (2015), Longo et al. (2017), Mulchandani et al. (2016) Venkatesh et al. (2013), Zeng et al. (2013) |
| Holistic sustainability assessment | Ahmed et al. (2016), Johansson et al. (2017), Murray et al. (2011), Opher et al. (2017, 2018), Papa et al. (2016), Verstraete et al. (2016), Woltersdorf et al. (2018), Zhou et al. (2009) |

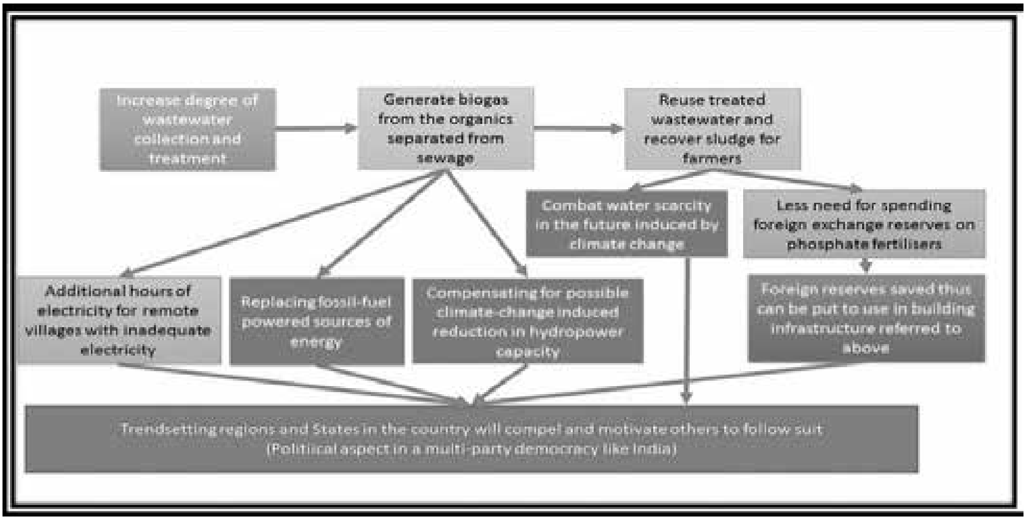


**Figure 2.** *The cascade of activities and outcomes which puts P-recovery projects in a favourable light.*

### Proposed methodology

Figure 2 presents the cascade of positive outcomes associated with efforts put into resource recovery, with P recovery being the primary driver and the main motivation. Figure 3 is a schematic sketch of the analytical methods (or steps) which will enable decision-makers to test the sustainability of different approaches and carry out a triple-bottom-line cost-benefit analysis; in other words, the environmental impacts associated with interventions versus the environmental impacts avoided thereby, the investments and expenses incurred vis-à-vis the long-ranging economic benefits that can be availed of, and also the development of social welfare vis-à-vis any socio-cultural / behavioural changes that may be indispensable for the success of the interventions. Robert White's definition of industrial ecology, which was cited earlier, is at once implicit in this. Industrial ecology, as a field of learning and research, and application in industry and society, is well-entrenched in the western world. It has gotten a toehold in India, and this is likely to develop into a foothold in the near future, so to speak.

The methods outlined in Figure 3, can be listed as under:

- Substance flow analysis (SFA; which is a form of MFA) at a national (aggregated and approximate, like Ott et al. (2012) has done for the EU and Senthilkumar et al. (2012) have done for the agricultural sector in France) and regional (specific and relatively more precise, like Schmid-Nesset et al. (2008), Theobald et al. (2016), or Do-Thu et al. (2011)) scale
- Geospatial modelling at a regional scale highlighting hotspots of phosphorus demand (e.g. agricultural crops) and phosphorus sources (e.g. wastewater treatment plants, population centres)
- Options development, including mapping the potential interventions, which include different feasible approaches to wastewater treatment and phosphorus recovery in an Indian context (as studied for an Australian case, in Bradford-Hartke et al. (2015), for example). Here, when it comes to feasibility, E-LCA and S-LCA will be useful tools to determine the environmental and social footprints of the options.
- Scenario analysis including developing and analyzing the impact of portfolios of technological and organisational options
- Economic analysis including cost effectiveness analysis (as in Nättorp et al, 2017), in which case LCC will be a useful industrial ecology tool.

### National Scale Studies

*Phosphorus SFA*

The major flows of P through the food system (measured in terms of kilotons per annum) are to be identified and quantified at a national level between major sectors, from imported phosphates to their application in agriculture to food consumption and excretion to wastewater collection/treatment networks, including the flows associated with virtual trade (phosphorus imported/exported in phosphate rock). The data sources which need to be availed of are diverse, and in some cases, experts need to be consulted for estimates regarding missing data. Keil et al. (2017), as referred to earlier, have carried out a time-continuous SFA for the period 1988–2011. Any possible changes that may have happened over the last 7 years, could be studied and modelled in the proposed research. Proxy data may need to be availed of, if literatures focusing on developing countries in similar climes and states of socio-economic and technological development can be accessed. This will result in formulation of what can be termed as a "National phosphorus SFA budget model and diagram".

*Water SFA*

Major flows of water (non-consumptive) and wastewater, relevant to the use of phosphorus, in the food system, are to be identified and quantified. Data gathered need to be modified suitably to facilitate an 'over-layering' with the P-SFA. This will lead to the development of a 'National water/wastewater SFA budget model and diagram'.

*Phosphorus – water intervention mapping*

The aforesaid 'over-layering' will enable one to assess the synergies between P and water/wastewater flows. This will assist in the identification of high-level hotspots of P demand (e.g. crops) and supply (e.g. animal waste, food waste, wastewater treatment plant outputs). This will clarify and quantify for the first time in India, the scale of the intervention points that could be used to analyze P recovery opportunities. The deliverable of this step will be the 'National phosphorus-water intervention diagram'.

### Regional-scale studies

*Set-up and context analysis*

To provide additional depth to the research methods and analysis, a case study region will be chosen so that one can zoom in to gather data on a finer level. This will enable the application of the methodology being developed, towards desired outcomes in terms of economic, environmental and/or social benefits. The choice of the case-study region chosen can be based on appropriate criteria developed for the purpose.

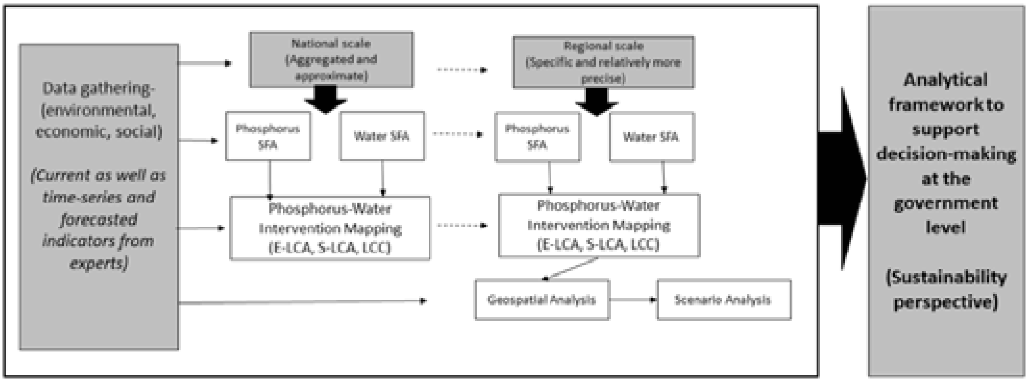


**Figure 3.** *The proposed methodology with the different types of analyses carried out to develop a framework for decision-making.*

- They may include for example,
- The extent to which the region is experiencing P and water/ wastewater stress
- Availability of and accessibility to data (e.g. partial or complete water/ wastewater budget of agriculture and/ or the food system)
- The extent of existing stakeholder interest/ engagement/ networks.

By engaging the stakeholders, an assessment of the regional drivers, pressures, opportunities for wastewater reuse and P recovery can be carried out, and the necessary data can be gathered for a more complete analysis.

*Regional-scale SFA and intervention mapping*
The deliverables include – analogous to the national SFA – a 'Regional P SFA budget model with diagram', and a 'Regional water/wastewater SFA budget model with diagram'. Water-P SFA synergies can then be assessed, as mentioned earlier for the national-level analysis, to identify high-level hotspots of P demand and supply and quantify the intervention points for P recovery.

*Geospatial analysis*
To enable geospatial mapping and analysis, data gathering for GIS mapping purposes will be imperative. These datasets pertain to catchments, agricultural areas, urban population areas, wastewater treatment facilities and major transport routes, among other aspects. Subsequently, aggregate physical supply and demand hotspot/ intervention intensity maps (kg/P/m$^2$) highlighting at a granular geographical level the demand for and availability of P in the flows analysed.

*Scenario analysis*
P recovery, as referred to earlier can be accomplished in different ways, using different technologies, some relatively tried-and-tested and some others which are novel. This means that feasible options/ alternatives in the regional context being considered, need to be analysed and compared among themselves, from economic (LCC) and environmental (E-LCA) perspectives. A life-cycle approach is mandatory in this case, to ensure that net costs and environmental impacts (occurring and avoided with respect to the status quo baseline case or business-as-usual (BAU) case, in which inorganic phosphate fertilisers are imported), all across a well-defined life-cycle are taken into account. The marginal costs vis-à-vis the BAU case (additional capital and operating costs of alternative technologies added to existing treatment processes, life cycle energy costs of transporting recovered phosphorus) need to be determined. Suitable metrics / indicators will be defined in order to facilitate clear comparison among the different alternatives proposed. Of course, the concomitant generation of energy and reclamation of wastewater also need to be factored in as co-benefits (as well as cost factors).

*Development of P recovery analytical framework*
Based on the application of the methodology proposed to the chosen case region within India, a modifiable framework/model will be developed for possible extension to other regions within India, and for that matter, other parts of the world as well. The framework will incorporate the social, economic and environmental aspects of an expanded system which will also factor in the possibility of studying the spill-over benefits for socio-economic development, environmental upkeep, national security and geopolitical stability, as illustrated in Figure 1 (as advocated by Woltersdorf et al. (2016), for Namibia). Keil et al. (2017) have identified the key limitations and advantages of various management options – recovery from manure, crop residues, wastes and wastewater, and control of soil erosion, and also identified the maximum unused-P potential with respect to the mineral P consumed annually.

Indicators will be defined for the different sustainability criteria so that the status quo and the expected outcomes of the interventions can be measured. By calculating the percentage change in each - % better or % worse (as was done in Venkatesh et al. (2013)), and developing a suitable weighting method (which would involve interactions with experts and stakeholders), the relative improvement in sustainability can be easily communicated to decision-makers, who may be hard-pressed for time to understand everything about the analysis.

*Engaging with decision-makers*

Research and analysis like the one proposed in this paper become meaningful when they can be used by decision-makers to bring about the necessary changes in systems. While intangible results (insights for further research and analysis) are obtained anyway, it is the physical results of such analyses that are important. Hence, communicating the results of this analysis carried out using industrial ecology tools in a convincing manner to decision-makers in the country at different levels of government and industry (all the three sectors of the economy) – as also recommended by Nedelciu et al. (2018), by approaching them in person, is crucial for its success.

## Recommendations and further research

The authors, in this methodology paper, have focused on the application of industrial ecology tools – E-LCA, LCC, S-LCA, singly or in different combinations – to analyse interventions which are now indispensable in order to secure P supplies for the agriculture sector in India, while also reclaiming wastewater and generating energy in the process. The motivations for such analyses have been outlined at the outset.

The literature review which has been segmented on the basis of the application of the different tools to the study and analysis of resource recovery from wastewater, provides insights into what has been done thus far, and prepares the bedrock for ta more detailed analysis, the outcome of which will be an useful addition to the body of knowledge of the application of industrial ecology tools for sustainability analysis, in the field of resource recovery.

## References

Ahmed, M., C.K. Hasan, H. Rahman, M. Ali Hossain, and S.A.Uddin. (2015) Prospects of using wastewater as a resource-nutrient recovery and energy generation. American Journal of Environmental Sciences 11(2): 99-114.

Al-Jasser, A.O. (2011) Greywater reuse in Saudi Arabia: Current situation and future potential. WIT Transaction on Ecology and the Environment 153: 159-169.

Bateman, A., D. van der Horst, D. Boardman, A. Kansal, and C. Carliell-Marquet. (2011) Closing the phosphorus loop in England: the spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. Resources, Conservation and Recycling 55: 1146-1153.

Bradford-Hartke, Z., J. Lane, P. Lant, and G. Leslie. (2015) Environmental Benefits and Burdens of Phosphorus Recovery from Municipal Wastewater. Environmental Science and Technology 49(14): 8611-8622.

Chen, M. and T.E. Graedel. (2016) A half-century of global phosphorus flows, stocks, production, consumption, recycling and environmental impacts. Global Environmental Change 36: 139-152.

Do-Thu, N., A. Morel, H. Nguyen-Viet, P. Pham-Duc, K. Nishida, and T. Kootattep. (2011) Assessing nutrient fluxes in a Vietnamese rural area despite limited and highly uncertain data. Resources, Conservation and Recycling 55: 849-856.

Ehrenfeld, J. (2002) Industrial Ecology: Coming of Age. Environmental Science and Technology 36(13):280A-285A, 2002.

Farchy, J. and E. Terazono. (2015) India's economy drives demand for phosphate fertiliser. Financial Times (May 28, 2015), London

Government of India. (2013) Policy for import of fertilisers. New Delhi: Government of India, Department of Fertilisers. http://fert.nic.in/node/1413. Accessed 16th August 2018.

Johansson, E and G. Venkatesh. (2017) Wastewater treatment plants as energy producers: Comparison of status quo in Sweden and India. Vatten 73(4): 151-160.

Keil, L., C. Folberth, M. Jedelhauser, and C.R. Binder. (2017) Time-continuous phosphorus flows in the Indian agri-food sector. Journal of Industrial Ecology DOI: 10.1111/jiec.12560

Kerstens, S.M., A. Priyanka, K.C. van Dijk, F.J. De Ruijter, I. Leusbrock, and G. Zeeman. (2016) Potential demand for recoverable resources from Indonesian wastewater and solid waste. Resources Conservation and Recycling 110:16-29

Kjerstadius, H., A. Bernstad Saraiva, J. Spångberg, and Å. Davidsson. (2017) Carbon footprint of urban source separation for nutrient recovery. Journal of Environmental Management 197:250-257.

Kleerebezem, R., B. Joosse, R. Rozendal, and M.C.M. van Loosdrecht. (2015) Anaerobic digestion without biogas? Reviews in Environmental Science and Biotechnology 14(4): 787-801.

Kumar, D., M.K.M. Chaturvedi, S.K. Sharma, and S.R. Asolekar. (2015) Sewage-fed aquaculture: a sustainable approach for wastewater treatment and reuse. Environmental Monitoring and Assessment 187(10): Article number 656.

Longo, S., N. Frison, D. Renzi, F. Fatone, and A. Hospido. (2017) Is SCENA a good approach for side-stream integrated treatment from an environmental and economic point of view? Water Research 125: 478-489.

McConville, J.R., E. Kvarnström, H. Jönsson, H.E. Kärrman, and M. Johansson. (2017) Is the Swedish wastewater sector ready for a transition to source separation? Desalination and Water Treatment 91: 320-328.

Meneses, M., J.C. Pasqualino, and F. Castells. (2010) Environmental assessment of urban wastewater reuse: Treatment alternatives and applications. Chemosphere 81(2): 266-272.

Miller-Robbie, L., A. Ramaswami, and P. Amerasinghe. (2017) Wastewater treatment and reuse in urban agriculture: Exploring the food, energy, water, and health nexus in Hyderabad, India. Environmental Research Letters 12(7): Article number 75005.

Mishima, S., A. Endo, and K. Kohyama. (2009) Recent trends in phosphate balance nationally and by region in Japan. Nutr. Cycl. Agroecosys. 86:69-77.

Molinos-Senante, M., F. Hernández-Sancho, R. Sala-Garrido, and M. Garrido-Baserba. (2011) Economic feasibility study for phosphorus recovery processes. Ambio 40(4): 408-416.

Mulchandani, A. and P. Westerhoff. (2016) Recovery opportunities for metals and energy from sewage sludges. Bioresource Technology 215: 215-226.

Murray, A., G.D. Mekala, and X. Chen. (2011) Evolving policies and the roles of public and private stakeholders in wastewater and faecal-sludge management in India, China and Ghana. Water International 36(4): 491-504.

Nedelciu, C-E., Ragnarsdottir, K.V. and Stjernquist, I. (2018) From waste to resource: A systems dynamics and stakeholder analysis of phosphorus recycling from municipal wastewater in Europe. Ambio, DOI: 10.1007/s13280-018-1097-9.

Nättorp, A., K. Remmen, and C. Remy. (2017) Cost assessment of different routes for phosphorus recovery from wastewater using data from pilot and production plants. Water Science and Technology 76(2): 413-424.

Opher, T., E. Friedler, and A. Shapira. (2018) Comparative life cycle sustainability assessment of urban water reuse at various centralization scales. International Journal of Life Cycle Assessment DOI: 10.1007/s11367-018-1469-1

Opher, T., A. Shapira, and E. Friedler. (2017) A comparative social life cycle assessment of urban domestic water reuse alternatives. International Journal of Life Cycle Assessment DOI: 10.1007/s11367-017-1356-1

Ott, C. and H. Rechberger. (2012) The European phosphorus balance. Resources, Conservation and Recycling 60: 159-172.

Pan, Q., F. Wang, J. Liu, and H.-Z. Yang. (2010) Cost-benefit analysis of treated wastewater reuse for large public building in Shanghai. China Environmental Science 30(4): 458-463.

Papa, M., G. Bertanza, and A. Abbà. (2016) Reuse of wastewater: a feasible option, or not? A decision support system can solve the doubt. Desalination and Water Treatment 57(19): 8670-8682.

Pasqualino, J.C., M. Meneses, and F. Castells. (2011) Life-cycle assessment of urban wastewater reclamation and reuse alternatives. Journal of Industrial Ecology 15(1): 49-63.

Pathak, H., S. Mohanty, N. Jain, and A. Bhatia. (2010) Nitrogen, phosphorus and potassium budgets in Indian agriculture. Nutrient Cycling in Agroecosystems 86(3): 287-299.

Posadas, E., R. Muñoz, and B. Guieysse. (2017) Integrating nutrient removal and solid management restricts the feasibility of algal biofuel generation via wastewater treatment. Algal Research 22:39-46.

Ratna Reddy, V., D.G.F. Cunha, and M. Kurien. (2018) A water-energy-food nexus perspective on the challenge of eutrophication. Water 10, 101; doi:10.3390/w10020101

Schmid-Nesset, T.-S, H.-P. Bader, R. Scheidegger, and U. Lohm. (2008) The flow of phosphorus in food production and consumption – Linköping, Sweden, 1870-2000. Science of the Total Environment 396:111-120.

Senthilkumar, K., T. Nesme, A. Molier, and S. Pellerin. (2012) Regional-scale phosphorus flows and budgets within France: the importance of agricultural production systems. Nutr. Cycl. Agroecosys. 92: 145-159.

Teah, H.Y. and M. Onuki. (2017) Support phosphorus recycling policy with social life cycle assessment: A case of Japan. Sustainability (Switzerland) 9(7): Article number 1223.

Theobald, T.F.H., M. Schipper, and J. Kern. (2016) Regional phosphorus flows Berlin-Brandenburg phosphorus flows in Berlin-Brandenburg, a regional flow analysis. Resources, Conservation and Recycling 112: 1-14.

Theregowda, R., R. Vidic, D.A. Dzombak, and A.E. Landis. (2015) Life cycle impact analysis of tertiary treatment alternatives to treat secondary municipal wastewater for reuse in cooling systems. Environmental Progress and Sustainable Energy 34(1):178-187.

Van Der Hoek, J.P. (2012) Climate change mitigation by recovery of energy from the water cycle: A new challenge for water management. Water Science and Technology 65(1): 135-141.

Venkatesh, G., and R.A. Elmi. (2013) Economic-environmental analysis of handling biogas from sewage sludge digesters in WWTPs (wastewater treatment plants) for energy recovery: Case study of Bekkelaget WWTP in Oslo (Norway). Energy 58(10):220-235.

Verstraete, W., P. Clauwaert, and S.E. Vlaeminck. (2016) Used water and nutrients: Recovery perspectives in a 'panta rhei' context. Bioresource Technology 215:199-208.

Venkatesh, G. (2018) Recovery of different types of resources from wastewater – A structured review. Vatten. 74(2): 65-82.

Villalba, G., Y. Liu, H. Schroder, and R.U. Ayres. (2008) Global phosphorus flows in the industrial economy from a production perspective. Journal of Industrial Ecology 12(4): 557-569+5.

Woltersdorf, L., M. Zimmermann, J. Deffner, M. Gerlach, and S. Liehr. (2018) Benefits of an integrated water and nutrient reuse system for urban areas in semi-arid developing countries. Resources, Conservation and Recycling 128: 382-393.

Wu, H., Z. Yuan, L. Zhang and J. Bi. (2012) Eutrophication mitigation strategies: perspectives from the quantification of phosphorus flows in socioeconomic system of Feixi, Central China. Journal of Cleaner Production 23: 122-137.

Zeng, S., X. Dong, J. Chen, and P. Li. (2013) Planning an urban wastewater system with centralized greywater reuse: A case in Beijing. Civil Engineering and Environmental Systems 301 (1): 40-55

Zhang, Q.H., X.C. Wang, J.Q. Xiong, R. Chen, and B. Cao. (2010) Application of life cycle assessment for an evaluation of wastewater treatment and reuse project - Case study of Xi'an, China. Bioresource Technology, 101(5): 1421-1425.