RECOVERY OF DIFFERENT TYPES OF RESOURCES FROM WASTEWATER – A STRUCTURED REVIEW

ÅTERVINNING AV OLIKA TYPER AV RESURSER FRÅN AVLOPPSVATTEN – EN LITTERATURSAMMANSTÄLLNING

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Abstract

As the population of the world increases, and economies continue to develop, energy, water, materials of different types, and nutrients for food production will be needed in ever-increasing amounts. The water-energy nexus is well-understood in research circles, but one could modify this paradigm to water-nutrients/materials-energy nexus in order to incorporate recovery of substances that can be recirculated to the anthroposphere. 'Resources' would thus include both energy and materials (elements, compounds and mixtures – both organic and inorganic). Research in, and implementation of, recovery of different types of resources – material and energy - from wastewater (municipal, agricultural and industrial) has been going on for quite some time now. It will not be wrong to say that the imperativeness and importance of research in this field has been earnestly appreciated by academia, industry, utilities and governments alike in many parts of the world, over the last decade. This paper is a literature review of selected publications from the period 2010–2018, from a wide range of journals, focusing on resource recovery from wastewater. The selected publications originate from 44 different countries (in six continents) of the world.

Key words: Wastewater, sludge, resource recovery, nutrient recovery, biogas, bio-hydrogen

Sammanfattning

När världens befolkning ökar och ekonomier fortsätter att utvecklas, ökar behövet av energi, vatten, material av olika slag och näringsämnen för livsmedelsproduktion samtidigt. Paradigmet vatten-energi-nexus kan ändras till vatten-näringsämnen / material-energi-nexus för att införliva återvinning av ämnen som kan recirkuleras till antroposfären. 'Resurser' innehåller både energi och material (element, föreningar och blandningar – både organiska och oorganiska). Forskning i och genomförande av återvinning av olika typer av resurser – material och energi – från avloppsvatten (kommunala, jordbruks- och industriella) har pågått under en längre tid. Det är inte fel att säga att betydelsen av forskning inom detta område har uppskattats av akademier, industrier, verktyg och regeringar i många delar av världen under det senaste decenniet. Detta dokument är en litteraturöversikt av utvalda publikationer från perioden 2010–2018, från ett brett utbud av tidskrifter, med inriktning på resursåtervinning från avloppsvatten. De valda publikationerna kommer från 44 olika länder (i sex kontinenter) i världen.

Introduction and background

Wastewater – municipal, industrial and agricultural – holds within itself a wide variety of organic and inorganic constituents - Human wastes (urine and faeces) from toilets, food wastes from kitchens, organic wastes from gardens and green areas comprising the former, and detergents, soaps from bathrooms and washrooms, paints and heavy metals, pharmaceuticals etc comprising the latter category. The water and some of the aforenamed constituents can be looked upon as resources, which can be recovered and recirculated to the anthroposphere, in a circular economy, which many countries in the world are striving to move towards. The motivations behind attempting to close the loop are manifold – economic and environmental, geopolitical and social. The primary driving factors, obviously, are not the same in all regions of the world. Research into the recovery of different constituents has been going on, and will continue to attract interest, support, investments and attention in the future. Recovery and recycling of resources from wastewater will aid in the conservation of virgin resources – both biotic and abiotic, and also of the quality of sinks into which the anthroposphere disposes its wastes. These resources can be categorised into energy, materials and nutrients.

In this article, the literatures (articles and reviews) which have been reviewed and discussed are from the period 2010-2018. The motivation is to present the diversity of research in this field – with respect to the resources which are being recovered (or will be recovered on a larger scale) from wastewater streams of different provenances – agricultural (run-off), industrial (once again different sectors) and municipal. Indirectly, the author will also be accounting for most of the relevant research conducted and results thereof disseminated, through the references, which are to be found in the publications reviewed in this particular paper.

Attention was paid to the inclusion of publications -

i) *originating* from different geographical loca tions (universities to which the authors belong or belonged),
ii) *spanning* the 9-year time period chosen
iii) *focusing* on different types of resources
iv) *analysing* different aspects of resource recovery – technical, economic, social, environmental and geopolitical, and
v) *using* different tools (Environmental LCA or E-LCA, Life-cycle costing or LCC etc.).

Observations and discussion

In a very recent overarching methodological paper, Zijp et al (2017) have presented an online tool with 30 different sustainability assessment methods for method selection when it comes to making strategic choices for resource recovery from wastewater. They rightly point out that there are factors which make decision-making far from easy and straightforward.

Energy recovery

Biogas, biomethane, bio-oil or bio-solids

In a South African case study (Stafford et al, 2013), the authors, in a detailed analysis of energy recovery possibilities from wastewater through biomass production, combustion and gasification of biosolids, generation of biogas, production of bioethanol, heat recovery and using microbial fuel cells running on biohydrogen to generate electricity, established the potential at 3.2 to 9 GWth of energy, which is equivalent to about 7% of the country's electricity generation. Apart from water reclamation and pollution control which are the primary benefits, the authors have identified certified emission reductions, fertiliser production and the production of secondary products as synergistic secondary benefits. Heubeck et al (2011) have contended that the energy recovery from wastewater can be almost sextupled for New Zealand if advanced technologies are adopted. Van der Hoek (2012) 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. Meneses-Jácome et al (2016) in a paper originating from Colombia has observed that the potential for recovery of clean and renewable energy from agro-industrial wastewaters is quite high in Latin America, but 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.

In Venkatesh et al (2013), a systematic double bottomline (economic and environmental) 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. According to Hale (2017), WWTPs which used to produce biogas and use it as a fuel for electricity and heat production are now realising the economic benefits of refining it to higher-value biomethane. Truong et al (2016) sees potential in WWTPs sewage treatment plants in remote locations doubling up as suppliers of renewable energy (biogas) to consumers in its vicinity. De Mendonca et al (2017) used a hybrid reactor consisting of an upflow anaerobic sludge blanket and an anaerobic filter in Brazil, put mesophilic bacteria to work on cattle wastewater and obtained biogas with methane content ranging between 69% and 75%. In Demirel, et al (2013), the focus is on wastewater and solid residues from ice-cream production units (part of the dairy industry) in Turkey. By anaerobically digesting just the wastewater, a methane yield of 0.338 litres per gram of COD (g COD) removed (70% of the biogas was methane) was achieved, while co-digesting the solid residues along with the wastewater reduced the methane output to 0.131 litres per g COD removed. Vaiopoulou et al (2011) utilised the carbon dioxide in the biogas generated by anaerobic treatment of wastewater rich in acetic acid, for neutralising alkaline wastewater and in the process, reduced the consumption of sodium hydroxide. An additional benefit was the enrichment of the biogas available finally as fuel (a lot of the carbon dioxide being consumed for the neutralisation).

The sewage sludge itself, after being dried, can be used as a source of heat in incineration, or so-called Waste-to-Energy (WtE) plants. Bianchini et al (2015) have recommended a symbiotic arrangement between a WtE plant which would use the dried sewage sludge and the WWTP in which the sludge would be dried, whereby waste heat from the WtE can be recovered and utilised for the thermal drying of the sludge. In other words, the previous mass of dried sludge becomes the source of some heat for drying the mass that would follow it to the WtE. 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. In an earlier paper, Cao et al (2012) had written in favour of pyrolysis of raw and digested sewage sludge which yields liquid and gaseous fuels and also produces biochar as a solid by-product which finds use in soil conditioning and sequestering heavy metals. They do not recommend pyrolysis of raw sludge over anaerobic digestion, but rather a combination of the two processes in series, to maximise energy recovery.

Heat from flowing wastewater

Wastewater contains significant quantities of thermal energy. Wastewater source heat pumps (WWSHP) can also be looked upon as devices extracting heat energy – which would otherwise be dissipated and wasted - from wastewater streams (Gu et al, 2015). Spriet et al (2017) in their study of wastewater heat recovery possibilities in Brussels, found out that at existing electricity tariff rates, the levelised cost of energy for WWSHP systems is lower than for traditional ASHPs, but higher than conventional gas boiler systems in households. However, the total equivalent warming impact of these WWSHPs is also lower than both the alternatives referred to, 49% less than gas boilers and 13% less than ASHPs. Heat can also be exchanged using simple heat exchangers too, to minimize the need for energy to provide hot water in bathrooms for instance. Here, we are referring to localized or decentralized heat recovery at the point of discharge of wastewater. While sewer pipeline networks can also be considered as heat energy sources to be harnessed, Kretschmer et al (2016) have warned that some treatment processes in the WWTPs downstream are temperature-sensitive, and thereby it is necessary to make sure that heat recovery from the network does not adversely affect the degree of wastewater treatment.

Sitzenfrei et al (2017) have modelled heat recovery from wastewater using continuous sewer temperature and flow measurements as the in-feed to the model, and concluded inter alia, that while it is possible to recover heat from the source, from the sewers and from the WWTPs, an uncoordinated installation of systems on such different levels can lead to competing technologies. The potential for heat energy recovery from wastewater has been appreciated by governments of provinces and countries. In the USA, as reported by Rudenko et al (2016), the Massachusetts Department of Energy Resources awarded a grant to the town of Barnstable in this Northeastern state, in 2014, to pilot a raw sewage heat recovery unit at the town's largest raw wastewater pumping station. Such initiatives tend to set the trend for other states and regions to emulate.

Electricity from flowing wastewater

Over the years, the kinetic energy in wastewater flowing down from an altitude has been harnessed using micro-turbines to generate a little electricity in some parts of the world. Patel (2010) has referred to the 4.5 MW micro-hydroelectric power plant installed in Sydney to utilise the kinetic energy in wastewater flowing down 60 metres. Bousquet et al (2017) have developed and applied a methodology to estimate the potential for micro-hydropower generation at WWTPs in Switzerland. They zeroed in on 19 profitable locations with a total potential of 9.3 GWh per year; of which six are already in vogue and contributing 3.5 GWh to the Swiss electricity mix. Having established the potential, one needs to get down to the practical details of design. Power et al (2017) arrived at optimised systems efficiencies close to 75%, with the micro-turbine costs ranging from 315 to 1708 Euros/kW. By using two pump-as-turbines arranged in parallel, the authors demonstrated a slight rise in efficiency of conversion of the kinetic energy of the wastewater to electrical energy.

Hydrogen gas

Use of hydrogen as a clean fuel in fuel cells for stationary as well as mobile applications is becoming more and more common. Baeza et al (2017) describes the design, building, start-up and operation of a microbial electrolysis cell pilot plant with a capacity of 130 litres, using urban wastewater as a substrate, to produce hydrogen. The authors have reported a hydrogen gas yield of 4 litres per day at a purity of 95%, and energy recovery of 121% with respect to the electricity input for the process. Ren et al (2015) have reported hydrogen production at the rate of 1508 ml/litre of starch (sweet potato) wastewater when the latter was subjected to treatment by a mixed culture of anaerobic sludge and microalgae, an approach that they recommend as an effective one to optimise nutrient recovery and production of an energy resource.

Sharma et al (2010) integrated anaerobic hydrogen production and a microbial fuel cell to optimise energy recovery – as hydrogen gas and electricity simultaneously - from wastewater. The paper reports a maximum hydrogen production of 2.85 moles per mole of glucose substrate in the wastewater, and a maximum electricity recovery from the fuel cell, of 559 Joules per litre of wastewater. In a related study, Teng et al (2010) concluded that the overall energy recovery efficiency can be increased from 15.7% (with only fermentative hydrogen production or FHP) to 27.4% (with an integration of FHP and microbial fuel cell). Combining acidogenesis with bio-hydrogen production prior to methanogenesis, can improve the energy recovery from wastewater biomass, and generate both hydrogen and biogas as fuels (Premier et al, 2015).

Jung et al (2012) subjected wastewater from a coffee brewery to treatment using a continuous two-stage up-flow anaerobic sludge blanket (UASB) reactor system and achieved a stable hydrogen production rate of 4.24 litres hydrogen per litre of wastewater per hour, courtesy thermophilic bacteria, while the mesophiles yielded 0.325 litres of methane per g COD in the wastewater. Ultrasonication pretreatment for enhancement of biohydrogen production from dairy wastewater was carried out by Gadhe et al (2015) and trials led them to conclude that sonication enhanced hydrogen recovery significantly (by between 10% and 100%) vis-a-vis the absence of any pretreatment. In another paper by Phalakornkule et al (2010), dye-containing wastewater (the dyes being Reactive Blue 140 and Direct Red 23) from a textile mill was electro-coagulated and hydrogen gas equivalent to an energy content of 0.2 kWh per m^3 was obtained. Though three to four times more energy was utilised for the process, hydrogen production was just a secondary purpose, the primary one being treating the wastewater and removing colour, COD and other impurities from it. Using soluble condensed sacchariferous molasses from the food industry in Taiwan as substrates, Lay et al (2010) produced 0.39 moles of biohydrogen per litre wastewater treated, at an organic loading rate of approximately 320 g COD/ litre-day, with a hydraulic retention time in the treatment unit of 3 hours. They claim this to be a commercially attractive route to biohydrogen production, given the continuous availability of the said substrate.

Materials recovery

Nutrients as fertilisers

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 to minimize losses along the entire chain from phosphate mining to consumption of food and feed. Mihelcic et al (2011) have estimated the availability of phosphorus from brown water (yellow water - urine + black water - faeces) discharged in urban settings, to rise from 0.88 million tons in 2009 to 1.68 million tons in 2050, and would account for over 20% of the global phosphorus demand. In a case study conducted in Vietnam, Antonini et al (2011) adopted a "No Mix" sanitation system to treat urine for the recovery of phosphorus as struvite (magnesium ammonium phosphate) and nitrogen as ammonium sulphate. An efficiency of 98% for P and 90% for N was achieved, with 110 grams of struvite produced from 50 litres of urine. The authors have also recommended the use of solar energy to cater to a substantial proportion of the energy needs for recovery during daytime, thus reducing the energy expenditure for the process. The efficacy of struvite as a fertiliser vis-à-vis phosphate-rock-derived di-ammonium phosphate (DAP) was tested by Talboys et al (2016) in pot trials; and they inferred that fertiliser mixes containing struvite and DAP have the potential to provide both optimal early and late season phosphorus uptake and improve overall phosphorus-use efficiency. This in effect, will reduce the demand for mined phosphates, and prolong the lifetimes of the global phosphate rock reserves. Taddeo et al (2018), tested the efficiency of crystallization and the amount of struvite in the precipitate for different types of agro-industrial wastewaters, and found that both these were inversely proportional to the total solids content of the feed. Analysis of the struvite crystals also showed the presence of important macro- and micronutrients like potassium, calcium, iron, sodium, copper, zinc, manganese and cobalt.

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 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. Caspersen et al (2018) tested plant performance in a peat substrate containing nutrient-enriched zeolite (NEZ) obtained by nutrient recovery from human urine in a source-separated wastewater system, and concluded that 20% NEZ in a peat substrate was effective as a macronutrient source for sunflower, producing similar biomass as in a conventionally-fertilized (with synthetic fertilisers) peat, if micronutrients could also be supplied in the desired quantities. 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, including nutrients other than merely phosphorus, 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. Batstone et al (2015), have reviewed practical applications of two nutrient recovery processes – a low energy mainline (LEM) process which adopts low strength anaerobic treatment, followed by mainline anaerobic nitrogen removal and chemical or adsorptive phosphorous removal, and a so-called partition-release-recover (PRR) process, 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. The authors recommend LEM as an option for the short term on account of its lower energy costs, but advise PRR for the medium-to-long term, owing to its ability to handle more concentrated sewage streams, and recover nitrogen, phosphorus and potassium.

Simha et al (2017) explains the concept of Ecological Sanitation to emphasize the importance of promoting closed-loop flows of resources and nutrients from sanitation to agriculture. Inter alia, these researchers who are affiliated to universities in Hungary, India and the UK, conclude that the provisioning of urine-diverting toilets tends to reduce sanitary risks; but the implementation of integrated technological pathways is necessary in the near future to completely eliminate these risks and improve the social acceptance for this paradigm-shift. Tian et al (2016) reported the results of using brine from a reverse osmosis membrane unit as a precipitant for recovery of phosphorus from urine – recovery of 2.58 and 1.24 kg of precipitates from 1 cubic metre of hydrolyzed and fresh urine respectively; containing 8.1–19 % of phosphorus, 10.3–15.2% of calcium, 3.7–5.0% of magnesium and 0.1–3.5% of ammonium nitrogen. Many different phosphorus recovery methods have been investigated by researchers around the world - using calcium silicate hydrate or tobermorite (Jiang et al, 2010), waste concrete (Mohara et al, 2011) and thermally-treated gastropod shells (Oladoja et al, 2015).

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. In a paper from Ireland, Brennan et al (2010) have observed that microalgae are photosynthetic microorganisms with simple growing requirements (light, sugars, CO_2, N, P, and K) that can produce lipids, proteins and carbohydrates in large amounts over short periods of time, and can subsequently be processed to biofuels. They emphasized the strengths of the synergistic (symbiotic) coupling among carbon sequestration, wastewater treatment (the nutrients and the water itself being the materials the microalgae avail of), and algal cultivation. Selvaratnam et al (2016) has described a model to simulate the optimal process for the recovery of nitrogen and phosphorus from wastewater by embodying them in an extremophile microalgal species - Galdieria sulphuraria; and subsequently utilizing the biomass as a source for biochar and bio-crude extraction via hydrothermal processing and recycling the aqueous residual for its nitrogen and phosphorus content. Posados et al (2017) 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. Sukacova et al (2017), after summarizing the trends in the use of suspended and attached microalgal-based systems for nutrient removal, contend that these systems will come to stay and find widespread applications globally, if challenges they may face can be effectively overcome. Molinos-Senante et al (2011) suggest that for phosphorus recovery projects to be economically viable in the years to come, one must also internalize the environmental externalities – the wider benefits which accrue by reducing the discharge of phosphorus to water bodies and controlling eutrophication and concomitant eco-system damages. Bradford-Hartke et al (2015) have compared the environmental benefits of different methods of phosphorus 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.

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). 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 phosphorus 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 phosphorus demands could be easily met, reducing the phosphate-based fertiliser import bill for the country. 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. 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.

Smith et al (2016) recommend an anaerobic/ion-exchange system as a 'simple, reliable, modular, scalable and adaptable' solution for the recovery of nitrogen from wastewater at source, to be supplied as fertiliser. They based their recommendation on tests carried out on cherry tomato cultivation, which showed that canopy volume and plant flowering and fruition were much better with recovered nitrogen vis-à-vis synthetic fertiliser.

Other materials

Material resources of different types can be recovered efficiently from wastewater streams from different industrial sectors, if they are treated at source for resource recovery. Anbalagan et al (2015) demonstrated using synthetic wastewater having a nickel ion concentration of 100 g/l, that Strychnos potatorum seeds could be utilised to recover nickel very economically, providing a solution for separation of nickel from wastewater streams which have a high concentration of this metal. 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. 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. They recommend the optimisation of organic acid production (the carbon and hydrogen in the wastewater not being converted to methane) which can be concentrated via membrane separation. They name polyhydroxyalkanoates (also refer Valentino et al, 2017 and Table 1) as end-products which are slated to have a high value in the future as bioplastics and substitutes for petroleum-derived polymers. Strong et al (2015) have looked at the possibility of utilising methanotrophic (methane-consuming) bacteria to feed on the methane and subsequently generate a string of valuable high-end products like protein, biopolymers, components for nanotechnology applications, methanol, organic acids, and vitamin B12. Methane in the biogas originating from anaerobic sludge digesters can be used as the feedstock for these bacteria. Table 1 summarises some of the possibilities, explored in publications over the time-period of analysis.

Wastewater reuse in cascade or after treatment

Municipal wastewater reuse after suitable treatment has a synergistic effect in agriculture, as along with water, nutrients are also recycled back to the soil and taken up by crops, in what is known as 'fertirrigation'. Zhang, Q.H. 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 metre of wastewater reclaimed, 1.1 m^3 of freshwater is not extracted.

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. In a Jordanian case study of the Mujib watershed where groundwater is the major source of both irrigation and drinking water, Al-Assa'd et al (2010) have developed a methodology and tested it to investigate the possibilities of artificial groundwater recharge using reclaimed municipal wastewater, and like the earlier paper, have recommended it for decision-makers in the Jordanian government. Alves et al (2011), while stating that wastewater needs to be treated as a dependable resource in Portugal's water resources management programme, had focused on the assessment of the economic viability of water reuse projects, like the tariff structure model, the internalization of costs, the burden on the users and the payback periods.

In agriculture, animal husbandry and aquaculture

Lavrnic et al (2017), emphasizing the expediency of water reuse in southern Europe, have pointed out that it would decrease the pressure on the environment and is especially suitable for agriculture since it already contains some nutrients required for plant growth. Libutti et al (2018) and Cirelli et al (2012), in case studies conducted in Italy, found that the use of tertiary-treated wastewater, under controlled conditions, for drip-irrigation of vegetables like eggplant, tomato and broccoli did not significantly affect the yield of these vegetables, and have recommended wastewater reclamation to tide over the impending climate-change-related challenge of agricultural water shortages in the Mediterranean region. In neighbouring Greece,

Table 1: *Summary of industrial sectors and associated material recoveries from wastewater streams (other than nutrients), from selected publications*

Industrial sector (including animal husbandry)	Publication	Material resource recovery focused on
Automobile ancillary sector	Martins et al (2013)	Palladium
Biotechnology sector	Wu et al (2016)	Gallic acid (organic acid which is a valuable resource for the pharmaceutical industry)
Desalination plants	Kim (2011)	Sodium, potassium and magnesium salts
Electrical and Electronics	Choi et al (2012)	Silver
Electroplating	Peng et al (2011)	Copper (97.9% purity; 99% recovery)
	Lee et al (2016)	Chromium (VI)
	Arredondo et al (2014)	Silver (98% recovery)
Etching	Yin et al (2018)	Fluorine
Leather industry (tannery)	Chattopadhyay et al (2012)	Chromium, which can be recycled back for use in tanneries or for other applications
Metallurgy / Metalworking	Umeda et al (2011)	Copper (99% recovery), Palladium (96%), Gold (85%), Silver (more than 91%), Platinum (more than 71%), Indium
	Xu et al (2014)	Zinc sulphide from galvanizing mills associated with steelmaking (85% purity of the recovered sulphide)
	Modin et al (2017)	Zinc from galvanizing mills
	Tansens et al (2011)	Caustic soda and aluminium (aluminium sector)
	Morita et al (2018)	Calcium flouride from hexafluorosilicic acid wastewater (from aluminium production units)
	Zhang, X et al (2012)	Hydrochloric acid (aluminium industry)
Mining	Nleya et al (2016)	Sulphuric acid (from acid mine drainage)
Mixed industrial (and municipal) wastewater	Pappalardo et al (2011)	Lead
	Pazos et al (2010)	Cadmium
	Valentino et al (2017), Morgan-Sagastume et al (2016)	Polyhydroxyalkanoates (bio-polymers or bio-plastics)
	Peng et al (2017)	Copper (originating from semiconductor and PCB manufacturing units, surface finishing and electroplating units)
	Lei et al (2012)	Copper (30.3% removal), nickel (43%) and zinc (34%)
	Tunc et al (2011)	Sodium sulphate
	Selvaraj et al (2017)	Sulphur (from contaminated pond which receives industrial effluents)
Nuclear power	Asiabi et al (2018)	Uranium
	Ding et al (2012)	Uranium (using tea waste)
Paper and pulp	Pervaiz et al (2011)	Recovered sludge protein for use as wood adhesive
	Périn-Levasseur, Z et al (2011)	Lignin for further recovery for valuable substances (from the black liquor)
Rubber industry	Hatamoto et al (2012)	Deproteinized natural rubber
	Chaiprapat et al (2015)	Sulphuric acid
Textile industry	Pensupa et al (2017)	Monosaccharides from cellulose fiber wastes in wastewater

Agrafioti et al (2012) tested the use of reclaimed wastewater for the irrigation of olive trees, vineyards and lettuce on the island of Crete. They concluded that if WWTPs adopt tertiary treatment (which they did not at the time the paper was written) and if all the wastewater could be recycled, approximately 4.3% of the irrigation water requirements on the island could be met. In another paper from Greece, Stathatou et al (2015) focused on the Aegean archipelago, islands in which face serious water scarcity problems in the summer months. Using a GIS (Geographic Information System) tool, they estimated the potential for treated wastewater reuse, which according to them is significant and needs to be harnessed. Brahim-Neji et al (2014), using binary logistic regression analysis as the statistical tool, found that both policymakers in the Tunisian government and over 80% of the farmers interviewed, agreed that wastewater which has undergone tertiary treatment (suitably disinfected) can be used for irrigation. The Gaza Strip deserves attention when it comes to water resources planning as Shomar et al (2010) recommended 8 years ago. The authors of the said paper, after analysing 51 treated wastewater samples, 51 sludge samples, 44 soil samples, as well as 30 alfalfa samples and samples of 24 oranges and lemon cultivated using treated wastewater for irrigation, for 27 trace elements, concluded that treated wastewater is safe to use for irrigation in Gaza. A little to the west, in Egypt, Abdel-Shafy et al (2017) have demonstrated that the total suspended solids, COD and BOD in source-separated black-water, treated first in a sedimentation tank followed by retention in wetlands, could be decreased by over 95% each, rendering the treated effluent suitable for unrestricted use for irrigation. The authors recommend this approach for countries in the Middle East and North Africa, which have been combating freshwater scarcity challenges.

Treated wastewater reuse has been firmly entrenched in Spain for many years now. However, Köck-Schulmeyer (2011) have attracted attention to the presence of five groups of organic contaminants (131 compounds) - namely pharmaceuticals, alkylphenols, polar pesticides, illicit drugs and estrogens, in that order of decreasing quantities. In Khan et al (2012), the authors, in a study done in India, concluded that treating municipal wastewater using upflow anaerobic sludge bed and flash aeration rendered it suitable for reuse in agriculture, with the nutrients in it also being available for the soil, but tertiary treatment would be necessary to remove the fecal coliforms from the wastewater prior to recycling. Robbie-Miller et al (2017) 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. However, an extremely small proportion of the nutrients from the wastewater could be recycled back to the soil. It was also observed that the crop pathogen content increased despite an appreciable decrease (99.9%) in the pathogen indicator organisms achieved during the treatment stages. But Elmeddahi et al (2016), after testing the quality of treated wastewater in Algeria, found out that the total coliform concentration of the treated wastewater was also within the national and international standards, while there was a total absence of toxic micro-pollutants such as heavy metals. While these 'ifs and buts' are inevitable, Reznik et al (2017) by using a Multi-Year Water Allocation System mathematical programming model to conduct statewide, long-term analyses of agricultural reuse of wastewater in Israel, determined inter alia, that enabling agricultural irrigation with treated wastewater significantly reduces the optimal capacity levels of seawater and brackish-water desalination over the simulated 3-decade period, and increases Israel's welfare by 3.3 billion USD in terms of present values, and that desalination to increase freshwater availability for agricultural irrigation is not optimal, as the costs far exceed the benefits to farmers and society.

Carr et al (2011) have however recommended that the farmers' perceptions of reclaimed water may be a function of its quality, but consideration should also be given to their capacity to manage the agricultural challenges associated with reclaimed water (salinity, irrigation system damage, marketing of produce), their actual and perceived capacity to control where and when reclaimed water is used, and their capacity to influence the quality of the water delivered to the farm. Irrigation with wastewater supports the livelihoods of millions of smallholder farmers associated with food, feed and fish production, in many parts of the world, and recovery and reuse of treated wastewater as a precious resource will become increasingly necessary in the future (Sato et al, 2013). The importance of documenting data about the generation of effluents, their qualities and the potential for reusing treated wastewater for different applications, has been highlighted by Sato et al (2013), and also Iglesias et al (2010). The latter provides a detailed overview of the status of wastewater reuse in Spain by Basin Departments and Autonomous Communities. A recent Iranian case study by Ansari et al (2018) has developed a holistic logical decision-making model to assess the technical feasibility of reclaimed water reuse in agriculture and tested it for Kordkuy in Iran. The model predicts that upto 718,560 m^3 of freshwater can be saved annually by planting soybean and rapeseed.

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. Among the benefits which accrued to the farmers (and to the economy and environment) were the reduction in the annual consumption of synthetic fertilisers, and a cost reduction per acre of crop of approximately USD 133 annually. Wastewater from a poultry-slaughterhouse was treated for potential reuse, using lab-scale membrane processes – reverse osmosis, ultrafiltration and nano-filtration - and analysed in Turkey by Coskun et al (2016). The operational expenses ranged between 0.66 and 1.66 USD per cubic metre treated, with the membrane processes being cheaper than the conventional treatment process.

In the industry

Recycling wastewater within industries after some in-plant treatment has become common, especially in cases where production/manufacturing is water-intensive. If there is a water scarcity in the region in which the industry is located and/or governmental regulations are strictly enforced, this becomes all the more necessary. Water pinch analysis enables the reuse of water in a cascade, as demonstrated by Wang et al (2018) in a printing and dyeing enterprise. Less-contaminated wastewater streams from processes within the enterprise, if separated at source (at the exit of the processes), could be reused sequentially at multiple levels, and a water (rather, wastewater) reuse rate of 62% could be achieved. In a Brazilian dairy sector case study, Andrade et al (2010) demonstrated the economic feasibility of using membrane bioreactors and nano-filtration in-plant, to remove organic matter, colour and dissolved solids from the wastewater in order to render it reusable within the dairy for alternate purposes - cooling, steam generation and cleaning of external areas. - use in a cascade again, similar to the case study of Wang et al (2018), but with intermediate treatment.

Zhang, M et al (2014) showed that the introduction of a sand filter to treat the process effluent enabled a Chinese paper and pulp mill to reuse the same, and decrease its fresh water consumption considerably. Karthik et al (2011), helped a paper mill in India to reduce its freshwater consumption by 40% by subjecting its effluent to chemical-aided clarification and simple membrane filtration (or micro/ultra-filtration). Majamaa et al (2010) had reported about the first time domestic wastewater was treated for reuse in industries in the Netherlands on a large scale. This facility had reported a 20% increase in the system recovery, and a halving of the operational expenses. In a textile industry case study presented in Pensupa et al (2017), the authors have observed that textile manufacturing processes are chemical-intensive and consume a lot of water. They have described different strategies for recovering sugars as monosaccharides from the cellulose fibre-wastes, along with wastewater recovery and reuse.

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. Simate et al (2011), while observing that the water footprint of beer is high enough to warrant investments in wastewater recycling within breweries, have analysed the challenges associated with decreasing the freshwater consumption in South African breweries. At the time of writing, this comes across as indispensable for the country, many cities of which (Cape Town especially) are facing imminent water shortages. Hydraulic fracturing for shale gas recovery is now a well-entrenched process in the oil and gas sector, especially the USA. Kausley et al (2017) have explored the feasibility of using electrocoagulation for the treatment of wastewater from shale gas recovery, for potential reuse. They found that a combination of electrocoagulation and aeration, under alkaline conditions gives the best results. Australia has been combating water shortages for quite some time now, and the world can learn from the implementation of novel technologies and approaches, in that country. Tunc et al (2011) have reviewed the use of membrane technologies for the treatment and reuse of water in industry, and in addition to recovery of sodium sulphate and energy in the process, they report water recovery in the range of 80 to 95%.

In society

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. They concluded 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. 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 can 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%.

Manawi et al (2017) have advocated an increase in the reuse of treated wastewater in Qatar, from the current 25 million m^3/year, which accounts for only 27% of it. While the current reuse applications are restricted to growing fodder for cattle and some landscape gardening, the authors believe that there is potential to extend the end-(re)user-profile to industries and households too. While Qatar is a rich country and desalination may be eminently affordable at the time of writing, affluence must not be a deterrent to the promotion of sustainable practices. Another oil-rich nation, Kuwait has also depended on the expensive desalination of seawater for many years to satisfy almost all of its water demands, and as reported in Abusam et al (2013), the importance of reusing treated wastewater in the future, has been appreciated by the government. Omole et al (2017) chose a university campus in Nigeria to assess the possibility of wastewater reuse. In year-2013, as indicated by the authors, approximately 874,081 litres of black and grey water were generated daily and discharged to a constructed wetland prior to disposal. Sampling the effluent from the wetland showed that the treated wastewater could be easily utilised on-campus for landscape irrigation and perhaps other purposes as well.

Conclusion

Different wastewater streams in different parts of the world can be looked upon as sources for recovery of different types of resources – energy (heat, electricity and transportation fuel), materials (organic and inorganic) and water for reuse. Often, a potential can be detected, but in the absence of political will, techno-economic ability and socio-environmental need (the more pressing, the better), the potential cannot and will not be harnessed. The drivers or factors promoting/urging/compelling resource recovery vary from country to country and region to region. Depletion of phosphate reserves will hurt one and all in the future, but some countries like India, which incur high import bills owing to their total dependence on imports of phosphate-based fertilisers will find incentives in nutrient recovery. A similar rationale can be furnished for recovery of materials of other types. Energy shortages combined with a pressing need for reducing the use of fossil fuels, may prompt energy recovery in some other parts of the world, like China, India, Indonesia etc. Likewise, water scarcity which may worsen courtesy climate change in the future will make wastewater treatment and reuse mandatory in some countries, like the ones in the Middle East and North Africa and also southern Europe. It helps to have regulations in place – these though while being necessary will not be sufficient.

For this paper, the author resorted to Scopus as a repository for recently-published (in the period 2010-2018) articles on resource recovery from wastewater and filtered down the search results in two steps to a more manageable one. Thereby, the publications referred to and reviewed in this article, form a small subset of the total. The publications originate from different parts of the world (44 countries, with China topping the Asian list with 19, USA leading the list of the Americas with 9, Spain being the numero uno in Europe with 8), and have a good spread over the 9-year period referred to (with 27 of them from 2017 and 22 from 2011). All this goes to show the importance which this field of research and endeavour has attracted over the years, and will continue to do so, in academic research, globally.

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