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Abstract

Under increasing demand for water, fertilizer and energy, waste and wastewater treatment can be potential options for considerably enhancing not only the supply of these valuable economic assets but also for improving sanitation and ecological conditions. Effluents and treated wastewater are important for meeting water demands for agricultural irrigation, landscape irrigation, and environmental system enhancement. Fertilizer and nutrients recovered though recycling organic waste and filtering wastewater, or embedded in effluents can be essential inputs for increasing crop biomass, timber output, and production of aquatic crops and marine species such as fish. Similarly, energy recovered from waste and wastewater recycling (including dry manure for cooking and heating) is important for enhanced energy supply especially in remote rural areas of the developing countries. Yet, the utilization of the waste and wastewater resources for additional gains should consider the accepted safety measures in order to prevent environmental and health risks. Focusing on potential benefits from resources recycling and recovery yet being cautious on their external effects, this review critically assesses the available waste and wastewater treatment options, and their economic, environmental and health benefits and risks.

Keywords: waste, wastewater, effluents, nutrients and energy recovery

1 Introduction

Enormous amount of waste and wastewater generated in both urban and rural areas is a key reason for air, soil and water pollution, especially in developing countries (Lazarova et al. 2013). Disposal of untreated waste or release of untreated wastewater into fresh water sources are serious threats which aggravate environmental pollution consequently leading to various water- or air- borne illnesses (Drechsel et al. 2010, Gebrezgabher et al. 2016). Given the increasing scope of environmental and health problems triggered by inadequate sanitation, UN sustainable development goals (SDGs) also underline the needs for improved sanitation measures in the developing countries (UNWATER 2016). These measures particularly aim at better access to potable water supply and sewage systems in residential areas, reduction of open defecation, improved waste management, and increased recycling of waste and wastewater. With the increasing land scarcity and environmental control requirements, recycling the waste and re-using the recovered products for value creation will be more viable than the waste disposal into dumping sites (land filling) (Tay and Show 1997).

Under conditions of growing water scarcity due to population growth, global warming and industrial development, treated wastewater can be suitable complement to fresh water supply (Schierling et al. 2011, Lazarova et al. 2013, Drechsel et al. 2015). Thus, treatment and reuse of wastewater not only improve sanitation and alleviate environmental concerns in the epoch of urbanization but also bear additional economic value added through recovering water, energy, and nutrients from waste and wastewater (Schierling et al. 2011). Under the currently increasing costs for traditional ways of water supply augmentation (e.g., building reservoirs or inter-basin water transfers) and given the rapid advancements in waste and wastewater treatment technologies, the costs of additional water supply through water treatment are expected to be competitive compared to the alternative options of water supply (Drechsel et al. 2015). Yet, distributing and matching water with varying quality for appropriate activities will be a challenge for water managers and policy makers (Drechsel et al. 2015, von Braun 2016).

Depletions of phosphate mines (Ashlay et al. 2011; Cordell et al. 2011) and fossil fuel stocks (Aleklett and Campbell 2003, Höök and Tang 2013) are other threats for food and energy security reflected through the recent sky-rocketed prices for food, energy, transportation, and fertilizer. For a stable and sustainable economic prosperity under such conditions, transformation towards the increased use of alternative and renewable sources of water, energy and nutrients will gain prominence. Recycling waste and wastewater can be a win-win option from both environmental and economic perspectives, consequently allowing not only for improving environmental habitats and increasing the value of ecosystem services but also supplying food, energy, and water for production processes and direct consumption.

This study provides a review of various types of waste, respective treatment technologies and available assets from waste treatment. Thus, first, the development stages of sanitation and waste management systems, and the waste availability and treatment levels across the regions of the world are presented. Next the availability and reuse of waste and wastewater across the world are described before a brief discussion of the available options for waste and wastewater treatment. Then, poverty alleviation effects and health-environmental risks related with RRR technologies are discussed. The last section summarizes the findings and provides final concluding remarks.

2 The development stages of waste management and re-use

Problems of pollution and the need for sanitation especially in urban areas have been known over centuries and the respective management practices have been evolved over time. As recently reported, four major epochs of the development of sanitation and waste management throughout the history are as follows (Ashley et al. 2011): 1) the use of night soil and sewage for farming purposes in period between 3000 BC till 1850; 2) the Era of sanitation awakening started from 1860 till 1960; 3) the period of wastewater reclamation and eutrophication monitoring continued between 1960 till 2000; and 4) the recent Era of ecological sanitation started from 2000s.

At the first stage, a waste from the residential areas, especially feces, sewage and manure were either directly applied to croplands or recycled through composting before the applications. The use of night soil for improving soil quality was known and widely practiced in China as early as 3000 BC (Ashley et al. 2011; Marald 1998). Human excreta was used as soil amendment in Japan since the 12th century and continued till the recent past (Matsui 1997). Seeing a night-soil man carrying buckets in the streets and collecting urine and feces was common in Singapore till mid-1980s. Following large scale land degradation and consequent famines in Middle Ages, sewage was also being applied for farming purposes in Germany and UK. In 19th century, England was importing large amounts of bones all across the European countries (Cordell et al. 2009) for applying it in agricultural lands. This technology was later improved for creating a liquid fertilizer through dissolving bones (Liu 2005). During that period, night soil companies were functioning in New York city (Ashley et al. 2011).

In the second stage, health risks related with the use of fecal waste imposed the implementation of disease prevention and hygienic measures. Particularly, the cholera epidemic in Europe in 1850s increased the importance of sanitation measures (Ashley et al. 2011). Thus, the main focus of waste management in this period was disposing the waste outside of the living areas for preventing further illnesses and disease epidemics. Wide-scale construction of sewage systems and introduction of septic tanks and cesspits were specific characteristics of this period.

However, enormous amount of waste disposal into environmental systems increased environmental pollution problems. Increased environmental consciousness and the need for more sustainable management of wastes after 1960s started a new Era of environmental protection (Ashley et al. 2011). Waste and wastewater was required to be treated before discharging it into the rivers or lakes. Different methods of wastewater treatment such as physic-chemical and biological treatment methods were invented and applied. Wastewater was treated and widely used for irrigation purposes, for instance, in Israel. Organic waste was composted and used as fertilizer for crops.

Since 2000s, given the increased scarcity of fertilizer and energy resources, technologies of producing nutrients and energy such as biogas, electricity, fertilizer and soil amendments have been developed and widely facilitated (Ashley et al. 2011). Particularly, these technologies aimed at separation of urine in the sewage system and its recycle for producing fertilizers, or composting fecal sludge or organic waste for further production of fertilizers and biogas (Tilley et al. 2014). The use of wastewater passed through advanced treatment process became more common in multiple sectors (agriculture, industry, and residential sites).

Indeed, these development tendencies in waste and wastewater treatment sector describe the changes in technological frontiers at global level. However, advancement level of waste and wastewater treatment largely varies across the countries. The developed countries of the world tend more towards 'environmental friendly' waste and wastewater treatment and re-use which offer multiple environmental and economic benefits through recycling (Table 1). Despite multiple benefits of waste and wastewater treatment and re-use, 'pollution inducing' practices of disposing waste and wastewater without adequate treatment are still common in developing countries of Africa, Latin America and South Asia.

Table 1: The comparison of 'pollution inducing' and 'environmental friendly' waste management

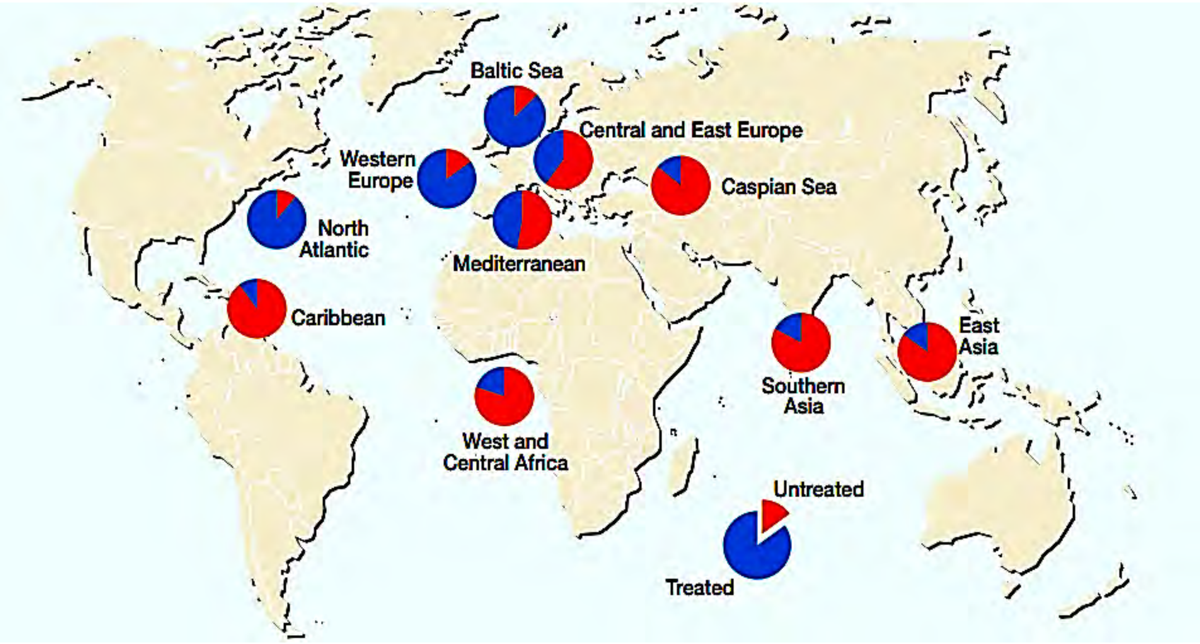
	'Pollution inducing' waste disposal	**'Environmental friendly' waste reuse**
Collection	• Lack of latrines and septic tanks • Lack of waste collection • Open defecation	• Flush toilets, septic tanks and latrines • Waste collection stations
Transportation	• Lack of organized transportation of waste • Discharge to drainage system	• Onsite of centralized sewage system • Special trucks to transport waste
Treatment	• Lack of treatment or minimal treatment	• Screening plastic waste • Removal of pollutants
Disposal/Reuse	• Disposal into dumping sites or discharge waste into water system	• Disposal to dumping site after proper treatment • Recycling soil conditioners, energy commodities, proteins, and effluents
Environmental effects	• Water and air pollution • Groundwater contamination • Land erosion and degradation • Reduced biodiversity • etc.	• Improved sanitation • Reduced water and air pollution • Reduced health risks • etc.
Economic effects	• Reduced environmental system and recreation benefits • Reduces agricultural yields	• Recovery of nutrients, energy, and effluents

Pearce (2015) differentiated four types of mental models (concepts) of waste management across the world. These concepts consider different levels of technological advancement and roughly match with the technological progress level observed across the four epochs of waste management and sanitation discussed above: 1) non-recognizant; 2) sanitation-oriented; 3) treatment-oriented; and 4) recovery-oriented. A non-cognizant model does not consider a proper management of waste or sanitation and appropriate infrastructure for waste collection or public facilities for sanitation does not exist. This model may characterize the conditions in urban slums across South America and Africa. A sanitation-oriented model prioritizes waste management for protecting health and avoiding human contact with waste. This approach may be more dominant in fast growing second-tier cities across China and India. A treatment-oriented model aims at environmental protection in addition to health protection and thus considers the prevention of pollutants from leaking into environmental system. This model is more common in most cities of the developed world. A recovery-focused model considers waste and wastewater not only from sanitation and environmental protection perspective but also treats as an economic resource which can be recycled and returned to the production circle. This model is less common in practice compared to the other three mental models and shared only in few places across the world. Yet, as implied from the 'Kuznetz curve', with the improved income levels and reduced technology costs 'environmental-friendly' waste and wastewater management systems should gradually replace the less advanced alternatives.

3 Wastewater and waste availability

Large amounts of waste and wastewater especially in urban areas is a potential resource valuable for recycled economic assets. Globally, total volume of wastewater is estimated to be between 0.68 and 0.96 km^3 per day or 250-350 km^3 per annum (GWI 2009, FAO 2010). It is almost 10-15% of annual agricultural water withdrawals (2,504 km^3; Siebert and Doel 2007). Yet, only 4% (32 million m^3 per day) of these wastewater passes through advanced treatment (GWI 2009) while the remaining 96% is disposed in lakes or river stream with very limited or without treatment. Although a large share of wastewater is treated in West European and North American countries, wastewater treatment rates are very low in developing countries located in South and Southeast Asia (Fig. 1).

Figure 1: The ratio of wastewater treatment across the word

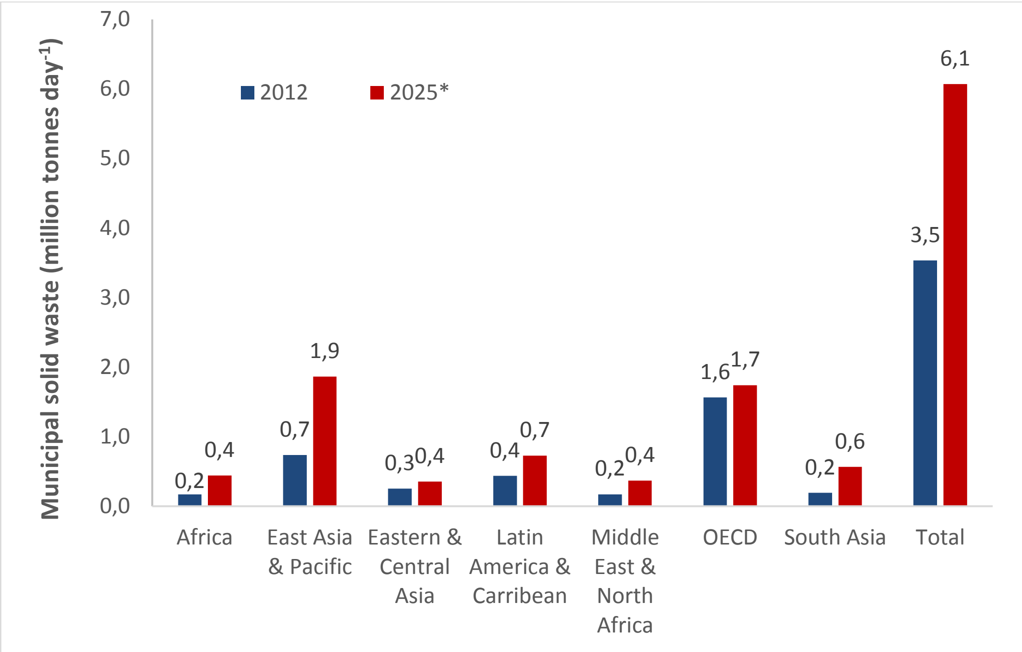


Source: Corcoran et al. (2010)

Release of untreated wastewater into fresh water aquifers not only reduce downstream water availability due to heavy pollution but also may have adverse effects on ecology of these water systems through increasing eutrophication problems and degrading living habitats for aquatic organisms (Schierling et al. 2011, Cai et al. 2013). Thus, adequate sanitation and appropriate treatment of wastewater are essential for both environmental and human health protection (Harada et al., n.d.). Moreover, wastewater treatment can be also turned into beneficial business thus allowing for recovery of useful economic assets. As estimated, each 1 US$ investment in improved sanitation and wastewater treatment may yield returns worth of 3 to 34 US$ (Hutton & Haller 2004). Re-use of wastewater resources can be also a potential option for considerably reducing water deficit in developing countries where irrigation water availability is a key challenge for sustainable agricultural production because of high population growth and temperature raise.

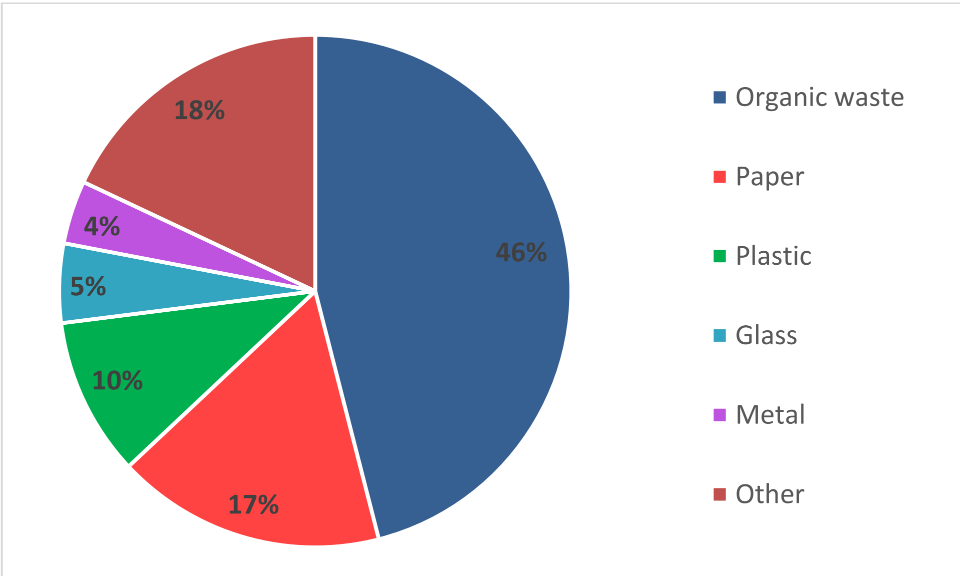
Massive quantity of municipal solid waste is another potential source for recycled energy and soil amendments. At present, daily 3.5 million tons (as of 2012) of municipal solid waste is generated across the world and is expected to increase over 6 million tons coming to 2025 (WEC 2016, Fig. 2). While almost half of this waste is generated in OECD countries rapid increase of waste generation is expected in East Asian and Pacific countries till 2025. Almost half of this municipal solid waste is organic waste which can be further composted or recycled to produce fertilizer or energy commodities (Fig. 3). In addition to wastewater and municipal solid waste, livestock manure and crop residues can be useful as soil amendments or biofuel.

Figure 2: Daily municipal solid waste generation across the world regions



Source: Based on Hoornweg and Bhada-Tata (2012)

Figure 3: Composition of municipal solid waste



Source: Based on Hoornweg and Bhada-Tata (2012)

4 Resources recovery and re-use technologies

4.1 General description

Waste such as municipal organic waste, sewage water and fecal sludge can be recycled and reused in multiple ways of recovering valuable assets such as effluents (treated water), nutrients (phosphates, nitrogen, protein) and energy (biogas, liquid fuel, electricity) (Table 2). Sewage and drainage waters can be reused for irrigation or aquaculture after appropriate level of treatment and thus considerably improve water availability for agriculture, especially in dry regions. Organic food waste and animal manure can be also recycled (composted) and reused for cultivating crops as soil amendments or for cooking as biofuel. Some of these resource recovery and reuse (RRR) technologies may allow for recovering multiple assets (e.g., not only water or fertilizer but both or even energy in addition) from waste. Next subsections provide a detailed description of various options of recovering water, nutrients and energy from the recycled waste and wastewater. For clarity, we separately describe recovery of particular asset (effluent, fertilizer, or energy) in each sub-section but it does not mean that a certain technology produces only a single type of asset.

Table 2: Options of resource recovery and re-use (RRR)

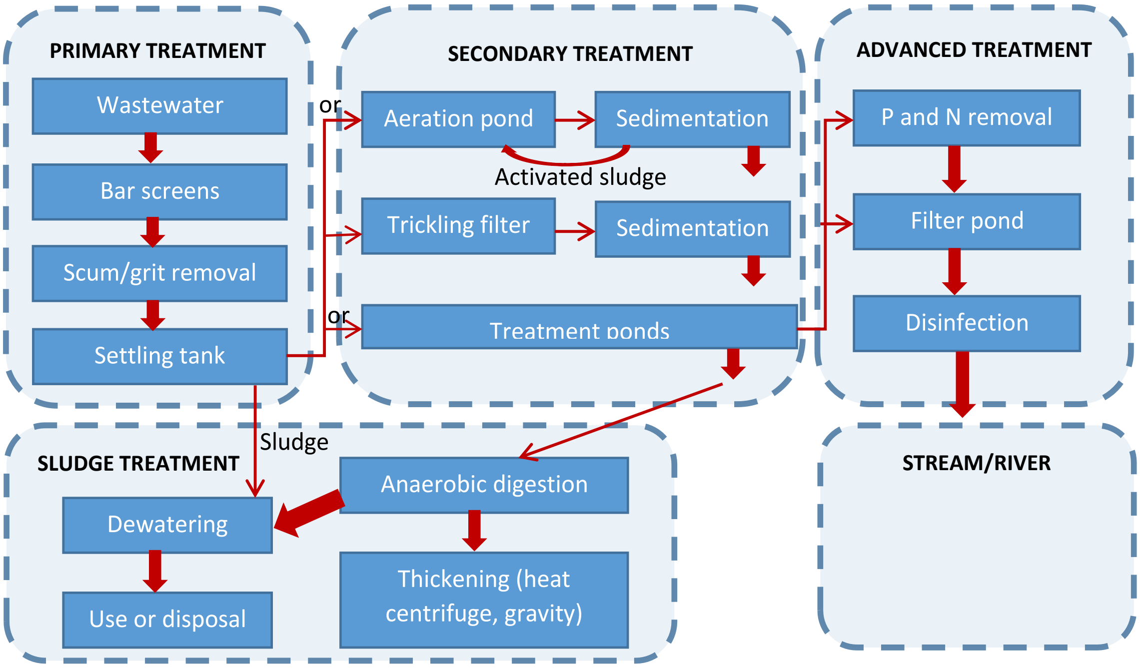
		Intermediate products												
		Raw sludge	Bio-solids	Biogas	Dewatered sludge	Steam	Compost	Sludge centrate	Sludge ash	Syngas	Oil	Liquid	Treated water	Soldier fly
WASTE STREAM														
Waste-water	Sewage	x	x	x	x	x	x	x	x	x	x	x	x	
	Fecal sludge			x										x
	Urine											x	x	
	Drainage												x	
	Algae			x			x				x			
Organic waste	Food waste			x			x							
	Waste from food processing			x		x	x							
	Manure			x		x	x							x
	Crop residues					x	x							
FINAL OUTPUTS														
Effluents (Treated waste-water)	For irrigation												x	
	For aquifer recharge												x	
	For fish pond												x	
Soil nutrients	Fertilizer	x	x					x	x			x		
	Soil amendments		x		x		x							x
	Struvites							x						
	Cover crop	x					x							
Energy	Gas			x										
	Electricity			x						x				
	Heat					x								
	Fuel										x	x		
	Protein													x
Crop protection	Pesticides									x				
Building materials		x			x				x					

Source: Based on Pearce (2015) and Tan and Lagerkvist (2011).

4.2 Wastewater as an economic asset: current status and potential options

Wastewater treatment first of all aims at safe disposal of wastewater after treatment (sanitation benefits) and thus protection of environmental resources. Yet, effluents and nutrients embedded in wastewater may bear additional economic benefits through enhancing biomass production and energy recovery. Water treatment options vary depending on the purpose of the treatment, the complexity of the process and investment and operating costs. In general, four steps of wastewater treatment can be differentiated: 1) primary treatment, 2) secondary treatment, 3) sludge treatment, and 4) advanced treatment (Razzak et al. 2013, Fig. 4). Primary treatment considers capturing large objects such as plastics and rag, removal of scum and grits, and separation of liquid and solid waste sequentially. In secondary treatment, water passed through primary treatment can be released to aeration or filtration ponds or lagoons where soild waste will be sedimented. Sedimented waste from primary and secondary treatment will be further recycled in sludge treatment stage while filtrated water from the lagoons will be further transferred for advanced treatment. In sludge treatment process, the solid sludge can be dewatered and disposed to dumping site or can be further recycled through incineration and thickening process to produce energy, compost, or nutrients. Meanwhile, the filtrated water may pass through advanced phosphate and nitrogen removal and clarification process before a release into water system, or before a re-use for irrigation or landscape reclamation.

Figure 4: Wastewater treatment system



Source: Adapted from Razzak et al. (2013)

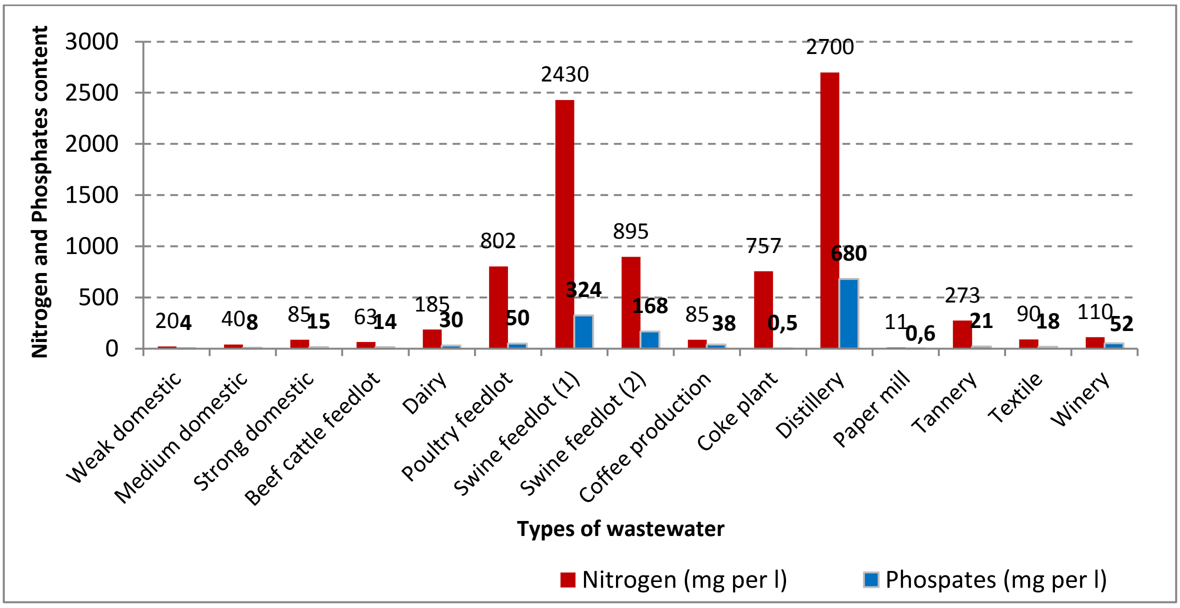
While wastewater re-use for agricultural and landscape irrigation are common practices, fish production, wastewater can be reused also for river ecosystem maintenance, potable and non-potable uses, recreation, and recharging aquifers (World Bank 2010, Schierling et al. 2011, Lazarova et al. 2013, Hettiarachchi and Ardakian 2016). At present, treated wastewater from different economic sectors is mostly reused for agricultural production (32%) (Table 3) because of its rich nutrient content (Fig. 5). Wastewater uses for irrigation are particularly common in areas near urban settlements (Schierling et al. 2011). Except for agriculture, large portions of wastewater are also used for landscape irrigation (20%), and industrial activities (19%, Table 3).

Table 3: Wastewater reuses for different purposes in the world

	Sectors	Share in total water reuse (%)
1	Irrigation	32
2	Landscape irrigation	20
3	Industrial activities	19
4	Environmental flow	8
5	Non-potable residential use	8
6	Recreation	7
7	Recharging aquifers	2
8	Other	4

Source: Based on GWI (2009)

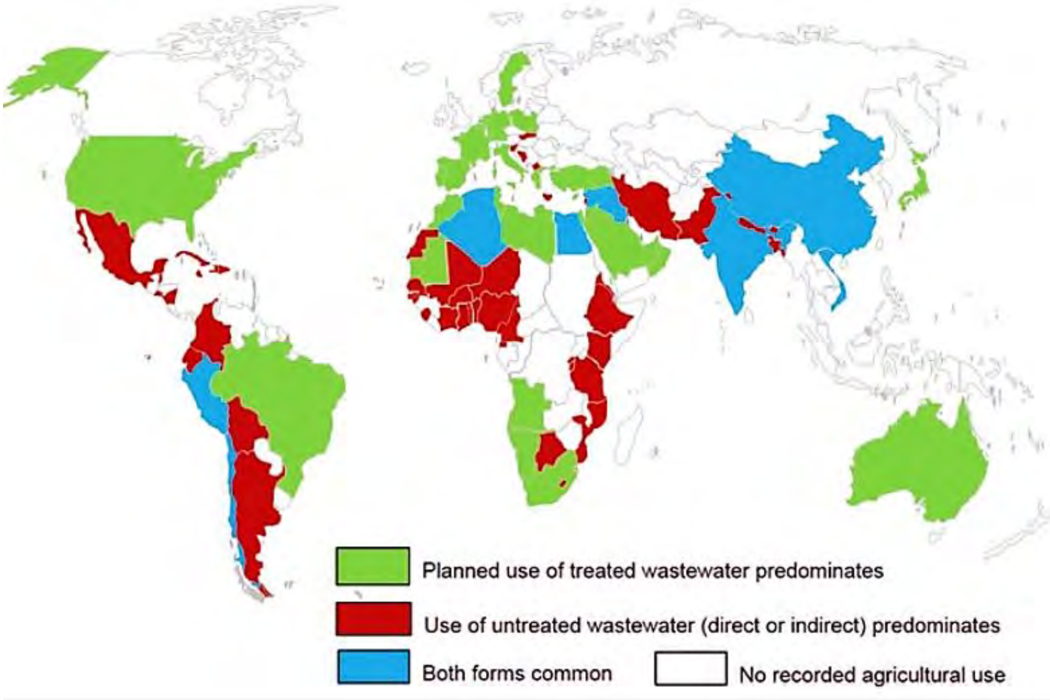
Figure 5: Nitrogen and phosphorus content of different types of wastewater



Source: Based on Christenson and Sims (2011).

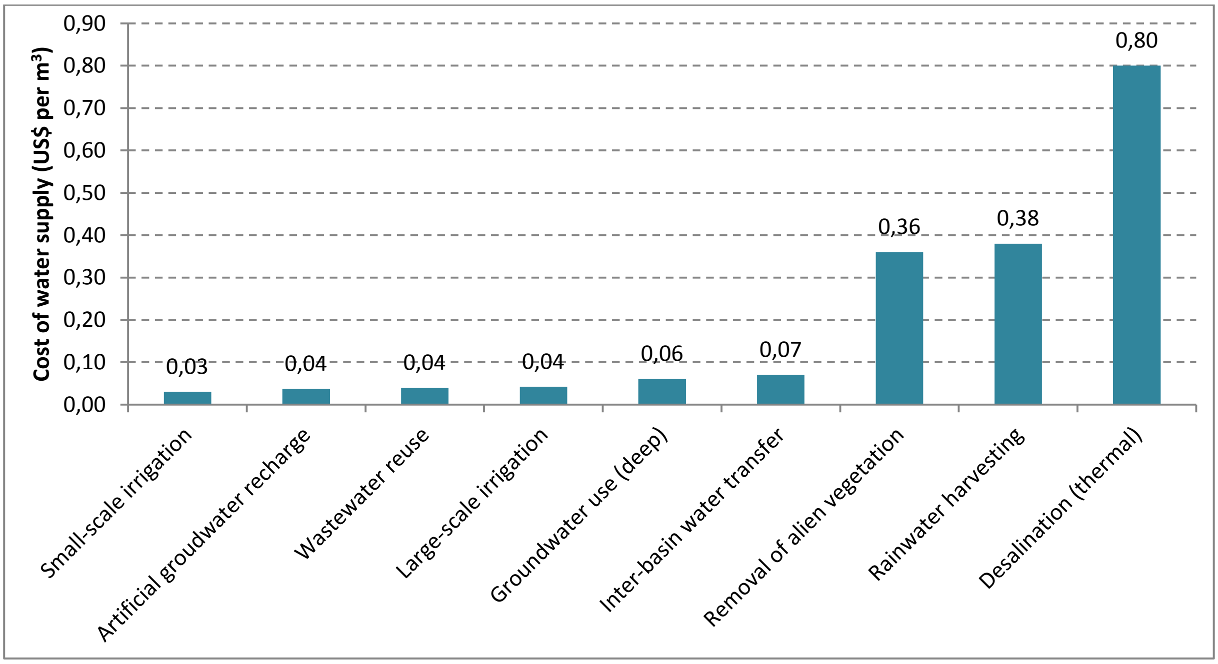
Wastewater was estimated to be used over 6-20 million ha of croplands in total (World Bank 2010, Drechsel et al. 2015). In China alone, wastewater is applied over 4.2 million ha irrigated lands which represents 5.7% of country's total irrigated lands (Xie et al. 2009). According to some estimates wastewater allows for producing about 10% of total crop production outputs from irrigation globally (Drechsel et al. 2010, Schierling et al. 2011). It is used for irrigation of cultivating both food and fodder crops (Lautze et al. 2014). While some level of wastewater treatment is required to apply wastewater for irrigation purposes, there are also cases that wastewater is directly applied for irrigation in some countries of South and East Asia and Africa. Wastewater was properly managed and formally used for irrigation purposes in the developed countries such as Israel, Australia, and the USA, however, informal (or unplanned) use of wastewater is common both in China and India (Fig. 6). Considerably lower costs of wastewater reuse compared to deep groundwater extraction or water transfer from the neighboring basins, for example, also adds to its financial viability (Fig. 7). Yet, advanced treatment of wastewater through the removal of undesired vegetation or desalinization for generating good quality water suitable for reuse in irrigation and non-irrigation activities (e.g., industry, maintenance of landscapes in municipal areas, drinking) may come at much higher costs since it may demand large amounts of energy use and capital investments.

Figure 6: Use of wastewater for agricultural production



Source: Drechsel et al. (2015)

Figure 7: Comparison of the costs of wastewater reuse to alternative water supply options



Source: Adapted from McKinsey&Company (2009), in the example of India

Wastewater is reused also for aquaculture (Drechsel et al. 2015, Tilley et al. 2014). Increased productivity of fish production was reported when reclaimed water was applied in fish ponds (Lautze et al. 2014). In ideal conditions, fish production may reach as high as 10 ton per hectare in wastewater ponds (Tilley et al. 2014). Effluents can be applied in fish ponds to maintain water supply. Sludge can be discharged to the pond to enrich the nutrient content of water and increase biomass of algae which is consumed by fish. Though this system cannot fully eliminate toxic elements in water, at least this system substantially reduces mechanical wastewater treatment costs (Tilley et al. 2014).

Cultivation of fodder crops, plants, and macrophytes in wastewater stabilization ponds or drying beds may also considerably improve feed stocks and provide construction materials for local village communities (Harada et al. *n.d.*, Tilley et al. 2014). Alternatively, nutrients in wastewater can be removed by cultivating microalgae in heavily polluted water systems (ponds, canals, etc.) and the biomass from this aquacrop later can be used as fish feed or bioenergy source (Drechsel et al. 2015). Removal of phosphorus, nitrogen, and toxic metals from wastewater also prevents unwanted phytoplankton blooms in aquatic systems (Cai et al. 2013). Some algal species (out of over 36,000 various species) are characterized by accumulation of oil and lipids in their cells and thus can be further used for producing not only animal feed and bioenergy, but also soil amendments, pharmaceutical materials, and dyes (Razzak et al. 2013). *Chlorella vulgaris* and *Phormididium laminosum* are two main species with high protein and lipid content and widely investigated for their potential of removing phosphorus and nitrogen content from the wastewaters (Razzak et al. 2013). Microalgae can be grown in all types of wastewaters from municipal (Li et al. 2011, Chi et al. 2011), agricultural (Mulbry et al. 2008, 2009), and industrial sectors (Chinnasamy et al. 2010, Markou and Georgakakis 2011).

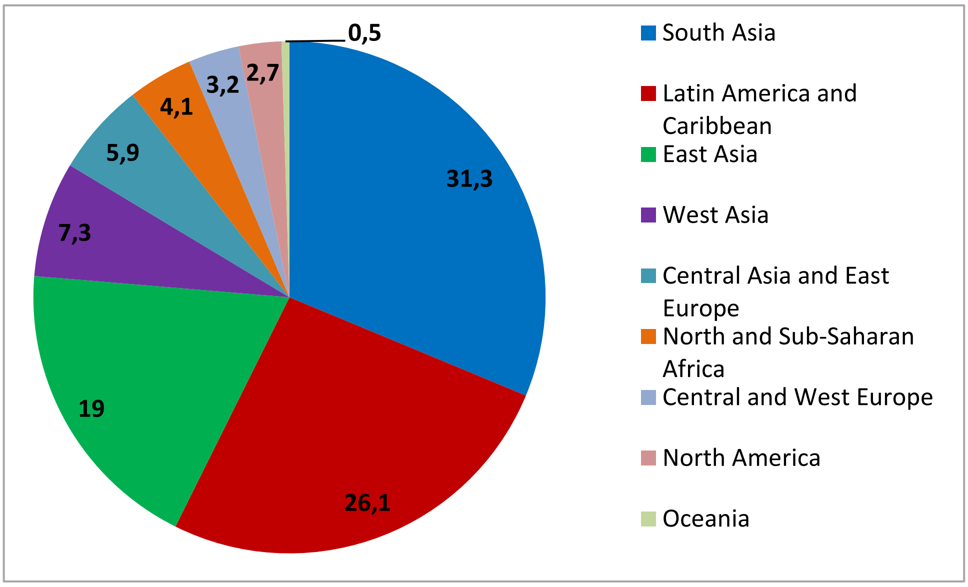
Use of algal species for biofuel production may partially replace demand for biofuel crops and thus reduce land use requirements for cultivating biofuel crops (Singh et al. 2011; Pittman et al. 2011). It may in turn lead to availability of more land for food crops and lower food prices. According to some estimations, biofuel productivity in lagoons culturing microalgae is 12-14,000 L ha^{-1} per annum which is twice as high as productivity of palm oil fields (5600 L ha^{-1} per annum, Cai et al. 2013). In addition to wastewater treatment and bioenergy production benefits, algae can also contribute to carbon fixation since its cultivation requires large amount of CO_2 consumption (Razzak et al. 2013). Yet, harvesting microalgae both through mechanical and chemical methods substantially increases the costs of bioenergy production from microalgae and reduces its competitiveness with other energy resources such as petroleum (Razzak et al. 2013). It is also reported that most of the studies on algae cultivation in polluted environments are conducted at laboratory scale yet the results of some pilot projects on microalgae cultivation at larger scale showed inconsistent purification of wastewater and unstable biomass outputs (Cai et al. 2013). Thus, lack of reliable and cost effective methods of harvesting and producing algae biomass at large scale may constrain the biofuel generation based on algae feedstock (Christenson and Sims 2011).

In industry, fully or partially treated wastewater can be circularly reused in most sectors such as commercial laundries, car washing stations, textile industry, meat processing, beverage production, and power plants (Jimenez and Asano 2008). Wastewater can be also used for cooling plants or heating the buildings. Moreover, wastewater can be applied for recharging aquifers through infiltration basins or injection wells (Lazarova et al. 2013). Wastewater use for refilling the depleted gas mines, for instance, may further prevent potential earthquake risks.

4.3 Nutrients from waste: current status and potential options

The importance of fertilizer for agricultural production and global food security is unquestionable though the criticality of phosphorus availability for meeting future food demands were not commonly recognized as of water and energy (Cordell et al. 2009). Global demand for phosphate is estimated to increase from 42.7 to 46.7 Mt by 2025 due to population growth and related increase in food demand (FAO 2015). Given the higher birth rates and currently underdeveloped levels of agriculture, the highest share (more than 30%) of this additional fertilizer demand growth is expected to occur in South Asia (Fig. 8). Substantial increase of fertilizer demand is also expected in Latin American-Caribbean and East Asian regions (with shares of 26% and 19% respectively).

Figure 8: Estimations on increasing fertilizer demand share by regions

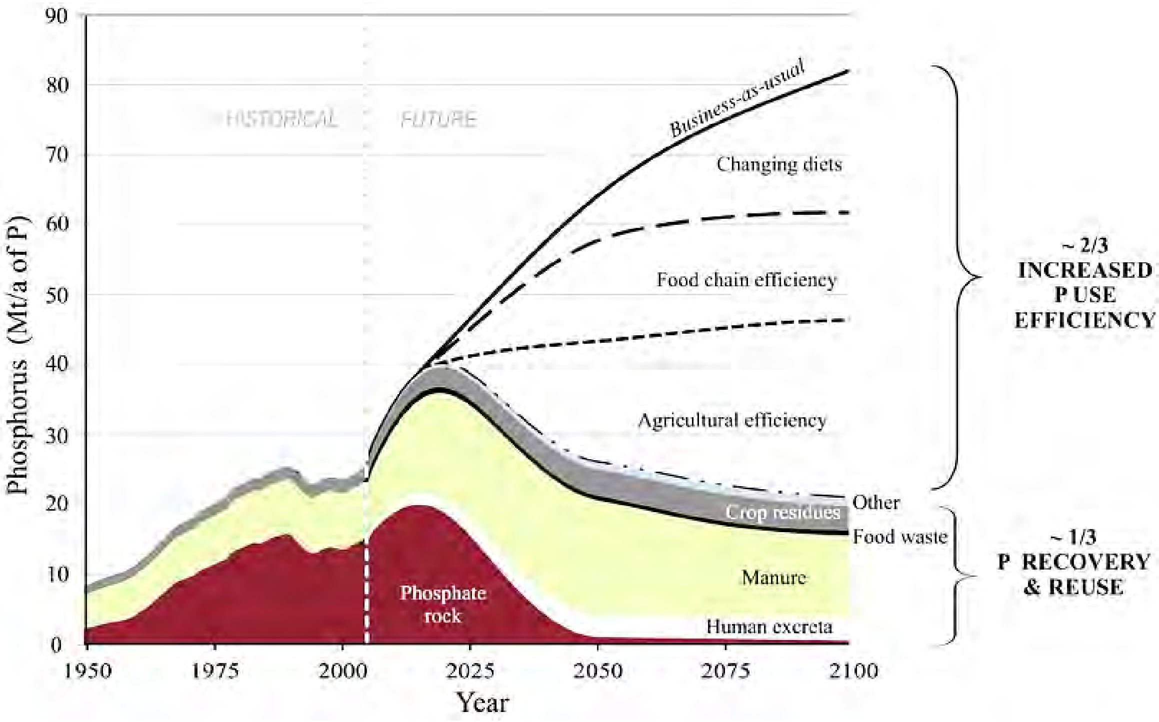


Source: Adapted from FAO (2015)

At present agriculture is not only dominant user of water resources but also fertilizer, consuming about 90% of phosphate resources (Smill 2000b, Rosemarin 2004, Mayer et al. 2016). Although opinions on the time of full depletion of phosphate rocks vary, the estimated amount of phosphate rocks from the currently known mines may suffice only till 2100s even under very optimistic scenario, unless new supplies are found (Steen 1998, Gunther 2005, Cordell et al. 2009). Declining quality of the reserves and increasing costs of extraction and transportation has been commonly admitted by the fertilizer industries (Runge-Metzger 1995, Smil 2000b, IFA 2008, Cordell et al. 2009). Rapid depletion of phosphate deposits and their availability only in countable number of countries such as Morocco, China, the USA, Jordan and South Africa would lead higher fertilizer prices and lower crop yields consequently threatening food security (Cordell et al. 2009, Jasinski 2010, Cieslik and Konieczka 2016). This would in turn increase poverty and hunger, especially for the poor in developing countries.

Given the depletion of phosphate rocks in near future, maintaining present and expected levels food security may require the dramatic transformation in phosphate production sources (Cordell et al. 2011). At present, phosphorus rocks and manure application contribute largely for overall phosphorus supply, though crop residues are also applied to nutrition plants (Fig. 9). About 15 million tons (Mt) of mined phosphates are estimated to be used for fertilizer production per annum globally (Rittman et al. 2011). However, its large portion (6-8 Mt) is being disposed to environmental systems through soil erosion and runoff losses, 5-7 Mt through animal waste, and 2-3 Mt through sewage waste (Rittman et al. 2011). Thus, two main opportunities of increasing the life expectancy of world's phosphate deposits and counterbalancing the expected higher fertilizer and food prices and increasing national phosphorus security are more efficient use of fertilizer in agriculture and recycling waste (especially manure) and wastewater (Cordell et al. 2009, 2011).

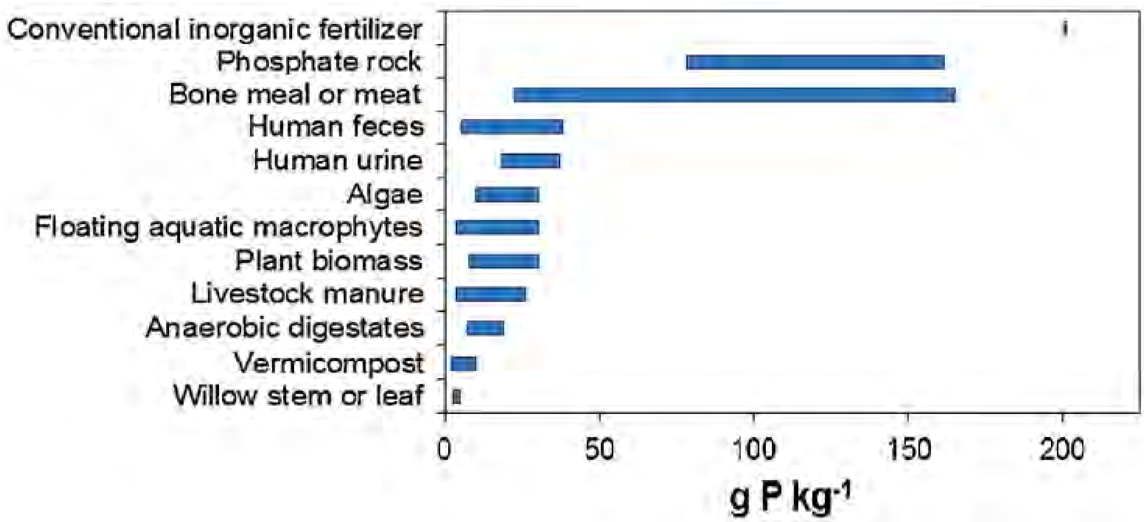
Figure 9: Options of meeting increasing demand for phosphorus



Source: Cordell et al. (2011)

Particularly, phosphate recovery from fecal sludge, urine, manure, crop residues, food waste and other organic wastes (bone meal, ash, algae, seaweed) may gain prominence in the long run (Karak and Bhattacharyya 2011, Ashley et al. 2011, Cordell et al. 2009). According to modeling estimations, the recovery of phosphates from urine and feces for instance may potentially yield about 20% of phosphates supply after 2050s (Mihelcic et al. 2011). Rich nutrition content of human and organic waste, especially bone meal, allows for production of fertilizer and soil amendments for agriculture from these wastes (Fig. 10). As estimated, the production of compost or soil amendments from fecal sludge may yield also net benefits worth of US$ 10 per ton in contrast to its disposal which may cost about US$ 42 per ton (Strauss et al. 2003).

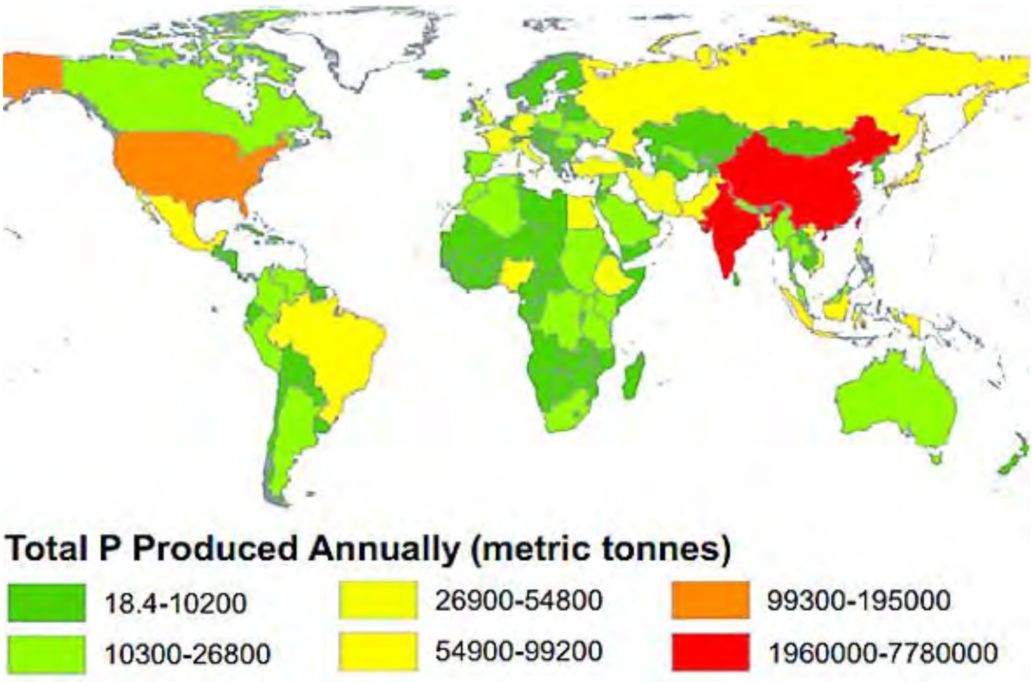
Figure 10: Phosphorus content of different types of waste



Source: Roy (2016)

As estimated earlier, large potential of recovering phosphates from fecal sludge exist in South and East Asian countries such as India and China (Fig. 11). Given the reliance of Indian agriculture on phosphates imports, phosphate recovery from feces can be particularly important in this country. Especially under conditions of hot climate the efficiency of waste treatment technologies based on anaerobic digestion will be higher (Drechsel et al. 2015), thus increasing the feasibility of waste treatment technologies in India.

Figure 11: Phosphorus available in feces and urine annually across countries (in 2009)



Source: Mihelcic et al. (2011)

Multiple technologies exist for producing valuable fertilizers from waste. Morse et al. (1998) classified these technologies as follows: chemical precipitation, biological removal, crystallization, tertiary filtration, absorbent application and sludge treatment. Although these technologies allow for safer application of recovered nutrients rather than direct application of fecal sludge for crop cultivation, their investment and operation costs, especially in developing countries may limit upscaling and wider impact (Cieslik and Konieczka 2016). Cheaper options may include cultivation of cover crops and retention of crop residues to improve soil quality. Tan and Lagerkvist (2011) described various methods of recovering phosphorus and other nutrients (nitrogen, carbon, potassium, magnesium, etc.) from biomass such as rice and wheat straws, rice husks, pine wood, peach stones, sugarcane bagasse, sunflower shells, sewage sludge, and paper sludge ash and found out high phosphorus content of peach stone ash and sewage sludge ash especially.

Systematic analysis of using human excreta (feces and urine) for producing fertilizer was carried out at EAWAG (Tilley et al. 2014). EAWAG researchers classified four key stages of waste stream within the supply chain of the treatment system and reviewed various technologies for each stage. These four key stage are (i) collection of the waste (e.g. from latrines and septic tanks), (ii) its transportation from the residential site to treatment site (e.g., composting or other advanced methods of treatment), and (iv) final use for production purposes as a fertilizer.

Open defecation is common practice in developing countries such as the ones in South Asia (Gupta et al. 2014). However, the collection of human waste requires changing the behavior of the people, building public and individual toilets, constructing sewage systems for more effective sanitation. Installing ventilated improved pit (VIP) and septic tanks may reduce the costs of sorting the waste in the later stages of waste treatment. Empting septic tanks may be either done manually or using motorized machines. In small communities of Africa and South Asia even using bikes for carrying urine containers was reported (Tilley et al. 2014). In advanced settlements, transportation can be done through sewage networks yet at higher capital costs. Waste treatment technologies vary depending on the purpose of recycling (e.g. fertilizer or biogas production) and availability of funds to establish them. Anaerobic baffled reactors and filters can be used to separate water from solid waste, consequently composting the solid waste for fertilizer production and releasing treated and disinfected water into environmental system. At cheaper costs, wastewater can be also treated in specially designed wetlands, stabilization reservoirs or lagoons that purify wastewater sequentially before re-use (Drechsel et al. 2015) and sedimented solid waste can be used for fodder or biomass production in these ponds. If wastewater is not directly used in the water treatment pond, treated wastewater can be diverted for irrigation purposes, for leaching fields, or for recharging groundwater aquifers. Compost directly or after co-composting with additional nutrients can be applied in crop fields. Composting stations can be also additionally equipped with biogas reactors to produce biogas or electricity and thus increase the benefits from recycling.

Application of compost and direct use of effluents or fecal sludge after even minimal treatment may have considerable impact on crop biomass and yields. Since urine has higher phosphorus content rather than feces (Rose et al. 2015), Karak and Bhattacharya (2011) reviewed the effects of urine application for the cultivation of various crops such as wheat, rice, corn, ryegrass, banana, cabbage, carrot, tomato, and spinach across several countries of the world and found out improved crop yields when urine was applied. In a similar review study, Singh and Agrawal (2008) also underlined the positive impact of applying sewage sludge on the yields of crops such as corn, barley, cotton, maize, sunflower and different types of tress (Table 4).

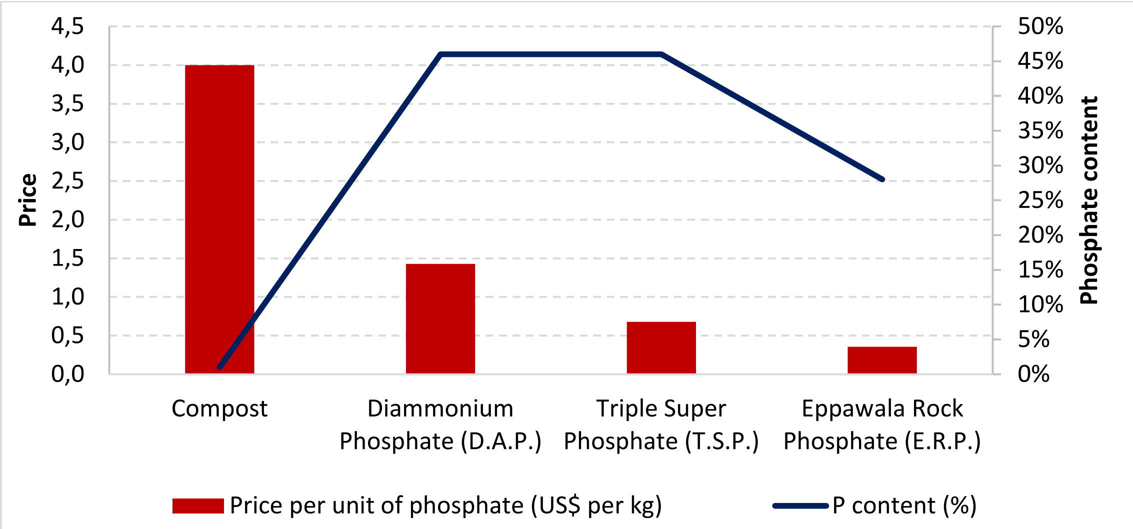
Table 4: Effect of sewage sludge application on crop biomass and yields

Crops	**Sewage sludge amendment application rate**	**Effects on crop biomass and yields**
Fescue	5.6 ton per ha	Yield increased by 30%
Corn	50-200 kg Nitrogen per ha	Higher yield
Barley	10 ton per ha over 17 years	Increased dry matter and yield
Cotton	2:1 and 10:1 – soil:sewage sludge ratio (together with tap water irrigation)	Increased seed production and fiber output
Maize	0-50 ton per ha	Increase in germination
Bahia grass	90-180 kg Nitrogen per ha	50% increase of forage and improved spring crude protein
Sunflower	0-320 ton per ha	Increase in dry weight
Bluegrama and *tobosa* grass	0-90 ton per ha	Increase in leaf area
Poplar tree	5:1 and 10:1 – soil:sewage sludge ratio (together with tap water irrigation)	Increase in height and diameter
Apple tree	0-75 ton per ha over 2 years	Higher fruit yield

Source: Adapted from Singh and Agrawal (2008)

Despite its yield and soil content improvement and soil humidity enhancement benefits, compost has lower comparative advantage over other fertilizers at present. The cost of compost that is adjusted considering its phosphate content can be considerably higher that the similarly adjusted prices for fertilizers with phosphates content (Fig. 12). Although adjusted price for *Diammonium Phosphates* (about 40% of compost price) is more expensive than other fertilizers and closer to compost price, it is because of additional nitrogen nutrients embedded in this fertilizer. Once the costs of transportation and application of compost is considered in comparative advantage analysis, willingness to buy and apply the compost by farmers may be further decreased given its bulky mass. Nevertheless, when the compost station is close to the farm and transportation of fertilizer increases due to bad road conditions some level of compost application can be unavoidable. The comparative advantage of compost increases also due to its additional, positive external benefits such as the organic natural content of compost, sanitation benefits and environment friendly nature (preventing soil erosion, reduced phosphate contamination of return waters and groundwater aquifers).

Figure 12: Prices per unit of phosphate content in different types of fertilizers

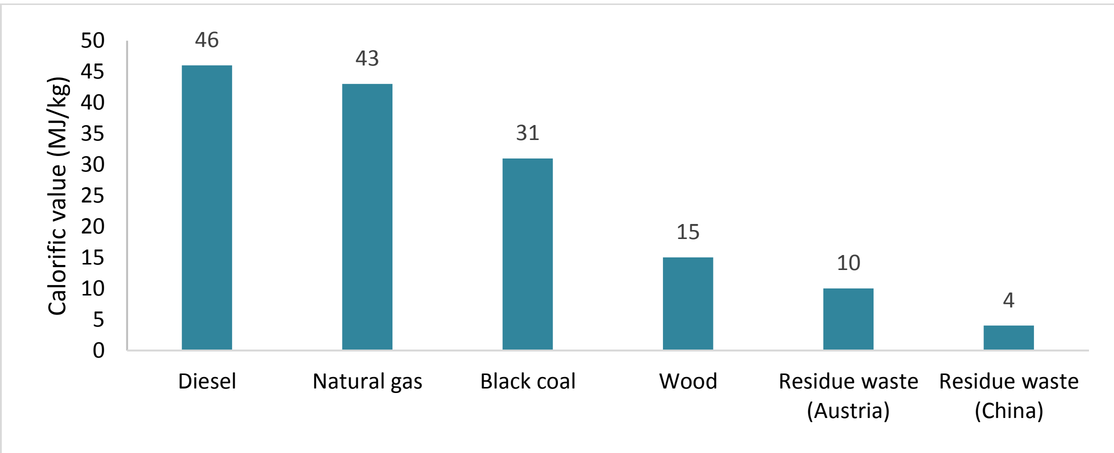


Source: Calculated using data from Ceylon Fertilizer Company Ltd. (2016)

4.4 Energy from waste: current status and potential options

Energy security is a crucial in many developing countries of the world since about 2.8 billion people will not have adequate access to modern energy facilities even coming to 2030 (IEA 2010). Especially, about 550 million people in India and about 400 million in China lives without electricity. This people mostly use solid fuels such as wood, crop residue, charcoal and dung for cooking and heating despite enormous health risks of these cooking practices (Gebrezgabher et al. 2016). Generation of heat, electricity, biogas, and biofuel from waste can not only reduce environmental degradation effects of waste disposal but also supply additional energy resources though the calorific value per unit of waste is much smaller than alternative energy sources such as diesel, gas, coal or wood (Fig. 13).

Figure 13: Calorific value of different energy sources



Source: Based on WEC (2012)

Waste and wastewater recycling requires enormous amount of energy (WEC 2016). Thus, improving energy use efficiency in the sector not only allows for saving substantial volumes of energy at low cost but also for reducing carbon emissions largely. For instance, the use of wastewater from towers of cooling power plants can be effectively used for heating purposes while reducing energy consumption and heating costs. In addition to large amount of energy savings through improved technologies, waste from municipal and rural residential areas can be recycled to produce various energy commodities such as biogas, electricity, and liquid fuel (biodiesel).

Main approaches of recycling waste for energy production are (i) thermochemical treatment, (ii) bio-chemical treatment, and (iii) chemical treatment (Table 5). At present, 90% of processes aiming at recovering energy from waste (REW) are based on thermochemical treatment (WEC 2016). Thermochemical treatment aims at burning waste at higher temperatures and thus using the heat energy or producing biogas. Bio-chemical treatment considers composting the organic waste and treating it with microorganisms and bacteria which consequently allows for biogas and power generation. Chemical treatment of waste considers reaction of waste with acids and consequently producing ethanol or biodiesel.

Table 5: Technologies of recovering energy from waste

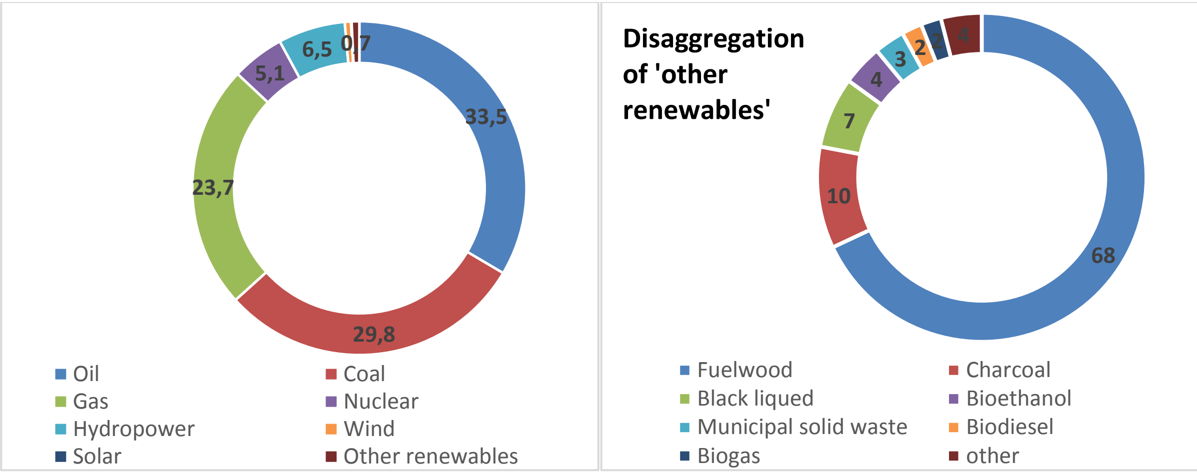
Treatment method	Treatment technology	Details of the technology	Output
Thermochemical treatment	Incineration	Mass burning at temperature higher than 1000C	Heat, power
		Co-combustion with coal or biomass	
		Using pre-treated waste fractions with higher energy contents	
	Thermal gasification	Conventional at temperature of 750C	Hydrogen, methan, syngas
		Passing waste into a kin at 4000-7000C	
	Pyrolosis	High pressure, no oxygen, and at temperature of 300-800C	Char, gases, aerosol, syngas
Bio-chemical treatment	Fermentation	Treating waste with bacteria in the absence of light (dark fermentation)	Ethanol, hydrogen, biodiesel
		Treating waste with bacteria in the presence of light (photo-fermentation)	
	Anaerobic digestion	Treatment of waste with microorganisms in the absence of oxygen	Methane
	Gas capture in dumping site	Extraction from dumping sites	Methane
	Microbial fuel cell	Conversion of the chemical energy of organic matter through catalytic reaction of microorganisms and bacteria	Power
Chemical treatment	Esterification	Reaction of an acid and an alcohol for creating an ester	Ethanol, biodiesel

Source: Adapted from WEC (2016)

About 130 million tonnes of municipal solid waste are recycled annually in over 600 plants of REW (Themelis 2003). Global energy output from municipal solid waste recycling thus valued at US$25.32 billion annually (in 2013) (WEC 2016). REW plants are located mainly in 35 countries and are built to deliver steam and electricity for heating and recover metals for reusing (Themelis 2003). The largest market for REW commodities is European Union which accounts almost half of global market revenue in this sector (WEC 2016). In Asia, Japan is a leader in REW, re-using almost 60% of its solid waste through incineration. REW facilities are relatively newly established in China where seven plants recycle over 1.6 Mt wastes per annum (Themelis 2003). Yet, REW is very rapidly growing sector in this country and more than doubled during very short period of time between 2011 and 2015 (WEC 2016).

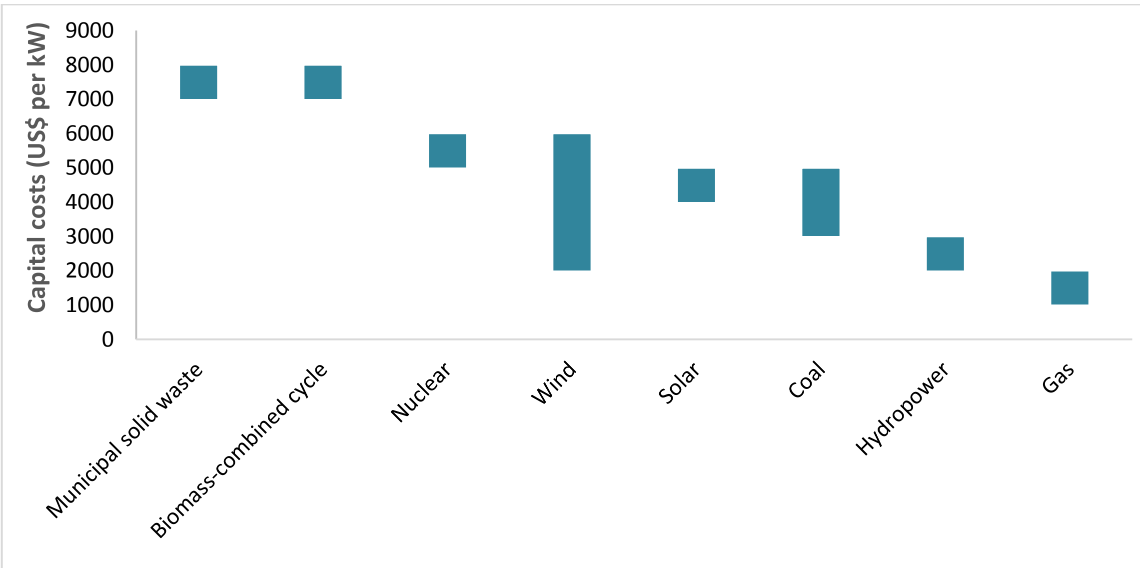
Despite the availability of multiple options of advanced treatment of waste for recovering energy, especially in the developed countries of Europe and Asia, the share of energy produced from municipal solid waste is only 0.02% (0.7% x 3%) of global energy output (Fig. 14). Given much higher costs of producing energy using waste compared to other alternative options of energy production (Fig. 15), the magnitude of waste recycling for energy production purposes are limited currently. Perhaps with the improvement of REW technologies and consequent cost reductions REW can be more attractive option compared to the alternative ways of energy production in developing countries. Large plants of REW in urban areas may also reduce the production costs of electricity from waste due to scale effect and thus may improve the feasibility of energy production from waste.

Figure 14: Main sources of energy supply globally (in 2016)



Source: Based on WEC (2016)

Figure 15: Costs of various energy production technologies in the US



Source: Based on WEC (2016)

4.5 Construction materials and protein from waste

Non-traditional approaches of using waste such as fecal sludge from wastewater for producing construction and building materials or protein was also earlier reported. Fecal sludge from wastewater can be converted to inert and odorless ash through incineration process and this ash can be mixed with clay for brickmaking to produce lightweight bricks (Tay and Show 1997). Up to 20% of addition of dry fecal sludge by weight was found not to considerably change brick's functional characteristics (Liew et al., 2004). Combusting sludge within bricks allows for creating small cavities which reduce vulnerability to freeze–thaw expansion (Alleman et al., 1990). Pelletized fecal sludge ash can be also used for producing masonry cement and lightweight concrete with moderate strength (Tay and Show 1997). Burned fecal sludge through incineration can be also easily handled and disposed to land filling. Despite beneficial use of sludge ash for producing building materials it is not always positively perceived by the producers of construction materials, especially in areas with abundant supply of conventional raw materials (Diener et al. 2014).

Fecal sludge is also used for rearing insect larva - black soldier fly (*Hermetia illucens*) – which subsequently used as protein addition to animal feed (Diener et al. 2009; Nguyen 2010). South African company, Agriprotein, uses this technology for producing feed for chicken and fish (van Huis et al., 2013). Many other studies also reported rearing insect larvae through using organic waste for producing feed not only for fish and chicken farms but also for farming frogs (Calvert et al., 1969; Hem et al., 2008; Ocio and Vinaras, 1979; Ogunji et al., 2007; St-Hilaireet al., 2007; van Huis et al. 2013). Productivity of larva mass can be higher especially when fecal sludge is applied together with municipal solid waste (Diener et al. 2009).

As experimented, one ton of fecal sludge with 40% dry solid content can yield 20 kg of dry animal meal from insect larvae with 35% protein content (Nguyen 2010). Considering that fishmeal with 70-80% protein content costs 0.7-1.2 US$ per kg (Diener et al. 2014), it can be estimated protein or fishmeal obtained through the treatment of one ton of fecal sludge with insect larvae may worth of 7-12 US$. Under increasing prices for fish feed (tripled during the period between 2005 and 2013) owing to increasing aquaculture production, economic feasibility of animal feed production using insect larvae is likely to be improved (Naylor et al., 2009). Processed solids remained after insect larvae treatment can be used as soil amendment thus further improving economic gains of insect larvae treatment (Diener et al. 2009).

5 Poverty alleviation and disease prevention effects of RRR

Recycling waste and wastewater resources for recovering effluents, nutrients and energy not only provide additional economically valuable assets but also further improve water, food and energy security in developing regions where these security improvements are highly demanded. Additional supply of water through wastewater treatment and replacement of fresh water use with the use of lower water quality when appropriate gain importance under increased frequency of droughts and higher crop water requirements (evapotranspiration) due to global warming (Meehl et al. 2007). Improved water supply in turn would improve food and biomass outputs, consequently counterbalancing potential hunger and malnutrition risks expected due to temperature rise.

Improved water access together with increased availability of nutrients and energy resources also essential for improved health of population and reduced incidents of illnesses among children. Safe access to water for drinking and sanitation and access to food supply at affordable prices are important as disease-preventive measures. Improved access to energy through waste and wastewater recycling, especially in winter months, may counterbalance frequent energy supply cuts in this period and thus indirectly add for disease prevention.

The establishment of well-organized waste recycling and wastewater treatment creates also new job opportunities to poor people residing in developing regions (IGES 2010). Thus, the wide-scale implementation of resource recycling and recovery technologies may have tremendous poverty alleviation effect. Yet, the improving the working conditions and mechanization of waste and wastewater collection and treatment system can be essential to improve the status of the employees in this sector (Zhu et al. 2008).

6 Health and environmental risks related with RRR technologies

Despite multiple benefits available from the recycling and reusing waste and wastewater, their re-use does not come without environmental and health risks. Although urine application may boost crop yields, increased soil salinity and groundwater contamination can be a challenging issue especially when the urine application rates are too high (Karak and Bhattacharya (2011). Similarly, untreated application of feces, sludge or sewage water may cause the accumulation of toxic content in the soil, higher carbon emissions, the spread of microbial organisms in the soil, and consequent contamination of both surface and groundwater resources. Indeed, proper treatment of waste and wastewater before any re-use may reduce these environmental risks. Especially, removal of phosphates from waste and wastewater may reduce environmental pollution and prevent or at least reduce eutrophication in water systems (Cordell et al. 2009). Yet, except high investment costs of advanced treatment technologies, their energy consumption and carbon footprint analysis should be additionally analyzed.

Direct and unplanned implementation of urine, feces, and sludge for crop cultivation also increases the health risks for plants, farmers and consumers. High salinization or pollution of soils with toxic matter squeezes crop growth and reduce crop biomass and yields (Scheierling et al. 2011). Bacteria and viruses contained in waste, sludge or wastewater can be transmitted to the farmers during the application process and trigger endemic and epidemic diseases. Chemical pollutants such as cadmium and mercury in sewage water and pharmaceuticals and antibiotics in waste also increase the risks of soil and groundwater contamination and consequent public health issues. Farm workers and consumers of vegetables and salads grown using feces, urine and wastewater face to an increased exposure to helminthic diseases such as hookworm and ascariasis and bacterio-viral diseases such as typhoid, diarrhea and cholera (Scheierling et al. 2011). Especially in periods right before harvesting food crops, untreated use of wastewater, urine and fecal sludge for irrigation may boost the incidents of these illnesses (WHO 2004). Direct use of wastewater, urine and fecal sludge for irrigation thus raise the issues of safeguarding farmers and public health in the developing countries. Given the possible contamination of urine after excretion, it should be prevented to be directly applied for crops during the last months of the pre-harvest season (Karak and Bhattacharya 2011). Moreover, it seems safer using feces and urine for biofuel, timber and fodder crops rather than for food crops. Furthermore, adequate treatment of wastewater can be required before any irrigation re-use or discharge into water bodies for minimizing health or environmental risks. Different water quality standards apply for the re-use of effluent across the countries (Table 6).

Table 6: Effluent water quality standards for different reuse choices in selected countries

	Country					
	India		Sri Lanka	Thailand	Costa Rica	Jordan
	DISF	*UI*	*DISF*	*UI*	*DISF, LI*	*DISF, IVCC*
pH	5.5-9.0	5.5-9.0	6.0-8.5	6.5-8.5	5.5-9.0	6.0-9.0
EC (mS/cm)				2,000		
Turbidity (NTU)						10
TSS (mg/l)	100	200	50	30		50
O&G	10	10	10	5	30	8
COD (mg/l)	250		250			100
BOD (mg/l)	30	100	30	20	40	30
NH4-N (mg/l)	50	50	50			
TN (mg/l)						45
TP (mg/l)						30

Source: Adapted from EAWAG (2006),
Notes: DISF – Discharge into surface water; UI – Unrestricted irrigation; LI – Landscape irrigation; IVCC - Irrigation of vegetables consumed cooked.

7 Conclusions

A brief overview of RRR technologies provided an initial insight on pros and cons of recovering effluents, nutrients and energy from waste and wastewater. In general, potential of effluents for irrigation and environmental reuse is much higher and more economically viable than recovering nutrients and energy from waste and wastewater. The availability of large amount of wastewater from the sewage and drainage system can considerably enhance water supply under water scarce conditions and given the increasing costs of dam building and inter-basin water transfers. Moreover, when it is appropriate lower quality water can be applied instead of freshwater, consequently reducing the treatment and water supply costs. In developing countries with low income level and abundance of lands, especially primary water treatment options such as filtration ponds can be economically and technically viable yet may require educational and extensional measures to improve the safety of effluents application. Advanced treatment options at higher costs perhaps can be limited only in remote areas where value of potable or industrial water is sufficiently high (for instance, in remote mining sites/towns).

Fertilizer from urine and fecal sludge is only the third best option among fertilizer augmentation measures, being feasible after the exhaustion of measures such as improving phosphates application efficiency and manure application. Improved phosphates application efficiency and livestock manure use are two best options preferable over fecal sludge compost and urine application both in terms of phosphates recovery potential (magnitude or availability) and implementation costs. Nevertheless, the potential of recovering phosphates from fecal sludge and urine may still allow for considerable recovery of phosphates and can be introduced once the other two better options reach their limits. Especially, reuse of fecal sludge and urine with minimal treatment can be recommendable in remote rural areas which are disconnected from fertilizer markets or depend on heavy importing costs. Using partially treated fecal sludge for cultivating fodder (clover and sorghum), timber (trees) and fiber (cotton) crops can be advisable and less risky for health compared to its implementation for growing food crops. Advanced treatment of human waste for pelletized compost and soil amendments may come at higher costs than its direct application and thus can be limited to be applied for some very economically valuable crops such as flowers or trees.

Energy recovery from waste through the use of advanced technologies can be much costly than effluents and fertilizer production from waste and wastewater. This option is characterized by lower economic and financial viability compared to many other options of generating renewable energy such as solar power or wind power technologies. Thus, energy recovery from fecal waste and wastewater has very limited potential to generate energy at least in the nearest future. Nevertheless, perhaps using waste (manure, dung, crop residues, feces and urine) for cultivating biofuel crops aiming at their later use for cooking or heating houses can be viable in remote areas without connection to the common energy grid. Thus, economic relevance of particular RRR option is very case specific and depends on environmental, geographic, demographic, socio-economic and institutional conditions of the region where the option is supposed to be introduced.

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