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Waste Treatment and Reuse

EPAR Literature Review No. 130

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Prepared for the Water & Sanitation Team of the Bill & Melinda Gates Foundation

May 10, 2011

I. Introduction

The purpose of this literature review is to provide qualitative and quantitative examples of technologies, constraints and incentives for efficient waste treatment and reuse in Sub-Saharan Africa and Southeast Asia. The review is structured to address several statements and questions posed by Water, Sanitation, & Hygiene project implementers; each section presents relevant case studies and expert observations and experiences. Section II discusses the nutrient content in urine and feces and Section III provides an overview of contaminants frequently found in untreated sludge and wastewater. Section IV discusses waste treatment technologies that may be relevant for low-income countries. Section V presents data on risks associated with reuse. The public health risks of incomplete sanitation are reviewed in depth in EPAR Literature Review No. 104. Section VI reviews benefits to resource recovery in agriculture and also includes an introduction to urine reuse, which was not a component of the original request. Further examination of relevant studies of human urine-fertilizer efficacy on crop yields is suggested. Sections VII and VIII discuss reasons for waste treatment failures, including urbanization. Section IX cites a small number of observations on challenges with market-driven reuse in less developed countries. Finally, Section X presents six examples of net-positive energy facilities in Europe and the United States.

Much of the evidence presented in the literature relates to wastewater treatment processes or the sludge produced from wastewater treatment as opposed to untreated fecal sludge. However, examples of risks, failures, and opportunities for raw sludge treatment and reuse are discussed when available. In some cases, empirical evidence or case studies were not available for developing countries and alternatives are presented. Overall we found the empirical evidence on waste treatment and reuse in developing countries is quite thin. A future literature review could examine the reuse potential of animal manures as a proxy for human waste since they possess similar characteristics and also harbor pathogens. A literature review of this nature was beyond the scope of the current brief.

Literature Review Methodology

This literature review was conducted using databases and search engines including: the University of Washington Library, Science Direct, JStor, PubMed, PLoS, Google Scholar, Google, as well as the United Nations Environmental Program, the United Nations Population Fund, the World Bank, the World Health Organization, UNICEF, and the Water Supply and Sanitation Collaborative Council websites. Searches used combinations of the following terms: agriculture, anaerobic digestion, application, assessment, aquaculture, behavior modification, bed, benefits, biogas, biosolids, California, challenge, city, cities, composting, constructed, contamination, content, co-composting, co-treatment, costs, developing countries, disposal, domestic, drying beds, east bay municipal utility district, EBMUD, ecological, economic, economies of scale, efficient, energy, excreta faecal, failure, fecal, feces, grease to biogas, groundwater, growth, health, helminth eggs, impact, incentives, institutional, irrigation, lagoon, landfill, latrine, management, market, marine, metals, methane, mega, municipal, net-positive, neutral, night, nitrogen, nutrient, off-site, on-site, OSS, phosphorus, plants, pollutants, pollution, population, pond, ponds, public, quality, raw, recovery, reclamation, recycle, recycling, reed, reuse, sanitation, septage, septic, settlement, settling, sewage, sludge, slum, soil, stabilization, subsidy, subsidies, surface, system, thickening, trace, treated, treatment, typhoid, unplanned, untreated, urban, urbanization, urine, use, Waco, waste, waste to energy, wastewater, water, West Lafayette, and wetlands.

II. What is the Nutrient Content of Fecal Sludge?

Fecal sludge, which is a by-product of on-site sanitation systems, is rich in the primary macronutrients essential to agriculture – nitrogen, phosphorus, and potassium. Theoretically, the fertilizer potential of raw faecal sludge is sufficient for a person to grow her own food.[1] In well-fed individuals, the average annual nitrogen content in excreted feces and urine has been estimated at 4.5 kg; by comparison, 5.6kg is the amount of fertilizing nitrogen needed to grow 250kg of cereals, an amount sufficient to feed one person for one year. Likewise, average annual human excreta of phosphorous totals 0.6kg, while sufficient cereal fertilization requires 0.7kg annually, and excrete potassium averages 1.2kg, the exact amount required to fertilize 250kg of cereals.[2]

Nutrient content is distributed differently between the urine and fecal factions of untreated sludge (and wastewater). Urine contains the greatest proportion of a human's daily excretion of nitrogen, phosphorus, and potassium available for reuse after treatment, although estimations of total nutrient load vary. Nutrient levels contained in urine and feces vary by country and individual according to differences in food and water consumption.[3, 4]

SJönsson and Vinneràs (2004) use 2003 FAO food supply data to estimate yearly caloric intake and subsequent excreted nutrient output per person per year for five different countries. The calculations, presented in *Table 1* below, take into consideration potential variations in protein, fat, and carbohydrate consumption. [5]

Table 1: Estimated Yearly Nutrient Excretion per Person in Five Countries.

Country	**Nutrient**								
	Nitrogen: Kg p^{-1} year $^{-1}$			**Phosphorus**: Kg p^{-1} year $^{-1}$			**Potassium**: Kg p^{-1} year $^{-1}$		
	Total	Urine	Feces	Total	Urine	Feces	Total	Urine	Feces
China	4.0	3.5	0.5	0.6	0.4	0.2	1.8	1.3	0.5
Haiti	2.1	1.9	0.2	0.3	0.2	0.1	1.2	0.9	0.3
India	2.7	2.3	0.3	0.4	0.3	0.1	1.5	1.1	0.4
South Africa	3.4	3.0	0.4	0.5	0.3	0.2	1.6	1.2	0.4
Uganda	2.5	2.2	0.3	0.4	0.3	0.1	1.4	1.0	0.4

Sources: Adapted from Jönsson and Vinneràs (2004)[6] and Langergraber and Muellegger (2005).[7]

Additional observations on the nutrient composition of human excreta vary. For example, Vinneràs and Jönsson (2002) state that feces contain, on average, between 10-20% of the nitrogen, 20-50% of the phosphorus, and 10-20% of the potassium found in human excreta.[8] Karak and Bhattacharyya (2011) state that urine contributes 88% of the nitrogen, 67% of the phosphorus, and 73% of the potassium found in human excreta.[9] Schönning et al. (2002), using data from the Swedish Environmental Protection Agency, indicate that human urine makes up only 80% of nitrogen, 55% of phosphorus, and 60% of potassium found in excreta.[10]

III. What Contaminants Persist in Untreated Fecal Sludge and Wastewater?

The relative quality of waste post-treatment is generally measured by a decrease in the persistence of contaminants present pre-treatment. In healthy individuals, human urine is sterile and not considered a significant health risk; therefore, the discussion below concentrates on contaminants contained in fecal matter.[11] These contaminants in human fecal matter include, but are not limited to, helminths, bacteria, viruses, and protozoa. In the absence of treatment processes, biological, physical and chemical degradation eventually lead to sufficient pathogen die-off to render fecal sludge safe; however, these processes takes months or years depending on the type of contaminants present. [12] [13] Definitions, sample studies, and expert observations on contaminants frequently cited as treatment quality measures are presented below. For additional information on the negative health effects of exposure to human fecal waste contaminants, please reference EPAR Brief 104: The Public Health Benefits of Improved Sanitation

<u>Helminthes</u>

Helminthes, such as *Ascaris lumbricoides* (roundworm), *Trichuris trichiura* (whipworm), and *Ancylostoma duodenale* and *Necator americanus* (hookworms) are intestinal parasites frequently found in raw fecal sludge. Prues-Ustun et al. (2008) and Zwane and Kremer (2007) state that humans exposed to high concentrations of helminthes are vulnerable to diarrhea, which is a leading cause of death among children in developing countries.[14] WHO guidelines and epidemiological studies suggest that wastewater reused for agriculture should contain less than one helminth egg per gram of total solids. Exposure to concentrations above this amount is believed to place humans at risk for infection.[15] [16]

Some studies suggest that Habbari et al. (2000) studied a random sample of 1343 farmers in Beni-Mellal, Morocco; 740 were from communities using soil treated with raw wastewater for agriculture and 603 were from control communities that did not use wastewater for irrigation. The authors found that, when controlling for behavioral risk factors, those in the community that use raw wastewater were nearly five times more likely to present with *Ascariasis*. Infection rates exceeded 20% in the exposed community compared to 3.8% in the control.[17] In general, exposure to helminthes and other contaminants can be minimized by utilization of wastewater irrigation methods which minimize contact between the contaminated water and the portions of the plant which will be consumed.[18]

Moubarrad and Assobhei (2007) found that children living near coastal waters receiving untreated sewage effluent flows were more likely to be infected with helminth eggs. The authors analyzed stool samples from two groups of school children living in the city of El Jadida, Morocco. The children who lived in neighborhoods bordering the coastal water discharge site (n=210) were 18 times more likely to present helminth eggs in their stool compared to a control group of children who lived far from the site (n=209). This difference was statistically significant.[19]

IWMI & SANDEC (2002) report that *Ascaris* eggs can persist from 2-3 years in temperate climates of 10-15 degrees Celsius, and from 10-12 months in tropical climates of 20-30 degrees Celsius.[20]

<u>Bacteria</u>

Lipson et al. (2010), citing Okoh et al. (2007) in EPAR Brief 104: The Public Health Benefits of Sanitation Interventions, state that "bacteria are the most common microbial pathogens in human waste and wastewater. Bacterial infections can cause a variety of intestinal infections characterized by diarrhea, such as dysentery and typhoid, as well as ailments including ulcers and cancer".[21] *Salmonella*, in particular, is frequently found in both treated and untreated sewage sludge. Sahlström et al. (2004) tested for the presence of various enteric bacteria at eight Swedish sewage treatment plants, and found *Salmonella* in 67% of untreated sewage sludge samples.[22]

IWMI & SANDEC (2002) report that *Salmonellae* typically have an environmental persistence in fecal sludge of less than 100 days in temperate climates of 10-15 degrees Celsius, and less than 30 days in tropical climates of 20-30 degrees Celsius; *Cholera* have a persistence of less than 30 days in temperate climates and 5 days in tropical climates; fecal coliforms persist up to 150 days in temperate climates and 50 days in tropical climates.[23]

WHO (2006) states that intestinal bacteria are a primary concern in lower income countries, where drinking water contaminated by excreta may lead to instances of typhoid fever[24] caused by *Salmonella typhi* bacteria or cholera (caused by *Vibrio cholerae* bacteria).[25] The organizational also asserts that individuals living in urban slums may be at increased risk for typhoid due to unimproved sanitation conditions.

A study of typhoid incidence in five Asian countries by Ochiai et al. (2008) appears to confirm this claim. The authors examined blood cultures in patients exhibiting febrile symptoms at hospitals and clinics across India, Pakistan, Indonesia, Vietnam and China. Results showed that infection rates were significantly higher among patients living in the urban slums of Kolkata and Karachi compared to urban regions of Hue, Vietnam and rural regions of Hechi, China.[26]

Viruses

A wide variety of enteric viruses may be present in fecal sludge and sewage, including adenoviruses, astroviruses, calciviruses, hepatitis A and E, parvoviruses, picornaviruses and rotaviruses.[27] Cliver (2009) notes that "the majority of viruses transmitted to humans via food and the environment are of human enteric origin, so preventing fecal contamination constitutes the first line of defense."[28]

IWMI & SANDEC (2002) report that viruses typically have an environmental persistence in fecal sludge of less than 100 days in temperate climates and less than 20 days in tropical climates.[29]

Protozoa

Crites & Tschobanoglous (1998) report that *Cryptosporidium parvum*, *Clyclospora* and *Giardia lamblia* are the three most problematic pathogenic protozoans found in human waste. Ingestion can cause diarrhea, stomach cramps, nausea and vomiting.[30]

IWMI & SANDEC (2002) report that Amoebic cysts typically have an environmental persistence in fecal sludge of less than 30 days in temperate climates and less than 15 days in tropical climates.[31]

IV. Waste Treatment Technologies

Basic Principles of Treatment

Nearly all waste treatment technologies rely on microbial digestion processes. Microorganisms in waste and wastewater decompose the organic materials present, including pathogens. Encouraging microbial decomposition or activity is one of the most efficient ways to reduce pathogens in sludge. These processes can take place with or without oxygen. Digestion in the presence of oxygen is considered aerobic, while digestion without oxygen is anaerobic. [32] Aerobic and anaerobic digestion processes are discussed in greater depth in a forthcoming EPAR literature review (EPAR Literature Review 141: Climate Change and Human Waste Management).

Waste treatment systems are typically categorized as centralized or decentralized. In centralized systems, waste is transported from the point of origin to treatment sites, usually via sewer systems but also through trucking. One of the defining features of traditional centralized systems is their reliance on water. The centralized systems presented below, while generally considered lower-cost and appropriate alternatives for developing countries, may pose a challenge in urban environments due to their dependence on trucking for waste transport and large areas of land for treatment.

Decentralized systems, which are commonly referred to as "on-site sanitation" (OSS), do not rely on water and are more common in developing countries due to their relatively smaller infrastructure requirements. [33] OSS includes septic tanks, pit latrines and composting toilets among other technologies. Koné et al. (2010) estimate that one third of the world's population relies on OSS installations.[34]

Empirical Evidence of Treatment Efficiency

We found no empirical evidence of waste treatment technologies in developing countries that perform consistently well across broad variations in weather, population densities, sewage loads, and institutional and environmental contexts. The literature is inconsistent in its definition of "performance". For example, some studies site removal of pathogens as a measure for performance, whereas others define performance in terms of management or financial efficiency, such as labor costs and human capital demand.

We were also unable to uncover data regarding global, country-specific, or regional failure rates based on sludge treatment type. There is an extensive literature on efficiencies of resource-intense, conventional treatment systems more common in developed countries. Many authors explicitly cite the lack of scientific research conducted within lower income countries as a major limitation to making recommendations for cost-effective and technologically feasible strategies for treating fecal sludge. [35]

Below we present expert observations and studies examining the efficiency of non-mechanized treatment options for fecal sludge. Efficiency is defined in terms of pathogen deactivation or suitability for reuse. Treatment options are categorized as either centralized or decentralized.

Centralized Waste Treatment Systems

Constructed Wetlands (Planted Drying Beds)

Constructed wetlands, also known as planted drying beds, are man-made wetlands that separate waste into two factions - dewatered solids and liquid - via planted vegetation, soils, and anaerobic and aerobic digestion. [36] Several studies suggest that constructed wetlands are a lower cost, technically feasible approach for wastewater stabilization in developing countries because they have low energy requirements. However, they do require significant land area.[37] [38] [39] Nelson and Murray (2008) report that this treatment option may only function well with small sludge loads during dry seasons.[40] Further treatment to both the liquid and solids factions may also be necessary to ensure sufficient pathogen removal.[41]

Some studies suggest there is economic value – apart from improved sanitation – from use of constructed wetlands. Kengne et al. (2009) conducted an experiment in Cameroon from July 2005 to July 2006 to test the efficiency of constructed wetlands without an initial separation of liquids and solids. The authors vegetated six dewatering beds with antelope grass, a valuable local plant. They speculated that the byproducts from the constructed wetlands – both biosolids and the emergent plants used in treatment – could be considered valuable for soil enhancement and forage to satisfy local farming needs.[42] After six months of testing varying mixed fecal sludge and wastewater loads on the beds, the authors found the biosolids to be high in nutrients. Antelope grass yields from the treatment beds were two to three times higher than yields on natural wetlands during the same time period.[43] The biosolids did require further treatment prior to widespread application since helminth egg concentrations exceeded WHO safety standards for reuse (79 eggs per gram of total solids compared to WHO recommendations of less than 1 helminth egg/g for unrestrictive use in agriculture).[44]

Ingallinella et al. (2002) reviewed a pilot constructed wetland project supported by the Asian Institute of Technology (AIT) since 1997. The planted drying beds used gravel and sand filters and narrow-leaved cattails to separate and treat raw septage produced by 3,000 people. Dewatered biosolids extracted from the bed showed favorable nitrogen and phosphorus levels. Nematode egg concentrations were high, but did not pose a health threat due to deactivation.[45]

Song et al. (2006) studied the treatment efficiencies of an 80-hectare constructed wetland in the Shandong Province of China. The authors sampled inflowing waste and constructed wetland effluent (after treatment) for a period of five years from 1999 to 2004. Results showed that treatment via constructed wetlands decreased the persistence of fecal coliforms by 99.6%, on average.[46]

Water Stabilization Ponds

Water stabilization pond systems typically consist of several engineered ponds that operate in a series. Sludge accumulates in the bottom of the first pond during treatment while effluent flows through a series of secondary and tertiary treatment ponds. Accumulated sludges are left to dewater until total solids concentrations are high enough to facilitate shoveling.[47] The US EPA (2004) suggests that low-tech solutions, such as stabilization ponds and lagoons, are well-suited for developing countries due to their low operations and management costs in comparison to mechanized systems. However, the agency cautions that large land requirements and elevated salinity concentrations may mean they are not suitable for urban populations.[48] [49]

Nelson and Murray (2008) consider water stabilization ponds to be favorable for developing countries since they require less energy, operations and maintenance compared to conventional mechanical systems.[50] However, some research suggests that this system may be subject to failure if periodic desludging is not practiced.[51]. Additionally, a 2007 report by Ammary indicates that treated effluent from water stabilization ponds increased soil salinity in Jordan, which consequently reduced crop productivity.[52]

According to Amahmid et al. (2002), water stabilization ponds have the capacity to remove parasites associated with fecal waste mixed with wastewater effluent. Over a period of two years, the authors collected samples from two adjoining ponds in Marrakech, Morocco to determine the protozoan cyst and helminth egg removal efficiency.[53] The authors measured *Ascaris* eggs and *Giardia* cysts since they are known to be resistant to "hostile environments" and are common in urban settings. [54] The first pond basin retained the mixed fecal sludge and wastewater for 9.5 days after which point the solids settled and the remaining effluent was transferred to a second pond for 6.5 days of treatment. After two years of testing (monthly) samples from different depths in both ponds, the authors found the following:

- Concentrations of both eggs and cysts were significantly higher during the warmer seasons ($p<0.05$).
- Humidity and rainfall influenced performance.
- No helminth eggs were detected in the treated wastewater after the full retention period (16 days) whereas 39.5% of raw sludge and wastewater samples presented eggs.
- Only two of the 48 samples had protozoan after 16 days compared to 50% of the raw samples.
- Parasites removed from the effluent were absorbed into the settled solids, which required additional treatment prior to reuse. Overall, the water stabilization ponds performed well and effluent was deemed suitable for reuse in irrigation after secondary treatment.[55]

A comparison of contaminant removal efficiencies between water stabilization ponds and constructed wetlands is presented in *Table 2*. Removal efficiencies are compared with US EPA reuse standards, which state that an acceptable range of fecal coliforms is less than $1\text{-}10^6$ colony forming unit per 100 milliliters and less than one active helminth egg per liter of effluent after secondary treatment. These standards are consistent with WHO guidelines.[56] [57]

Table 2: Estimated Fecal Coliforms and Helminth Egg Persistence after Treatment

System	Fecal Coliforms	Helminth eggs	EPA Treatment Standard
Stabilization Pond + maturation pond	1×10^3 FC/100ml	≤ 1 egg/L	Meets standard for both fecal coliforms and helminth eggs
Stabilization Pond + high rate pond	1×10^5 FC/100ml	> 1 egg/L	Meets standard for fecal coliforms only
Stabilization Pond + algae removal	1×10^5 FC/100ml	> 1 egg/L	Meets standard for fecal coliforms only
Constructed Wetlands	1×10^5 FC/100ml	≤ 1 egg/L	Meets standard for both fecal coliforms and helminth eggs

Source: Adapted from Sperling et al. (2002) and US EPA (2004).

Decentralized (On-Site) Waste Treatment Systems

Pit Latrines

Pit latrines rely on the creation of anaerobic conditions to stimulate microbial digestion of pathogens. They have low energy and water requirements, but can lead to significant public health and environmental impacts if collections are not well management or if incompletely digested waste leaches into surrounding soil.[58] EPAR Brief 104: the Public Health Benefits of Improved Sanitation presents a comparison of unimproved pit latrine use to improved latrine technologies. The study is summarized below.

Corrales et al. (2006) studied the frequency of disease across eight communities in El Salvador to determine the effectiveness of improved pit latrines on health outcomes. The sample included 449 people in 107 households.[59] Four of the communities used pit latrines or no latrine, while the other four communities used Ecological Sanitation latrines.[60] Ecological sanitation, or EcoSan, is based on four primary principles according to Moe and Rheingans (2006): water conservation, excreta containment to prevent contamination, excreta treatment to inactivate contaminants and nutrient recycling for agricultural use.[61] Of the EcoSan latrine communities, two featured solar-augmented latrines, and two featured double-vault desiccating latrines without a solar heating component.[62] After regression analysis to control for confounding variables including pig ownership, dirt floors, medication and agricultural employment, the study found that compared to traditional latrines, users of double-vault EcoSan toilets had lower rates of hookworm, *giardia*, and E. histolytica, but higher rates of *Ascaris* and *Trichuri*s helminth prevalence. In contrast, users of solar latrines had lower rates than controls of Ascaris, but higher rates of *E. histolytica* infection.[63] The authors suggested that solar EcoSan toilets may have been more effective than the double-vault EcoSan toilets at heating the *Ascaris* eggs in EcoSan fecal containers to intolerable levels, reducing pathogen risks. The authors also suggested that the primary health risks to users of both types of EcoSan toilets might be from exposure to pathogens during the process of emptying supposedly-neutralized biosolids from the toilets.[64]

Composting and Dehydrating Toilets

Dry sanitation systems, such as composting toilets and dehydrating toilets, are a viable alternative to waste management in developing countries according to Scott (2002). Composting occurs if human waste is kept below a certain moisture level, either by separating urine and feces (for example, by urine diverting toilets) or by mixing dry carbon sources such as ash, sawdust, or straw into the combined fecal/urine sludge. Pathogen removal is highly dependent on composting temperatures, pH levels and time. If the fecal sludge or urine is removed too early or if temperatures do not reach 50-60 °C, handlers may be at risk – especially if the human excreta were originally contaminated with *Ascaris* or schistomsomiasis.[65] [66] [67]

Agricultural reuse of urine captured from urine diverting toilets has been tested in Sweden for over 15 years. Storage time and temperature have been shown to have the greatest impact on pathogen removal efficiencies[68] Schönning (2001) conducted bacteria and virus survival experiments on source-separated urine to determine potential health risks for reuse. The author found that bacteria such as *Salmonella* were inactivated quickly and presented a low risk of transmitting gastrointestinal infections via crops.[69] Viruses, such as *Rotavirus*, were removed after one month of storage at 20° Celsius. Ninety percent of protozoa were eliminated after six months of storage at 4° Celsius.[70]

V. What are the Risks of Reusing Untreated or Undertreated Waste?

In addition to presenting public health risks (discussed in Section IV), the agricultural reuse of untreated waste can have negative consequences on soil and water quality. The excessive application of biosolids, as with petroleum-based fertilizers, can produce an oversaturation of nitrogen and other nutrients that is beyond the capacity of plants to utilize and receiving environments to absorb.[71] Reuse of human waste can also poison the soil and groundwater with concentrations of salts and heavy metals, especially when industrial wastes are commingled.[72] [73] [74]

Singh et al. (2004) conducted an assessment of the quality of soil, surface water, ground water, and crops surrounding two sewage treatment plants in Varnasi and Kanpur, India. The goal of the study was to determine whether exposure to treated and untreated wastewater for agriculture presented a health risk to farmers.[75] Seventy-four samples were drawn from farms that use treated and untreated wastewater for irrigation as well as biosolids for soil amendment. Seventy-five samples were drawn from farms not exposed to wastewater or biosolids. Results showed that soils receiving wastewater or biosolids for fertilizer contained high concentrations of nickel, cadmium and pesticides – all of which have been associated with neurobehavioral and gastrointestinal disorders. A significant number of individuals in the exposed group exhibited gastric symptoms, decreased concentration, depression and irritability[76], which the authors attributed to the high concentrations of contaminants present in surface waters, soils, and foods.[77]

Van der Hoek et al. (2003) report that the groundwater beneath wastewater irrigated agricultural fields in Pakistan had higher concentrations of contaminants (coliform bacteria, helminthes, heavy metals) and fertilizers (nitrates) than did the groundwater in areas not utilizing wastewater irrigation. The level of total nitrogen contained in the wastewater was 78.3 mg/l, which exceeded the FAO irrigation water quality standard of 5.0 mg/L. [78]

VI. What Benefits Does Reuse or Resource Recovery Provide to Agriculture?

The reuse of treated wastewater, biosolids and urine in agriculture could reduce the dependency on chemically manufactured fertilizer, [79] improve soil productivity, [80] reduce pollution, and conserve water. [81]

Reuse of Biosolids and Treated Wastewater

Koné et al. (2010) report that the International Fertilizer Industry Association estimates that nearly 170 million tons of chemical fertilizer is produced annually. The authors suggest that nitrogen, potassium, and phosphorus recovered from human waste could provide a low-cost alternative to expensive inputs in developing countries.[82] Cofie et al. (2006) and Kengne et al. (2009) state that biosolids are preferable to industrial fertilizers because they contain organic carbon, which improves soil texture, enables aeration, and promotes root development.[83] Klingel (2001) agrees, stating that properly composted fecal sludge is an excellent soil conditioner[84] because it replenishes the humus layer, which improves water retention.[85]

According to Murray and Ray (2010), treated wastewater that is reused for irrigation has the potential to improve crop yields, conserve water, and offset the demand for (and thus costs of) chemical fertilizer. The authors used FAO crop, farmer survey, and Agricultural Bureau data from Pixian[86], China (a peri-urban district of nearly 500,000 people) to model the output potential of various crop yields based on water consumption, cropping patterns, and two alternatives irrigation strategies. The first model simulated expanded irrigation from canal and river sources, largely believed to be polluted.[87] The second model simulated replacing existing irrigation sources with treated wastewater. Their results indicate that a wastewater reuse strategy could boost productivity by an additional US$20M annually and would conserve approximately 35 million cubic meters of surface water.[88]

Cofie et al. (2010) examined farmers' perceptions of the economic benefit of human excreta use in the Manya Krobo district of Ghana. They hypothesized that the negative nutrient balances in the soil could be remedied by the proper and safe application of raw fecal sludges from un-sewered toilets. They also believed that the decision to use excreta would be influenced by factors such as access to extension services, land tenure, education, and age.[89] The authors interviewed 30 farmers who used excreta and 30 who did not. Perceived agronomic benefit had the strongest influence on the probability a farmer would use excreta.[90] The differences among the groups were significant. Users believed the excreta were good for soil structure and an important source of nutrients compared to non-users. Non-users believed the excreta deposited on farms had low quality, based on visual appearance.[91] Net income for excreta users was US$412.47 compared to $147.35 for non-users.[92] Non-users cited the foul smell, distance for excreta delivery, poor road conditions, and low quantity as major constraints to excreta adoption.[93]

Montangero et al. (2007) used a Monte Carlo simulation to estimate the benefits of improved waste reuse in Hanoi, Vietnam, a city of approximately 3 million people. The authors estimate that replacing septic tanks with urine diversion latrines could recover anywhere between 18-45% of the phosphorus currently "lost" in the landfill or co-composting process70% of the city's solid waste is collected and deposited in landfills.[94]

Reuse of Urine as a Fertilizer

Karak and Bhattacharyya (2011) conducted an analysis of several studies that estimate the efficiency of crop yields after human-urine fertilizer application. The authors found that human urine could outperform other forms of fertilizer, such as animal manure, when other factors such as rainfall were taken into consideration.[95] Over-application of urine-based fertilizer can, however, damage the salinity and electrical conductivity of soils.[96]

Klingel et al. (2001) believe that the benefits of urine reuse are great since the cost of treatment is relatively low and usage is believed to reduce dependency on chemical fertilizers that potentially pollute surface and ground waters.[97] The World Health Organization (2006) appears to agree with Klingel et al. (2001), stating that the fertilizing capacity of urine compares well with ammonium and urea-based chemical fertilizers due to its naturally high nitrogen and urea content.[98]

Table 5 below presents several studies that have examined the effects of urine use on crop productivity.

Table 5: Sample studies of human urine-fertilizer efficacy on crop yields

Country	Crops	References	Summary of Findings
Finland	Cucumber	Heinonen-Tanski et al. (2007)	Cumulative urine-fertilized yields were statistically higher ($p<0.05$) than conventional mineral fertilizer yields. Crops met hygiene standards but nitrate levels were not studied.
India	Indian banana	Sridevi et al. (2009)	Net returns, size of fruit, and yields were higher with urine fertilized bananas compared to a control, however, TSS were also higher.
South Africa	Spinach	Kutu et al.	Tested combinations of urine, urine and feces, and chemical fertilizer on spinach. Urine only fertilizer had higher yields compared to inorganic fertilizer; a 1:7 ratio of human feces nitrogen to human urine nitrogen had highest cumulative yields.
Zimbabwe	Maize	Guzha et al. (2005)	10 m x 10 m plots of maize were analyzed; combination human feces and urine plots has significantly larger yields ($p<0.05$) compared to commercial fertilizer plots. Does not take into consideration different application rates.

VII. Why Do Some Waste Treatment Systems Fail?

A large body of literature cites the lack of political will, tax and fee-based cost recovery systems, urban planning, and incomplete health hazard information as key catalysts to waste treatment failures. Below are examples of failures frequently cited in the development literature.

Human Capital, Operations and Maintenance

Sujaritpong and Nitivattananon (2009) compared the performance of 63 waste treatment systems within suburban housing estates in Nonthaburi Province, Thailand. The systems were categorized as either on-site sanitation (OSS) or community centralized. The on-site sewage systems predominantly used septic, anaerobic filter (package) treatment tanks that required periodic pumping. The community centralized systems relied on fixed film aeration to treat wastewater.[99] Each onsite system (n=30) housed between 40 and 500 domestic connections. The community centralized systems (n=33) serviced between 182 to 4,436 connections each. At the time of the study, none of the facilities had undergone a required environmental impact assessment and only 50% met effluent standards required by law.[100] The authors found that the poorest performing OSS systems suffered from human capital problems – in particular a lack of knowledge of proper maintenance practices and subsequent consequences. The community centralized systems with the poorest performance also had substandard operations and maintenance procedures, which were characterized by the following:

- Improper or no desludging practices;
- Infrequent plant and effluent checks;
- Inability to recover more than 50% of overall expenditures; and a
- Lack of plant manual documentation.

Sato et al. (2006) examined the efficiency of 15 sewage treatment plants (STPs) in the Yamuna River Basin, India. Each STP used a combination of Upflow Anaerobic Sludge Blanket (UASB) reactor and post-treatment polishing pond technology. The approach, which was funded by the Government of India (the Yamuna Action Plan), was seen as an energy efficient, low cost alternative to capital intensive conventional sewage processes.[101] Suspended solid, biochemical oxygen demand (BOD), and fecal coliform (FC) concentrations exceeded national standards at all STPs, rendering the treated wastewater unsuitable for irrigation reuse. Interviews revealed that personnel were not taking the proper measures to regularly analyze sludge composition and periodically remove excess sludge build-up in both the reactors and ponds. The authors concluded that the suboptimal operation and maintenance had the greatest influence on overall STP performance, and suggested the development of strict operational guidelines and training to improve performance with a relatively limited financial investment.

Cofie et al. (2006) believe that at a minimum, high performing waste treatment systems are characterized by consistent operational care and maintenance. Minimal care, in their view, includes removal of settled and accumulated solids, de-blocking conduits, and disposal of screenings. Kengne et al. (2009) agree, stating that many systems fail due to an absence of consistent, operational processes.[102,103]

Strauss and Montangero (2002) assert[104] and the empirical studies presented above suggest, that a lack of adequate training and standardized managerial and operational practices limit waste treatment performance, regardless of technological solution.

Gumbo et al. (2005) believe that the devolution of service provision to local municipalities within the Southern African Development Community will increase the demand for management and maintenance education. Results from a training needs survey, which they do not directly present, purportedly indicate that there is "an acute shortage of human resource capital" necessary for the development of efficient water and sanitation strategies.[105]

Costs and Willingness to Pay

Many sanitation treatment technologies are inappropriate for lower income countries due to the high cost of infrastructure and energy. Whittington et al. (2009) suggests that the capital, operations, and maintenance costs of wastewater treatment alone represent 15% of the overall cost of improved water and sanitation services in developing countries.[106] Using the World Bank's recommended water and wastewater infrastructure investment rate of 1.5% of gross national product, Nelson and Murray (2008) estimate it would take many less developed countries hundreds of years to pay for the infrastructure necessary to meet EU effluent standards.[107]

Muga and Mihelcic (2008) estimate the cost of conventional, mechanical waste treatment systems (such as activated sludge treatment) to be between US$300 to US$1000 annually, which is infeasible in lower income countries who often only realize US$300 in annual household income.[108] Cairncross and Valdmanis (2006) offer different, albeit equally prohibitive figures. The authors suggest that the average cost of conventional sewerage is 10 times greater than the cost of implementing improved OSS systems, which they price at US$12 per capita per year for one latrine.[109]

Whittington et al. (1993) point out that subsidies for the development of large-scale sanitation systems may be difficult to obtain in lower income countries. User fees for connections and maintenance may therefore be necessary to sustain the ongoing financing of capital improvements.[110] Some households may not want to invest in connection fees or improved sanitation technologies if they do not own the home they live in.[111] In a survey of 1,224 households in Kumasi, Ghana in 1989, Whittington et al. (1993) found that home ownership had a positive and significant effect on willingness to pay for improved sewerage and water infrastructure. Homeowners were 238 times more willing to pay for improved ventilated pit latrines compared to individuals and families living in multistory housing units, who were less likely to pay for improved ventilated pit latrines by a factor of 60.[112]

Some literature suggests that households would be more willing to pay if they were made aware of the true costs and benefits – both economic and health – of improved sanitation systems.[113,114] Kengne et al. (2009) suggest that a lack of knowledge of the negative consequences associated with high pathogen and nutrient concentrations may be a factor influencing the widespread discharge of fecal sludge into public spaces such as drains and water bodies and the devaluing of improved sanitation.[115]

VIII. Can Treatment Systems Keep Pace with Rapid Urbanization?

The annual urban population growth rate in lower income countries[116] was estimated to be 4.1% from 2005 to 2010, compared to 1.69% in rural regions over the same time period.[117] Over 100 million people are added to urban communities in developing countries every year.[118] Urbanization is frequently cited as a constraint to expanded sanitation service provision but few studies empirically link failures directly to population growth.

Experts agree that scaling city-wide sanitation systems to meet the demand of constituents is not affordable or feasible in most urban centers of the developing world.[119] According to UNICEF and the World Health Organization, urban sanitation coverage is estimated to be 32% higher than rural coverage in developing regions.[120] Still, many cities are unable to meet the demand for expanded infrastructure that accompanies such growth. Public utilities in Bangkok, for example, have struggled to effectively treat rising wastewater volumes resulting from rapid population growth. It is estimated that municipal wastewater management facilities only accommodate the needs of approximately 30% of the Bangkok metropolitan population.[121]

These statistics likely mask large variances in coverage *within* urban settings. Komives et al. (2003), using data from the World Bank's Living Standards Measurement Survey (LSMS),[122] found household income to be a significant and positive influence over the presence of sewer connections.[123] Twenty-five percent of the poorest urban households in the LSMS sample lacked access to any sanitation facility.[124] And of those that did have access, only 40-50% chose to connect. Home ownership also had a strong effect on the probability of having a sewer connection. Those that did not own a home were 52.7% less likely to have access to sewer infrastructure.[125]

In Sub-Saharan Africa, rural-urban migration is taxing public infrastructure and increase the percentage of the urban population that live in slums (62%).[126] Schouten and Mathenge (2010) believe that high population density, high poverty levels, limited basic infrastructure, and the "haphazard layout" of slums mean that near-term, improved sanitation is not feasible for most slum dwellers.[127]

IX. Can Reuse of By-Products from Waste Help Drive Cities' Capture and Treatment Programming?

Examples of market-driven reuse of by-products in developing countries are limited in the literature. Many authors discuss the failure to capitalize on reuse markets due to imperfect information and infrastructure. Strauss and Montangero (2002) believe that the lack of promotion and marketing of biosolids produced from sound treatment practices decreases incentives for trade and reuse uptake.[128] Cofie et al. (2009) believe most recovery markets fail due to the lack of collection infrastructure, marketing, and imperfect legal frameworks. The author's cite the Njenga and Naranja (2006) study of farmer's willingness to pay in Nairobi, where demand was so low that only 30% of the biosolids and compost generated were sold.[129]

X. Are There Examples of Net Positive Energy Treatment Facilities?

Caldwell (2009) defines net positive energy as a site that produces more energy for reuse than is required for treatment.[130] We found no examples of net positive energy treatment facilities in developing countries. Two examples of conventional systems with net positive energy in Europe include the Anglian Water Company in the United Kingdom and the Strass Municipal Wastewater Treatment Plant (WWTP) in Austria. The gains in efficiency realized at these plants were dependent upon technological upgrades to aerobic sludge treatment processes.[131] [132] Four municipal wastewater treatment facilities and public utilities in the United States, also presented below, achieved improvements in energy reuse by adding post-consumer food wastes to anaerobic digestion processes.

In a case study of Anglian Water, a wastewater treatment plant that serves approximately 150,000 customers, Caldwell (2009) reports that efficiency gains were realized by reducing the necessary air volume required for the activated sludge aeration process.[133] In conventional treatment facilities, aeration can account for approximately 50% of total plant electricity consumption.[134, 135] Installing more efficient aerators ("turbo blowers") allowed the facility to reduce overall energy-input requirements by nearly 20%. Caldwell (2009) states that the capital cost for aeration was "cost-neutral" even with increased loads due to population pressure.[136]

Strass WWTP serves up to 200,000 people. The facility uses a two-step process to treat waste: the first stage reduces organic load, while the second stage reduces nitrogen and ammonia loads through aeration. Jonasson (2007) found that, similar to Anglian Water, the aeration process consumed the majority of electricity for the entire plant (50 percent).[137] Strass WWTP installed a new, combined heat and power unit that converted biogas produced from anaerobic processes into thermal and electrical energy to power the plant.[138] The plant's energy self-sufficiency improved to 108% in 2005, up from 49% in 1996.[139]

East Bay Municipal Utility District (EBMUD) serves the water and wastewater needs of approximately 640,000 customers in the San Francisco Bay region.[140] In 2004, EBMUD began co-digesting pretreated postconsumer food wastes – hauled from wineries, processing plants, restaurants and rendering facilities - with municipal wastewater solids in anaerobic digesters.[141, 142] According to Gray et al. (2008), the goal of co-treatment was to increase methane yields – a byproduct of anaerobic digestion – by decreasing the amount of organic material sent to regional landfills and adding "energy rich" products to the treatment process.[143] Analysis conducted by EBMUD staff in 2010 indicates that methane production was approximately 3 to 4 times higher when pretreated food wastes were co-treated with municipal wastewater.[144] The destruction of volatile solids also improved from an average of 77% in municipal solids to 85-90% in the co-treated waste.[145] The utility self-reported $3 million in savings due to the generation, use, and sale of renewable energy sources such as hydropower, biogas, and solar.[146] The project, however, has not been without its drawbacks. For example, despite a net surplus of 100,000 megawatt-hours of energy from renewable sources, the utility had to purchase 81,500 MHz worth of power to match daily electricity demands due to variability in the renewable energy supply.[147]

The City of Millbrae, California offset cost-prohibitive energy purchases and decreased the amount of biosolids disposed of in landfills by converting food waste into fuel for electricity. Existing anaerobic digestion processes did not fully support the electricity needs of the plant so energy-rich fats, oil and grease (FOG) were added to the digester as feedstock for increased biogas production.[148] According to York and Magner (2010), FOG is the "most common cause of blockages" in conventional sewage systems.[149] The plant, therefore, re-engineered treatment processes to improve the miscibility of the post-consumer and industrial food waste.[150] The $6.3 million upgrade, designed by FOG Energy Corporation, smoothed daily methane production, reduced dependency on chemical and enzyme inputs, and increased methane concentrations by approximately 11%.[151, 152] Today, the treatment facility is effectively off-grid and produces approximately 90,000 BTUs of energy per gallon of processed FOG.[153, 154]

In 2000, the Waco Metropolitan Area Regional Sewerage System (WMARSS) regularly reported experiencing clogged pipes due to FOG influent from area food processing industries. The clogs led to frequent sewerage overflows during storms and required excessive amounts of electricity to keep aerobic digesters oxygenated during secondary treatment.[155] The City of Waco and the WMARSS took several steps to reduce system inefficiencies, environmental hazards, and the amount of FOG waste deposited in landfills, including introducing an anaerobic digester into the treatment process to help reduce overall operating costs.[156] The inherently high biochemical oxygen demand of food wastes allowed the plant to skip the secondary treatment process and reduce the overall required energy for processing.[157] The FOG feedstock, when co-treated with municipal waste, produced 30% more biogas compared to traditional feedstock resulting in a 30% decrease in operating costs. Half of the biogas produced was used as fuel for the plant. Energy usage dropped from 532,000 kW per hour in 2002 to 391,000 kW per hour in 2008.[158] Today, methane produced from the anaerobic digester powers one generator, resulting in nearly $350,000 in annual energy savings.[159]

Finally, the City of West Lafayette, Indiana uses energy produced from grease and food waste to provide 15% of the electricity required to treat nearly 9 million gallons of water daily.[160]

Conclusion

Fecal sludge collected from on-site sanitation systems is rich in the primary macronutrients essential to agriculture – nitrogen, phosphorus, and potassium. The reuse of resources recovered from treated waste – in the form of biosolids for direct land application and urine for irrigation – could improve crop productivity, reduce the amount of waste transported to landfills, reduce pollution, and conserve water.

The quality and applicability of waste for reuse is highly dependent upon treatment. Human urine is sterile and not considered a significant risk to human health. Fecal matter, however, includes dangerous contaminants such as helminthes, bacteria, viruses and protozoa. If waste is left untreated and reused in agriculture, exposed humans may be susceptible to gastrointestinal disorders and even cancer. Encouraging microbial decomposition or activity in treatment is one of the most efficient ways to reduce pathogens in sludge.

Conventional treatment systems that rely on water for transport generally require expensive infrastructure and energy investments and therefore may not be appropriate for lower income countries. Decentralized, or on-site sanitation systems (OSS), generally do not require water and are less resource-intense because they are non-mechanized. Improved pit latrines and composting and dehydrating toilets are all cited as potential low-cost OSS treatment options relevant for developing countries. Water stabilization ponds and constructed wetlands are also cited as lower-cost alternatives, but their reliance on large areas of land mean they are likely unsuitable for urban environments constrained by population growth.

The availability of adequate – and reliable – energy can determine the choice of sanitation system technology in a developing country. Examples of methane reuse at facilities in the United States and Europe provide promising examples of energy efficient treatment options. However, the human resource, operations and maintenance, and considerable upfront capital investment may still render net positive energy technologies irrelevant for developing countries.

Please direct comments or questions about this research to Leigh Anderson, at eparx@u.washington.edu.

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