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Quantitative microbial risk assessment of wastewater and faecal sludge reuse in Ghana

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The probabilistic health risks of rotavirus and Ascaris infections associated with different scenarios of diluted wastewater and faecal sludge agricultural reuse in Ghana were estimated based on the Quantitative Microbial Risk Assessment (QMRA) approach. The annual risks of rotavirus and Ascaris infections associated with diluted wastewater reuse scenarios were 10^{-2} and 10^{-3} to 10^{-4} respectively compared with the WHO tolerable health risk of 10^{-4} per person per year. The risk of Ascaris infection for the different scenarios of faecal sludge reuse ranged from 10^{-4} to 10^{-2} while it was $<10^{-14}$ to 10^{-1} for rotavirus infections per single exposure. The treatment of faecal sludge significantly reduced the risk of rotavirus infections but had less effect on the reduction of Ascaris infections. It is stressed that the estimated risks of infection need to be validated against follow-up data obtained from epidemiological investigations coupled with studies on different health risk barriers.

Introduction

Wastewater and excreta reuse in agriculture is increasingly used globally in response to water demand for irrigation, the realization that their nutrient content may decrease the fertilization needs and due to the lack of economically feasible treatment and management options. The recycle practices have the potential to improve agronomic productivity, soil fertility and add to cost effectiveness and sustainability in agriculture and of wastewater management. The practice should however not impair on health due to its content of pathogens after direct exposure or through crop contamination or negatively impact soil fertility due to accumulation of metals or organic chemicals if it should be considered a sustainable sanitation worldwide. According to current estimates, 3.5 to 20 million hectares of agricultural fields worldwide are irrigated with untreated, partially treated or wastewater-polluted river/stream (Scott et al., 2004; IWMI, 2006). In Ghana, where less than 5% of the population is connected to centralized wastewater treatment systems (Obuobie et al., 2006), a substantial proportion of wastewater and excreta is recycled to agricultural lands with minimum treatment. Wastewater is used mainly for irrigating vegetables eaten raw while partially stabilized faecal sludge from on-site wastewater systems is applied as soil ameliorants. The practice serves as a source of livelihood for a number of farming households and contributes towards food production. However, due to public health concerns, the reuse of wastewater of all kinds has been banned by local authorities, but is anyhow practiced. The more recent studies performed have attempted to characterize the health risks through investigations of the microbial hazards associated with diluted wastewater reuse in urban agriculture (Obuobie et al., 2006) and health problems, treatment options and nutrient value of faecal sludge. Even though these studies provided benchmark measures for comparison with the World Health Organization's guidelines for wastewater reuse; they limited in quantifying the health risks associated with wastewater reuse. An assessment of health risks based on local realities is vital not only for the development of local guidelines; but also to provide the basis for assessing the efficacy of risk reduction measures. In this paper, a quantitative microbial risk assessment (QMRA) approach is applied based on data from several studies on the microbial quality of wastewater and faecal sludge from Ghana and other tropical regions, with the aim to assess the health risk associated with wastewater and excreta reuse in the country.

Quantitative Microbial risk assessment takes it roots from chemical risk assessment (Haas *et al.,* 1999). Unlike, epidemiological surveys, which depends on comprehensive analysis of health outcomes QMRA applies mathematical models to *predict* potential health risks associated with exposure to microbial hazards. The application of the tool in assessing health risks associated with wastewater reuse in agriculture has gained momentum in recent years. It has also been adapted by the World Health Organization (WHO) in the most recent guidelines (WHO, 2006) for monitoring and measuring health risks associated with wastewater and excreta application in agriculture. Data on most pathogenic organisms known to cause enteric infections is limited in Ghana. Therefore, more conservative assumptions based on quantitative data from other regions in the developing world were made in this assessment. These conservative estimates were fitted with probability distributions functions (PDFs) thus allowing for a better estimate of health risk.

Methods

The methodological framework for QMRA presented by Haas *et al.,* (1999) was followed in *seriatim* for the risk assessment. This includes: hazard identification, exposure assessment, dose response relationship and risk characterization.

Hazard identification

For purposes of our assessment, we chose rotavirus and *Ascaris lumbricoides* as the model QMRA organisms. Rotavirus is associated with gastroenteritis (Parashar *et al.,* 2003) and has been widely used as a representative index organism for enteric viruses in QMRAs of wastewater reuse (Hamilton *et al.,* 2006). It has also been identified as a major diarrhoeal pathogen in Ghana, accounting for 20% of all diarrhoeal cases especially among children (Armah *et al*., 1995). *Ascaris,* on the other hand, is the most prevalent parasitic infection worldwide with a prevalence rate of 52% in Ghana (Hortez *et al.,* 2003). Some studies have also associated the incidence of *Ascariasis* with diluted wastewater and faecal sludge reuse among adult farmers and children (Blumenthal *et al.,* 2001) and consumers of wastewater irrigated vegetables (Bryan, 1997). *Ascaris*, can also persist for months to years in soils under harsh conditions (Jimenez, 2007) thus making it an ideal organism for QMRAs in developing regions (Hamilton *et al.,* 2006). In this work, we focused on the health risks associated with the reuse of the most polluted diluted wastewater (storm drain and stream) and faecal sludge (high strength). For this, we used data from studies in Ghana. Faecal coliform data were transformed to rotavirus using the approach described by Shuval *et al.,* (1997). All the data inputs were then described with probability distribution functions to allow for stochastic modeling (Table 1).

Table 1: Probability distribution functions describing the concentration of Rotavirus and *Ascaris* in faecal sludge and diluted wastewater used in the assessment

Model Organism	**Faecal sludge (g^{-1})**	**Diluted wastewater**	
		Storm drain (L^{-1})	**Stream (L^{-1})**
Rotavirus	Uniform* (97, 727)	Normal** (0.776, 0.00013)	Normal** (0.997,0.00013)
Ascaris lumbricoides	Uniform*** (16.8-50.4)	Normal** (3.02, 1.99)	Normal** (3.98, 3.98)

* Based on faecal material from pit latrines in Botswana (Wheeler and Caroll, 1989)
** Based on Shuval *et al.,* (1997) ratio of 10^5 FC to 1 rotavirus particle with base data from Amoah *et al.,* (2006) and Obuobie *et al.,* (2006)
*** High strength Faecal Sludge from Public toilet and bucket latrine sludge stored for days or weeks reported by Heinss *et al.,* (1997) and transformed with the distribution of helminths ova genera in wastewater reported by Hays (1997)

Risk factors, scenarios and exposure assessment

Diluted wastewater irrigation

The sources of irrigation water indicated in Table 1 exceed the WHO monitoring guideline of 1000 *E.coli* /100ml and <1 helminth egg/100ml (WHO, 2006) and are used without treatment (Obuobie *et al.,* 2006). Different kinds of vegetables including those eaten raw are irrigated with water from these sources with potential health risks to consumers (Keraita and Drechsel, 2004). During irrigation, farmers wear no protective clothes and are in direct contact with the irrigation water while children playing on the farm are also exposed. Based on the foregoing risk factors, the following scenarios were assessed: a) accidental ingestion of irrigation water by farmers and children and b) consumption of irrigated lettuce. In scenario a), we assumed there will be no rotavirus and *Ascaris* reduction in the irrigation water and that farmers will ingest 1-2 ml of irrigation water per day, a narrow range based on Ottosson and Stenstrom (2003) while children ingest 2 ml (Westrell *et al.,* 2004). The exposure days per year for children and farmers were taken as 30 and 90 days respectively. For scenario (c), it was assumed that 10-15ml of the irrigation water will be left on the lettuce after harvest (Mara *et al.,* 2007). The rotavirus reduction on the harvested lettuce was uniformly distributed with reported ***k*** values of 0.45day^{-1} (Asano *et al.,* 1992) and 0.69day^{-1} (Petterson *et al.,* 1999). We allowed 2 days between lettuce harvest and consumption and assumed no further rotavirus reduction during salad preparation. For *Ascaris,* 1-2 log reduction due to washing of the lettuce before consumption was assumed (WHO, 2006). The amount of lettuce salad consumed per person per day was taken as 10-12g, a narrow uniform distribution based on Obuobie *et al.,* (2006).

Faecal sludge application

Sludge is treated on farm either by spreading on random spots or by containment in shallow pits for 2-3months (Cofie *et al.,* 2004). Following treatment, the collection and incorporation of treated sludge into the soil is carried out by farmers without wearing protective clothes. Children living within the faecal sludge communities also play on the sludge farms. For these risk factors, we estimated the health risks for: a) accidental ingestion of small amounts of sludge by farmers and children during collection and spreading of sludge b) accidental ingestion soil-faeces mixture by farmers and children after sludge incorporation into the soil. For scenario (a), we assessed the health risk for 0 to 3months of treated sludge under the two treatment methods. Scenario (b) was based on a sludge to soil ratio of 1:100 after incorporation of the 0 to 3months treated sludge (Westrell, 2004). The reductions of the model organisms for both scenarios are presented in Table 2. The amounts of sludge or soil-sludge mixture ingested were assumed to be 200mg and 100mg for children and adult farmers respectively (WHO, 2006).

Table 2: Reduction rates for Rotavirus and Ascaris during treatment and soil incoporation

	Organism	Surface spreading	Pit method
Treatment	Rotavirus	*k*= 1 day^{-1*}	*k*= 0.25 day^{-1**}
	Ascaris	*K(N)*=(0.0035; 0.0153) day$^{-1§}$	*k*= 0.0027 day^{-1***}
Soil Incorporation	Rotavirus	*k* (*U*) = (0.5; 1)day^{-1*}	
	Ascaris	*k* (*N*)= (0.0035; 0.0153) day$^{-1§}$	

U= Uniform Probability Distribution Function (PDF) N= Normal PDF
Based Poliovirus inactivation in a field study at a temperature of 33°C by Straub *et al.,* (1993).
** Based on the deactivation of poliovirus over 4 days at a temperature of 21°C assuming a final % sludge solid of 65% (Ward and Ashley, 1977).
§ - *k* value calculated based on T_{90} values reported by Westrell (2004)
*** Based on inactivation of *Giardia* in stored faecal sludge assuming a 1 log removal for 12months (Gibbs *et al.,* 1995).

Dose response relationship

For the dose response relationships, the **ß**-poisson dose response model described by Haas *et al.,* (1999) was used for rotavirus while the single hit exponential dose response model was applied to *Ascaris*. In the case of a single exposure, the **ß**-poisson and exponential dose response models are respectively expressed as:

$$\mathbf{P_I\,(\mathit{d}) = 1 - [1 + (\mathit{d}/N_{50})\,(2^{1/\alpha} - 1)]^{-\alpha}} \text{ and}$$
$$\mathbf{P_I(\mathit{d}) = 1 - exp(-r\mathit{d}).}$$

Where P_I (***d***) is the probability of becoming infected by ingesting ***d*** number of organisms, N_{50} is the median infection dose representing the number of organisms that will infect 50% of the exposed population; and **α** and ***r*** are the dimensionless infectivity constants. For rotavirus, N_{50} and ***a*** are 6.17 and 0.253 respectively (Haas *et al.,* 1999) and for *Ascaris,* r =0.02 (Rose and Gerba, 1991).

Risk characterization

For the faecal sludge scenario, all the risks of infections were characterized as single exposures due to a wide range of uncertainties surrounding the exposure durations. The annual risk of infections were calculated for the diluted wastewater reuse scenarios using the method of Sakaji and Funamizu (1998). For each of the scenario, we run a Monte Carlo Simulations using @Risk version 4.5.2 professional edition (Palisade Corporation) added on to Microsoft Excel with Latin hypercube sampling at 10,000 iterations. The mean risks of infections from the simulations were reported.

Results and discussion

Table 3 shows the risk of rotavirus and Ascaris infections for the diluted wastewater scenarios. For all the scenarios, the annual risk of rotavirus infection exceeded the WHO tolerable risks of 10-4 per person per year by a 2 order magnitude (i.e.10-2). The annual risk of Ascaris infection was however less and ranged from 10-3 to 10-4 per person per year. For children the health impact of these infections is expected to be high as they are more susceptible to these microorganisms than adult farmers. The risk of for exposed children could be reduced by fencing the wastewater gardens. For exposed farmers, the application of simple treatment methods such as sandfilters and the wearing of protective clothing could significantly reduce health risks. The cessation of irrigation for some time on farm before harvest and the washing of irrigated vegetables with mild disinfectants during salad preparation could lead to some risk reduction for consumers (WHO, 2006).

Table 3: Mean annual *Ascaris* and Rotavirus infections for different scenarios of diluted wastewater reuse

Organism	**Irrigation water**	**Accidental ingestion of untreated irrigation water**		**Consumers**
		Children	**Farmers**	
Ascaris	Drain	3.61×10^{-3}	8.11×10^{-3}	9.4×10^{-4}
	Stream	4.76×10^{-3}	1.06×10^{-2}	1.25×10^{-3}
Rotavirus	Drain	2.7×10^{-2}	6.02×10^{-2}	3.60×10^{-2}
	Stream	3.48×10^{-2}	7.66×10^{-2}	4.62×10^{-2}

From Tables 4 and 5, considerable risk of *Ascaris* infection was associated was associated with the reuse of faecal sludge. For this, the risk of infection for children was 1 order magnitude greater than adult farmers in most cases and the treatment method and duration did not assure any considerable reduction in the risk of *Ascaris* infection. On the other hand, the type of treatment method used and the duration of treatment had a significant impact on the risk of rotavirus infections. In this regard, the spread treatment method was an effective barrier against rotavirus infection for all the scenarios. By spread treating faecal sludge for two weeks, the risk of rotavirus infection per single exposure decreased from 10^{-1} to 10^{-13} for the collection scenario and to 10^{-15} for the soil incorporation scenario. There was no detectable risk of rotavirus infection ($<10^{-15}$) after 3 weeks of spread treatment for both scenarios. Rapid dewatering of sludge due to direct due to high temperatures ranging from 25^0C to 33^0C could explain the efficacy of the method. On the other hand, treatment of sludge in pits did not rapidly reduce the risk of rotavirus infections but provided enough barrier against infections when the sludge was treated for 2 months by the method. This treatment duration is considered acceptable as farmers often use 2 to 3 months for the treatment of sludge before collection and incorporation. Further reductions in the treatment duration of the pit method in connection with risk reductions can be achieved by pit co-composting the faecal sludge and household waste. In addition, risk reduction measures such as the wearing of protective clothes and the observation of strict hygienic practices during faecal sludge handling by farmers has to be encouraged through well designed educational programmes. Deworming of children living within faecal sludge farming communities have to be built into health programmes if their exposure cannot be curtailed by any means.

Table 4: Mean risk of Rotavirus and Ascaris infections associated faecal sludge collection

Treatment method	Treatment duration	Risk of Ascaris Infection		Risk of Rotavirus Infection	
		Children	Adult	Children	Adult
None	0	1.25 x10^{-1}	6.49 x 10^{-2}	7.26 x10^{-1}	6.74 x10^{-1}
Spreading	1 week	1.19 x 10^{-1}	6.15 x 10^{-2}	4.89 x10^{-6}	2.45 x10^{-6}
	2 weeks	1.13 x 10^{-1}	5.82 x10^{-2}	4.89 x10^{-13}	2.45 x10^{-13}
	3 weeks	1.07 x10^{-1}	5.51 x10^{-2}	nr	nr
	1month	1.00 x 10^{-1}	5.14 x10^{-2}	nr	nr
	2months	7.95 x10^{-2}	4.06 x10^{-2}	nr	nr
	3months	3.93 x 10^{-2}	1.98 x10^{-2}	nr	nr
Pit	1 week	1.21x10^{-1}	6.23 x10^{-2}	2.99 x10^{-1}	2.13 x10^{-1}
	2 weeks	1.16 x10^{-1}	5.97 x10^{-2}	1.48 x10^{-2}	7.56 x10^{-3}
	3 weeks	1.11 x10^{-1}	5.72 x10^{-2}	2.75 x10^{-4}	1.37 x10^{-4}
	1month	1.05 x10^{-1}	5.42 x10^{-2}	1.54 x10^{-6}	7.73 x10^{-7}
	2months	8.84 x10^{-2}	4.52 x10^{-2}	4.89 x10^{-14}	2.45 x10^{-14}
	3months	7.39 x10^{-2}	3.76 x10^{-2}	nr	nr

nr- negligible risk.

Table 5: Mean risks of Rotavirus and *Ascaris* infections during Incorporation of faecal sludge into the soil

Method	Treatment duration	Rotavirus infection		Ascaris infection	
		Children	Farmers	Children	Farmers
None	0	2.27 x 10-1	1.51 x10-1	1.34 x10-3	6.7 x10-4
Spreading	1	4.89 x10-8	2.45 x10-8	1.26 x10-3	6.3 x10-4
	2	4.80 x10-15	2.12 x10-15	1.2 x10-3	6.0 x10-4
	3	nr	nr	1.1 x10-3	5.6 x10-4
	1month	nr	nr	1.05 x10-3	5.2 x10-4
	2months	nr	nr	8.2 x10-4	4.14 x10-4
	3months	nr	nr	6.51 x10-4	3.25 x10-4
Pit method	1	8.49 x10-3	4.30 x10-3	1.28 x10-3	6.43 x10-4
	2	1.55 x10-4	7.74 x10-5	1.23 x10-3	6.16 x10-4
	3	2.75 x10-6	1.38 x10-6	1.18 x10-3	5.9 x10-4
	1month	1.55 x10-8	7.74 x10-9	1.12 x10-3	5.58 x10-4
	2months	nr	nr	9.25 x10-4	4.63 x10-4
	3months	nr	nr	7.68 x10-4	3.84 x10-4

nr- negligible risk.

Conclusion

Given the annual risk of *Ascaris* and rotavirus infections associated with diluted wastewater irrigation in agriculture, the practice should be considered as unacceptable and more so when children are involved. By this assessment, *Ascaris* should be the main microbial hazard of concern if faecal sludge is to be used in agriculture under the conditions in Ghana. As our rotavirus and *Ascaris* reductions in the assessment was based on literature data, field studies on the reduction of these model organisms and other pathogenic microorganisms will be valuable for future risk estimates. Eventhough not covered here, other scenarios such as ground/surface water contamination and aerosols from sludge applied farms as well as pharmaceutical residues/heavy metals in the sludge could lead to considerable health risks to farmers and populations living within and outside faecal sludge farming communities. More investigations are needed in this regard to have an overarching understanding of the health effect of faecal sludge application. The risk estimates made here also has to be validated through rigorous epidemiological surveys.

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