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Effect of low-cost irrigation methods on microbial contamination of lettuce irrigated with untreated wastewater

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Summary

objective To assess the effectiveness of simple irrigation methods such as drip irrigation kits, furrow irrigation and use of watering cans in reducing contamination of lettuce irrigated with polluted water in urban farming in Ghana.

methods Trials on drip kits, furrow irrigation and watering cans were conducted with urban vegetable farmers. Trials were arranged in a completely randomised block design with each plot having all three irrigation methods tested. This was conducted in both dry and wet seasons. Three hundred and ninety-six lettuce, 72 soil, 15 poultry manure and 32 water samples were analysed for thermotolerant coliforms and helminth eggs.

results Lettuce irrigated with drip kits had the lowest levels of contamination, with, on average, 4 log units per 100 g, fewer thermotolerant coliforms than that irrigated with watering cans. However, drip kits often got clogged, required lower crop densities and restricted other routine farm activities. Watering cans were the most popular method. Using watering cans with caps on outlets from a height <0.5 m reduced thermotolerant coliforms by 2.5 log units and helminthes by 2.3 eggs per 100 g of lettuce compared with using watering cans without caps from a height >1 m.

conclusion Simple, cheap and easily adoptable irrigation methods have great potential to reduce crop contamination in low-income areas. When used in combination with other on-farm and post-harvest risk reduction measures, these will help to comprehensively reduce public health risks from using polluted water in vegetable farming.

keywords Low-cost irrigation methods, wastewater, lettuce, microbial, contamination, urban agriculture

Introduction

Developing countries lack the capacity to effectively treat wastewater before disposal (Carr & Strauss 2001). Large volumes of untreated wastewater end up in urban water bodies, which farmers use for irrigation. Vegetables are the crops most commonly irrigated with polluted water as they are the most demanded cash crops in urban areas (Scott *et al.* 2004; Obuobie *et al.* 2006). However, the use of contaminated irrigation water poses health risks to farmers and consumers (Blumenthal *et al.* 2000). In Ghana, water used by urban vegetable farmers has high levels of microbial contamination, and vegetables produced are equally contaminated (Amoah *et al.* 2005). This has been associated with the transmission of diarrhoea in the cities (Mensah *et al.* 2002).

One of the factors influencing the microbial quality of farm produce, and thus health risks, is the type of irrigation (Brackett 1999; WHO 2006). Based on health impacts from wastewater, WHO has classified irrigation into three distinct categories: flood and furrow, spray and sprinkler, and localised irrigation methods (WHO 2006). Flood and furrow irrigation (FI) methods apply water on the surface and pose the highest risks to field workers, especially when protective clothing is not used (Blumenthal *et al.* 2000). Spray and sprinkler are overhead irrigation methods and have the highest potential to transfer pathogens to crop surfaces, as water is applied to edible parts of most crops and because aerosol-borne pathogens are carried further. Localised techniques, such as drip-and-trickle irrigation, present the lowest risk to farmers and cause minimal pathogen transfer to crop surfaces because water is directly applied to the root (Pescod 1992). Localised irrigation is most expensive and prone to clogging because of the turbidity of polluted water (Martijn & Redwood 2005). However, cheap bucket drip kits (Chapin Watermatics, USA; International Development Enterprises, India) with better potential for use in low-income countries are now available (Kay 2001).

Drip irrigation causes less contamination on crops than furrow and sprinkler irrigation (Bastos & Mara 1995; El Hamouri *et al.* 1996; Oron *et al.* 2001; Armon *et al.* 2002; Solomon *et al.* 2002). However, there is hardly any documented study on traditional methods such as watering cans in regard to crop contamination. The studies also used pressurised drip irrigation systems rather than drip irrigation kits that have more potential to be used by urban vegetable farmers in poor countries. Studies conducted on drip kits have, so far, centred on improving performance and evaluating economic returns from using them (Kay 2001; Postel *et al.* 2001; Sijali & Okumu 2002). In this paper, we present findings from on-farm trials of watering cans, bucket drip kits and FI in reducing vegetable contamination.

Methods

Study area

The study was conducted at Gynyase vegetable farming site in Kumasi, Ghana. The site was in a low-lying area where farmers had access to irrigation water, and soils are predominantly sandy. Polluted urban streams, ponds and shallow dugouts are common sources of irrigation water, and watering cans are used for irrigation. When irrigating, farmers lift the watering cans to different heights. Watering cans are supplied with removable caps (like shower heads) at the outlet. However, some farmers remove these caps while irrigating as large debris in water may sometimes restrict its flow.

The four main vegetables cultivated are lettuce, spring onion, green pepper and cabbage. These vegetables are mostly eaten raw in salads. We chose lettuce for investigation as it is eaten raw, widely cultivated and the most contaminated (Amoah *et al.* 2005). The cultivar grown in Ghana is the bunching type, which takes 1 month to mature after transplanting. Poultry manure is used as a source of nutrients, which is applied to lettuce 1 week after transplanting. Average application rates are about 5 tonnes per hectare. Usually, farmers collect manure from poultry farms and store it at the farming site rather than using fresh manure.

Trials were first described to all 30 farmers at the Gynyase farming site. Five of these farmers agreed to participate in the study. They had plots large enough to conduct all trials, were well established in the area, and therefore unlikely to move away. Agricultural practices were the same at all five farms, and all extensively grew lettuce that was used for this study. Farms were located at different parts of the farming site. Other farmers were encouraged to comment on the performance of the systems.

Gynyase farmers have an informal tenure agreement with the local university, which owns the land they farm. Because of the risk of eviction, they have no incentive for larger on-farm investments. Field trials were conducted in the dry season from December 2004 to February 2005, and wet season trials between March and June 2005. Climatic data, represented by total monthly rainfall, average daily temperature and average daily sunshine duration, are shown in Table 1.

Irrigation methods

The watering can method (WC) is the common irrigation method used by farmers in the area. An average watering can has a capacity of 15 l. The average crop density was 15 lettuce plants per square metre, and each WC plot was about 20 m^2.

Bucket drip irrigation kits (DIK) are home garden micro irrigation kits fitted with micro-tube emitters (Bhinge Brothers, Maharashtra, India) provided by International Development Enterprises (IDE). Each kit is designed to cover an area of 4 m by 5 m, has two 5-m-long laterals spaced 1 m apart with emitters spaced 0.6 m apart. One kit has 32 micro-tube emitters, and each emitter supplies water to two plants. This would have given a crop density of 3.2 lettuce plants per square metre, which appeared too low for a comparative study and to attract farmers' attention in our pilot trials. We modified the kits to increase densities by adding two laterals and extra emitters to reduce emitter spacing to 0.3 m. This raised the crop

Table 1 Climatic data for Kumasi in the field trials period (December 2004–February 2006)†

Month	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb
Total monthly rainfall (mm)	43.5	12.5	48.9	136.4	66.9	272.1	121.3	18.3	36.7	174.1	236.9	49.8	29.8	111.1	98.4
Average daily temp. (°C)	27.1	26.7	28.7	28.2	28.3	27.1	25.5	24.4	23.9	26.0	26.7	27.4	27.1	27.9	27.5
Average daily sunshine duration (hrs)	6.8	6.2	6.2	6.7	6.7	7.0	3.7	2.6	1.9	3.8	6.9	7.0	6.0	6.3	6.5

†Months with total monthly rainfall of less than 60 mm were used for dry season trials and the rest for wet season trials.
Source: Ghana Meteorological Services, Kumasi, Ghana.

density to 12.8 lettuce plants per square metre. Water was supplied by a 40-l plastic bucket and filtered with a cotton cloth supplied with the kits. The bucket was raised 1 m high and supported by a simple wooden structure.

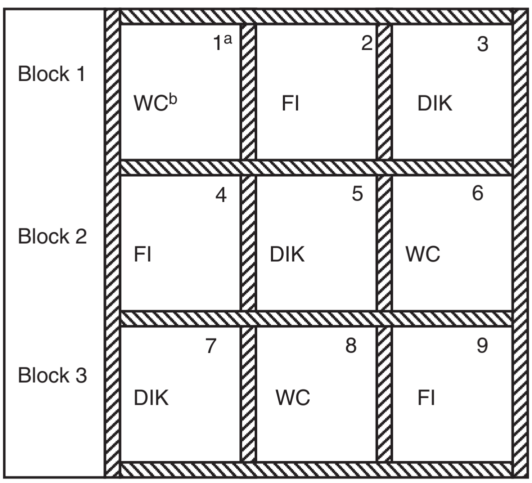
For FI, each plot had four parallel corrugated furrows spaced about 0.5 m apart according to standard furrow design in sandy soils (GIDA-JICA 2004). Lettuce was planted on each side of the ridges, making eight rows with 30 lettuce plants each. Irrigation water was applied to furrows, which had a gradient of about 0.3%. Furrow plots measured 3 × 8 m. The average crop density was 10 lettuce plants per square metre.

Sampling

Plots for irrigation methods were completely randomised in three blocks such that each block comprised all three methods (Figure 1). Blocks were separated by a 1-m-wide walking path to avoid cross-contamination. Four sequential trials were conducted in each dry and wet season. Three lettuce samples were collected from each plot by cutting lettuce leaves randomly on each plot, giving a total of 216 samples. Each sample was packed into a sterilised polythene bag, and fresh sterilised gloves were used for each plot.

Soil samples were taken at the start of each trial from six random points on each plot at depths of 0.1–0.2 m. The six sub-samples collected from each plot were combined into a composite sample. Seventy-two composite soil samples were taken in total. In addition, three poultry manure samples were taken from each of the five trial farms at the time farmers were applying it to lettuce plants. All lettuce, soil and poultry manure samples were collected in sterilised polythene bags, and each sample weighed more than 200 g. A weekly sample was taken from each water source used to irrigate all the three blocks in each trial. Sterilised 2-l bottles were used for water sampling at depths of 0.2 m (UNEP-WHO 1996). All sampling was done between 7.00 and 9.00 AM. Water, lettuce, poultry manure and soil samples were transported in separate ice-cold containers to reach the laboratory in Kumasi within 1 h of collection.

To quantify crop productivity, fresh weights of lettuce were taken by weighing 20% of the number of lettuce plants per treatment on site just after sampling. Amounts of water used daily for each irrigation method were recorded after each watering session.



WC - Watering cans, FI – Furrow irrigation and DIK– Drip irrigation kits

Figure 1 Field layout of the three irrigation methods: WC – Watering cans, FI – Furrow irrigation and DIK – Drip irrigation kits.

Other related trials

Trials on the effects of watering can caps and pouring from different heights were conducted on plots with mature lettuce plants. Three distinct heights were used, i.e. <0.5 m, 0.5–1.0 m and >1.0 m, to which farmers could lift the watering cans. At each of these levels, watering cans were used with and without caps. Five sequential trials were conducted in each dry and wet season. Three samples were collected for microbiological analysis for each treatment in each repeated trial, giving a total of 180 samples. Collection and transportation to the laboratory followed the procedure described above.

Laboratory analysis

Water, soil and lettuce samples were analysed for indicator thermotolerant coliforms and helminth eggs. The most probable number (MPN) method was used to determine counts of thermotolerant coliforms in all samples. Ten grams of lettuce samples were aseptically cut into a stomacher bag and washed in a pulsifier (Microgen Bioproducts Ltd, Surrey, UK). For soil and poultry manure samples, 10 g of moist soil and manure were weighed and mixed with 100 ml of sterile distilled water. Tenfold serial dilutions were made and a set of triplicate tubes of MacConkey broth (MERCK, Darmstadt, Germany) was inoculated with sub-samples from each dilution and incubated at 44 °C for 24–48 h (APHA–AWWA–WEF 1998). The number and distribution of positive tubes (acid or gas production or color change in broth) was used to obtain the population of coliform bacteria in water samples and lettuce from the MPN table.

Helminth eggs were enumerated using the US-EPA modified concentration method (Schwartzbrod 2001) and identified using the WHO Bench Aid (WHO 1994). All species of helminth eggs were enumerated after washing 100 g of lettuce samples in 2 l of tap water using the pulsifier. For soil and manure, 10 g were weighed into 2 l of tap water and thoroughly mixed before enumeration.

Qualitative data collection

Participating farmers were given record sheets to keep daily notes on the amounts of water used, rainfall days, farming practices such as fertilization, and key observations on each plot. A similar observation record sheet was filled by a field technician. The farmers' perceptions of the methods were recorded through in-depth interviews with participating farmers after each trial, followed by focus group discussions with all 30 farmers at farming site.

Data analysis

Two-way ANOVA in randomised blocks was done with GENSTAT-32 for Windows (Rothamsted Experimental Station). Counts of thermotolerant coliforms and helminth eggs were normalised by log transformations for anova. Other data analysis, graphs and tables have been done with Microsoft Excel (Microsoft Corporation).

Results

Microbial quality of irrigation water, soils and poultry manure

Thermotolerant coliform levels were slightly higher during the dry season with a mean difference of 1.3 log units per 100 ml (Table 2; $P < 0.001$). However, the numbers of helminth eggs did not vary much (anova $P < 0.188$). *Ascaris lumbricoides* were the most common helminths, followed by *Trichuris trichiura, Fasciola hepatica* and *Schistosoma sp*.

Soils were more contaminated in the wet season than in the dry season (Table 3). The levels differed by an average of 2 log units per 100 g of soil for thermotolerant coliforms and two eggs per 10 g of soil for helminth eggs. Helminths isolated from irrigation water were also isolated from soil. In 15 random samples of poultry manure, thermotolerant coliforms ranged from 4.36–7.86 log units per 100 g of manure and from 3 to 14 helminth eggs per 10 g of manure, which could be an additional source of indicator organisms (Drechsel *et al.* 2000; Amoah *et al.* 2005). To reduce its influence on the trial results, application rates for all plots were kept uniform at 5 tonnes per hectare; application was done on the 7th day after transplanting, and poultry manure was taken from the same heap.

Microbial quality of lettuce

In both dry and wet seasons, counts of thermotolerant coliforms and helminth eggs on lettuce were highest in WC plots and lowest in DIK plots (Table 4). In the dry season, DIK plots had no helminths and less than 1 log unit per 100 g of lettuce of thermotolerant coliforms. The differences in levels of indicator organisms between irrigation methods were more pronounced during the dry season. In the wet season, the difference between DIK and WC was, on average, 2.4 log units of thermotolerant coliforms per 100 g of lettuce. In the dry season, this difference was 6.1 log units. Average levels of indicator organisms were lower during the dry

Table 2 Thermotolerant coliforms and helminth eggs levels in irrigation water

		Thermotolerant coliforms (log of MPN per 100 ml)		Helminths (no. of eggs per litre)	
Season	No. of samples	Mean	95% CI	Mean	95% CI
Dry	16	5.83	5.44–6.21	1.9	1.6–2.3
Wet	16	4.53	4.26–4.81	1.6	1.2–2.0

Table 3 Thermotolerant coliforms and helminth eggs levels in soil

		Thermotolerant coliforms (log of MPN per 100 mg)		Helminths (No. of eggs per 10 g)	
Season	No. of samples	Mean	95% CI	Mean	95% CI
Dry	36	6.30	6.04–6.55	3.6	3.0–4.1
Wet	36	8.17	8.00–8.36	5.6	4.9–6.3

Table 4 Counts of thermotolerant coliforms and helminth eggs on lettuce irrigated by different irrigation methods

Irrigation method	No. of samples	Thermotolerant coliforms (log of MPN per 100 g)		Helminths (No. of eggs per 100 g)	
		Mean	95% CI	Mean	95% CI
Dry season					
WC	36	6.53	6.41–6.64	0.6	0.4–0.8
FI	36	5.29	5.22–5.37	0.5	0.3–0.6
DIK	36	0.47	0.22–0.71	0.0	0.0–0.1
Wet season					
WC	36	8.21	8.08–8.34	1.5	1.3–1.7
FI	36	7.79	7.67–7.91	1.0	1.0–1.3
DIK	36	5.65	5.56–5.75	0.6	0.4–0.8

WC, watering cans, FI, furrow irrigation; DIK, drip irrigation kits.

season, and indicators for both treatments differed significantly in both seasons ($P < 0.001$). The same types of helminth eggs were isolated from irrigation water and lettuce; three-quarters of all eggs were *Ascaris lumbricoides*.

Effects of using watering cans with caps and watering height

Increasing watering height when using watering cans, whether capped or not, increased both thermotolerant coliforms and helminth counts on lettuce significantly ($P < 0.001$; Table 5). The average difference in counts on lettuce irrigated between the highest and lowest watering heights was 1.5 log units per 100 g for thermotolerant coliforms and 1.3 helminth eggs per 100 g. Using capped watering cans had reduced counts of both indicator organisms at each level in both seasons. The average difference between capped and uncapped watering cans was about 1 log unit for thermotolerant coliforms and one helminth egg per 100 g of lettuce in both dry and wet seasons. An average reduction of 2.5 log units for thermotolerant coliforms and 2.3 helminth eggs per 100 g of lettuce can be achieved if farmers use watering cans with capped outlets and raise them no higher than 0.5 m, compared with using watering cans without capped outlets raised higher than 1 m.

Effects of irrigation methods on productivity

Furrow irrigation resulted in much lower fresh weights, both per plant and per crop area, especially during the dry season than DIK and WC (Table 6). The differences in fresh weights were statistically different in both seasons but more pronounced in the dry season. Fresh lettuce from DIK plots weighed 7–10% more, but yield per square metre was

Table 5 Levels of thermotolerant coliforms and helminth eggs on lettuce irrigated using watering cans from different heights

Irrigation height (m)	No. of samples	Thermotolerant coliforms (log of MPN per 100 g)				Helminths (No. of eggs per 100 g)			
		Capped[a]		Uncapped[b]		Capped		Uncapped	
		Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Dry season									
<0.5	30	4.69	4.57–4.81	5.43	5.16–5.70	0.3	0.1–0.5	1.1	0.6–1.5
0.5–1.0	30	5.37	5.00–5.75	5.68	5.42–5.95	1.0	0.8–1.3	1.6	1.3–1.9
>1.0	30	5.94	5.57–6.32	7.77	7.36–8.18	1.6	1.3–1.9	2.6	2.1–3.0
Wet season									
<0.5	30	6.45	6.32–6.59	7.52	7.38–7.67	0.7	0.4–1.1	1.4	0.9–2.0
0.5–1.0	30	6.64	6.50–6.78	7.69	7.53–7.85	1.5	1.1–1.9	2.0	1.6–2.4
>1.0	30	7.73	7.63–7.82	8.47	8.34–8.61	1.4	1.1–1.7	2.9	2.5–3.3

[a]Capped – watering cans used in irrigation were fitted with caps at the outlet.
[b]Uncapped – watering cans used had no caps at the outlet.

Table 6 Lettuce yields in the dry and wet seasons

Irrigation method	No. of samples	Fresh weights per plant (kg per lettuce plant)			Fresh weights per cropping area (kg/m^2)	
		Mean	95% CI	% change	Mean	% change
Dry season						
WC	24	0.129	0.128–0.130	–	1.94	–
FI	24	0.056	0.056–0.058	−56.6	0.56	−71.1
DIK	24	0.142	0.141–0.143	+10.1	1.85	−4.6
Wet season						
WC	24	0.147	0.146–0.149	–	2.21	–
FI	24	0.130	0.129–0.131	−11.6	1.30	−41.2
DIK	24	0.158	0.157–0.159	+7.5	2.05	−7.2

WC, watering cans; FI, furrow irrigation; DIK, drip irrigation kits.

slightly lower on DIK than on WC plots because of lower crop density (12 *vs.* 15 plants per square metre, respectively).

Farmers' perceptions of different irrigation methods

Furrow irrigation and DIK irrigation are new methods to farmers in the area. Farmers found it hard to maintain FI plots as the sandy soil slid during weeding, causing to block the furrows. By removing soil from the furrows, farmers deepened the furrows over time, which affected the slope of water flow and made it harder for lettuce to access water. It was also harder to apply poultry manure to furrow ridges than to flat beds. Farmers generally used more water and more labour on FI plots, and thus were quite negative about using FI methods. Drip kits were much appreciated because of the physical quality of the lettuce produced. As water reached the root zone, foliar injury is avoided. The kits used much less water, and saved time and labour. Farmers also noticed that the average size of lettuce was much bigger, and weeds were more suppressed. The biggest limitation of the kits was occasional clogging and wide emitter spacing, especially of initial drip kits, which resulted in lower crop densities.

Although the modifications of DIK improved crop densities, farmers had problems in moving the greater number of drip laterals and micro-tubes while weeding, preparing land and applying manure. In general, farmers appreciated DIK, but expressed it was important to modify them to fit their practices. They observed that drip kits were better suited for other crops with a longer cultivation time and requiring wider spaces, such as watermelon and green peppers. The general perception of farmers was that the WC method remained most suitable for irrigating lettuce.

Discussion

This study shows very notable differences in the levels of indicator organisms on lettuce during the dry season between lettuce irrigated with watering cans and the two other methods, especially drip kits. Differences in the number of thermotolerant coliforms per 100 g of lettuce were as large as 6.1 log units in the dry season and 2.5 log units in the wet season. Overhead methods, such as watering cans, sprinkler and spray irrigation, expose lettuce leaves most to irrigation water. In a related study, more than 90% of spray-irrigated lettuce had *E. coli* 0157:H7, whereas less than 20% of surface-irrigated lettuce did (Solomon *et al.* 2002). Comparing furrow and drip kits, this study confirmed that furrow-irrigated lettuce is more contaminated (Oron *et al.* 1991, 1995). This is because furrows are often filled with irrigation water at the time of application, which causes more soil wetting leading to lettuce contamination from soils. Lower leaves of lettuce also come in direct contact with irrigation water in the furrows at such times causing more contamination. Similar observations were made in Mezquital Valley in Mexico where chillies were dipped into irrigation water in the furrows, which caused contamination (Blumenthal *et al.* 2000). Besides irrigation water, soils and poultry manure had high levels of indicator organisms. This could have contributed to additional lettuce contamination especially during the wet season. Appropriate irrigation methods should, therefore, also reduce soil wetting and splashing onto lettuce.

The reported average pathogen reduction through drip irrigation was 2 log units for low growing crops like lettuce (WHO 2006). The average difference of thermotolerant coliforms levels on lettuce of 4 log units per 100 g obtained was on the high side. This could be attributed to the type of drip irrigation systems used. Pressurised systems have emitters with high flow rates, usually more than 2 l/h, while the drip kits used had a flow rate of <0.5 l/h. Higher flow rates increase soil wetting and splashing. Research focusing on crop contamination from low-cost drip kits is very limited, but it shows that they potentially reduce contamination, and further assessments should be encouraged.

Drip irrigation is associated with high yields (El Hamouri *et al.* 1996). Compared with watering cans, drip-irrigated plot yields were on average 8% higher while furrow-irrigated plots had much lower yields especially in the dry season (57% lower) in terms of fresh weights per plant. However, yields (kg/m^2) on drip-irrigated plots were slightly lower by about 5% than watering can plots, since watering cans had a slightly higher cropping density. Lettuce irrigated with drip kits was more attractive and could sell better than watering can-irrigated lettuce, because drip irrigation avoids foliar injury, which is most pronounced when watering cans are used. However, drip kits often clogged and were cumbersome during weeding. They should be modified further to suit farmers who have no land tenure security and where security of the kits and storage barrels is not guaranteed. Socioeconomic quantifications of some of these strengths and limitations will help to better evaluate these methods. However, for now, based on the yields from the tested alternatives (FI, DIK) and perceptions gathered from farmers, it is most unlikely that farmers will switch to FI.

We also tested caps at outlets and lower pouring heights to reduce contamination while using watering cans, which is the preferred method. Based on empirical pathogen transportation models, detachment and transportation of pathogens from soils are minimised by reducing the size and velocity of water particles striking the soil (Tyrrel & Quinton 2003). Caps at watering can outlets reduce the size of irrigation water particles, and lower irrigation heights reduce the soil-striking velocities. Using watering cans with caps reduced thermotolerant coliforms on lettuce by an average of 1 log unit and one helminth egg per 100 g of lettuce. Using capped watering cans raised less than 0.5 m achieved reductions of 2.5 log units thermotolerant coliforms and 2.3 helminth eggs per 100 g of lettuce as compared with using uncapped watering cans from a height of more than 1 m, which is in addition more labour intensive. This shows that simple changes in the practice of using watering cans can reduce crop contamination. As these changes met with the least resistance from farmers, research should not only develop new techniques but primarily focus on improving commonly used ones.

More cheap and simple irrigation methods need to be developed and assessed to reduce health risks. Such methods are more likely to succeed in informal urban irrigation settings, where low tenure security prevents farmers from investing in sophisticated methods or on-site treatment ponds. However, safer irrigation methods will still have to be complemented by other on- and off-farm measures for health risk reduction (including crop washing practices) in countries without comprehensive wastewater treatment.

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Conflicts of interest

All authors declare no conflicts of interest.

References

Amoah P, Drechsel P & Abaidoo RC (2005) Irrigation urban vegetable production in Ghana: sources of pathogen contamination and health risk elimination. *Irrigation and Drainage* **54**, S49–S61.

APHA–AWWA–WEF (1998) *Standard Methods for the Examination of Water and Wastewater*, 20th Edn. American Public Health Association, Washington DC, USA.

Armon R, Gold D, Brodsky M & Oron G (2002) Surface and subsurface irrigation with effluents of different qualities and prescence of Cryptosporidium oocytes in soils and on crops. *Water Science and Technology* **46**, 115–122.

Bastos RKX & Mara DD (1995) The bacterial quality of salad crops drip and furrow irrigated with waste stabilization pond effluent: an evaluation of WHO guidelines. *Water Science and Technology* **12**, 425–430.

Blumenthal UJ, Peasey A, Ruiz-Palacios G & Mara DD (2000) Guidelines for wastewater reuse in agriculture and aquaculture: recommended revisions based on new research evidence. *WELL study*, Task No: 68 Part 1.

Brackett RE (1999) Incidence, contributing factors, and control of bacterial pathogens in produce Postharvest. *Biology and Technology* **15**, 305–311.

Carr R (2001) Excreta-related infections and the role of sanitation in the control of transmission (Chapter 5). In: *Water Quality: Guidelines, Standards and Health; Assessment of Risk and Risk Management for Water-related Infectious Disease* (eds L Fewtrell & J Bartram) International water Association (IWA) on behalf on the World Health Organisation, London, UK. pp. 89–113.

Drechsel P, Abaidoo RC, Amoah P & Cofie OO (2000) Increasing use of poultry manure in and around Kumasi, Ghana: is farmers' race consumers' fate? *Urban Agricultural Magazine* **2**, 25–27.

El Hamouri B, Handouf A, Mekrane M *et al.* (1996) Use of wastewater for crop production under arid and saline conditions: yield and hygienic quality of crop and soil contaminations. *Water Science and Technology* **33** (10–11) 327–334.

GIDA-JICA (2004) *Technical Guidelines for Irrigated Agriculture. Small Scale Irrigated Agriculture Project – Follow Up*. Ghana irrigation Development Authority, Accra.

Kay M (2001) *Smallerholder Irrigation Technology: Prospects for Sub Sahara Africa*. IPRTRID, FAO, Rome.

Martijn E & Redwood M (2005) Wastewater irrigation in developing countries – limitations for farmers to adopt appropriate practices. *Irrigation and Drainage* **54**, S63–S70.

Mensah P, Yeboah-Manu D, Owusu-Darko K & Ablordey A (2002) Street foods in Accra, Ghana: how safe are they? *Bulletin of the World Health Organization* **80**(7), 546–554.

Obuobie E, Keraita B, Danso G *et al.* (2006) *Irrigated Urban Vegetable Production in Ghana: Characteristics, Benefits and Risks*. IWMI-RUAF-CPWF, IWMI, Accra, Ghana.

Oron G, DeMalach Y, Hoffman Z & Ciboratu R (1991) Subsurface micro-irrigation with effluent. *Journal of Irrigation and Drainage Engineering, ASCE* **117**(1), 25–36.

Oron G, Goemans M, Manor Y & Feyen J (1995) Poliovirus distribution in the soil-plant system under reuse of secondary wastewater. *Water Research* **29**, 1069–1078.

Oron G, Armon R, Madelbaum R *et al.* (2001) Secondary wastewater disposal for crop irrigation with minimal risks. *Water Science and Technology* **43**, 139–146.

Pescod MB (1992) *Wastewater Treatment and Use in Agriculture*-FAO Irrigation and Drainage paper 47. FAO, Rome.

Postel S, Polak P, Gonzales F & Kelly J (2001) Drip irrigation for small farmers: a new initiative to alleviate anger and poverty. *Water International* **26**(1), 3–13.

Schwartzbrod J (2001) *A Collection of Methods of Analysis of Helminth Eggs and Cysts in Wastewater, Sludge, Soils and Crops*. University of Nancy, France.

Scott CA, Faruqui NI & Raschid-Sally L (2004) Wastewater use in irrigated agriculture: management challenges in developing countries. In: *Wastewater Use in Irrigated Agriculture: Confronting the Livelihood and Environmental Realities*. (eds CA Scott, NI Faruqi & L Raschid-Sally) CABI Publishing, Oxfordshire, UK, pp. 1–10.

Sijali VI & Okumu RA (2002) New irrigation technologies. In: *The Changing Face of Irrigation in Kenya: Opportunities for Anticipating Changes in Easter and Southern African Paper* (eds GH Blank, CM Mutero & H Murray-Rust) International Water Management Institute, Colombo, Sri Lanka. pp. 55–70.

Solomon EB, Potenski CJ & Matthews KR (2002) Effect of irrigation method on transmission to and persistence of *Escherichia Coli* O157:H7 on lettuce. *Journal of Food Protection* **65**(4), 673–676.

Tyrrel SF & Quinton JN (2003) Overland flow transport of pathogens from agricultural land receiving fecal wastes. *Journal of Applied Microbiology* **94**, 87–93.

UNEP-WHO (1996) *Water Quality Monitoring; A Practical Guide to the Design and Implementation of Fresh Water Quality Studies and Monitoring Programs*. Chapman and Hall, London.

WHO (1994) *Bench Aids for Diagnosis of Intestinal Parasites*. World Health Organization, Geneva, Switzerland.

WHO (2006) *Guidelines of the Safe Use of Wastewater, Excreta and Grey Water; Vol. 2: Wastewater Use in Agriculture*. World Health Organization, Geneva, Switzerland.

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