A probabilistic assessment of the contribution of wastewater-irrigated lettuce to *Escherichia coli* O157:H7 infection risk and disease burden in Kumasi, Ghana

Razak Seidu, Amina Abubakari, Isaac Amoah Dennis, Arve Heistad, Thor Axel Stenstrom, John A. Larbi and Robert C. Abaidoo

**ABSTRACT**

Wastewater use for vegetable production is widespread across the cities of many developing countries. Studies on the microbial health risks associated with the practice have largely depended on faecal indicator organisms with potential underestimation or overestimation of the microbial health risks and disease burdens. This study assessed the *Escherichia coli* O157:H7 infection risk and diarrhoeal disease burden measured in disability-adjusted life years (DALYs) associated with the consumption of wastewater-irrigated lettuce in Kumasi, Ghana using data on *E. coli* O157:H7 in ready-to-harvest, wastewater-irrigated lettuce. Two exposure scenarios – best case and worst case – associated with a single consumption of wastewater-irrigated lettuce were assessed. The assessment revealed wastewater-irrigated lettuce is contributing to the transmission of *E. coli* O157:H7 in Kumasi, Ghana. The mean *E. coli* O157:H7 infection risk and DALYs in the wet and dry seasons, irrespective of the exposure scenario, were above the World Health Organization tolerable daily infection risk of $2.7 \times 10^{-7}$ per person per day and $10^{-6}$ DALYs per person per year. It is recommended that legislation with clear monitoring indicators and penalties is implemented to ensure that farmers and food sellers fully implement risk mitigating measures.

**Key words** | diarrhoeal disease burden, *E. coli* O157:H7, Ghana, infection risk, lettuce, wastewater irrigation

**INTRODUCTION**

Globally, diarrhoeal disease and its complications account for billions of illnesses and millions of deaths annually. Developing countries, particularly those in Africa, have the highest incidence as well as burden of diarrhoeal disease (WHO 2013). In Africa, diarrhoeal disease is the third ranked cause of mortality after HIV/AIDS and lower respiratory tract infections, and led to 800,000 deaths and 55 million lost life years (expressed as diarrhoeal disease burden and measured in disability-adjusted life years (DALYs)) on the continent in 2011 (WHO 2013). A plethora of risk factors have been implicated for the occurrence of diarrhoeal disease in developing countries. These risk factors include, but are not limited to, unimproved water and sanitation facilities, poor hygiene practices and unhygienic food handling. In many cities in developing countries with rapidly expanding populations, wastewater use in vegetable farming is contributing to the mix of diarrhoeal disease risk factors. In these cities, a significant proportion of the vegetables consumed are irrigated with raw or partially diluted wastewater. Farmers using wastewater for irrigation rarely adopt risk-mitigating measures and thus expose themselves and their families, as well as consumers of the wastewater-irrigated vegetables, to pathogens causing diarrhoeal disease (Seidu & Drechsel 2010). However, in most developing countries

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the link between wastewater irrigation and the transmission of diarrhoea-causing pathogenic organisms is poorly understood. This is partly due to inadequate resources to collect and analyse wastewater and wastewater-irrigated vegetables for pathogenic organisms and a general weakness in existing epidemiological surveillance systems to assess and relate the cause(s) of disease outbreaks. Consequently, the actual contribution of diarrhoeal disease attributed to wastewater irrigation is less well characterized.

In urban Ghana, a significant proportion of vegetable salad served by restaurants and street-food sellers originates from wastewater-fed fields (Seidu & Drechsel 2010). It is estimated that daily, about 800,000 people across the cities of the country consume wastewater-irrigated lettuce salad (Seidu & Drechsel 2010). This number is likely to increase in sync with rapid urbanization, which is now 3% in Ghana (Ghana Statistical Service 2010). Studies on potential disease-causing organisms in wastewater and wastewater-irrigated vegetables in Ghana have focused mainly on indicator organisms, particularly faecal coliforms (Keraita et al. 2007; Amoah et al. 2007), and have not addressed the pathogens directly. These faecal indicator organisms have formed the basis in the construction of models to assess the diarrhoeal disease risk and burden associated with wastewater irrigation (Seidu et al. 2008; Seidu & Drechsel 2010). The use of faecal indicator organisms in risk assessment can lead to an underestimation or overestimation of diarrhoeal disease risk and burdens in the absence of data on pathogenic organisms.

In 2011, the Research Council of Norway (RCN) funded a study to, among other things, assess the diarrhoeal disease risk and burden associated with wastewater use in urban Ghana. As part of the RCN study, wastewater-irrigated vegetables were analyzed for Escherichia coli O157:H7 in wastewater-irrigated vegetables. E. coli O157:H7 diarrhoeal disease outbreaks have been associated with the consumption of vegetables (Jay et al. 2004). Following the outbreak of E. coli O157:H7 in the United States in 1982 from fast-food chains (Riley et al. 1983), additional outbreaks have been related to contaminated vegetables (Michino et al. 1999; Hilborn et al. 1999). From 1996 to 1999, an estimated 22 outbreaks of E. coli O157:H7 reported in California were attributed to the contamination of lettuce and spinach in watersheds due to heavy and increased river flow rates (Cooley et al. 2007). Outbreaks associated with the consumption of E. coli O157:H7-contaminated vegetables have also been reported in Japan (Michino et al. 1999) and Sweden (Söderström et al. 2008). In the United States, E. coli O157:H7 causes about 73,000 infections and 60 deaths annually (Mead et al. 1999), and increased morbidity and mortality has raised public concern due to the fact that infection develops into haemorrhagic colitis and haemolytic uremic syndrome (HUS) which is more pronounced in children, the elderly and the immunocompromised (Abu-Ali et al. 2010). E. coli O157:H7 diarrhoeal disease outbreaks have also been reported in African countries such as Kenya (Sang et al. 1996), Cameroon (Germani et al. 1998), Ivory Coast (Dadie et al. 2000) and Nigeria (Olorunshola et al. 2000). The objective of this study was to assess the E. coli O157:H7 infection risk and disease burden associated with the consumption of wastewater-irrigated lettuce in Kumasi, Ghana, where vegetable farmers mainly depend on diluted wastewater from storm water drains and streams as a source of irrigation water (Seidu et al. 2013).

METHODS

Farm sites, sampling and analysis of E. coli O157:H7

Kumasi is the second largest city in Ghana with a population of over two million and an annual growth rate of 2.7% (Ghana Statistical Service 2010). The city has a number of hotels, restaurants and street-food vendors that serve salad prepared with wastewater-fed vegetables as a side-dish to consumers. Within the city two cross-sectional surveys were undertaken in all the diluted wastewater-irrigated farms (n = 8) in the wet (August–November, 2012) and dry (December 2012–May 2013) seasons to assess the level of E. coli O157:H7 in ready-to-harvest lettuce.

In each survey, lettuce heads were aseptically collected from beds in the farms with sterile knives into sterile plastic bags (Stomacher® laboratory system, Seward, UK) and sealed. From each bed, the lettuces were collected from the far ends and in the middle to represent triplicate samples. The samples were transported in cooling boxes to the laboratory for analysis. A total of 107 and 89 ready-to-harvest triplicate lettuce heads were collected from the farms in the wet and dry seasons, respectively.
Lettuce samples were weighed, aseptically cut and homogenized with a blender. One millilitre of the blended lettuce was transferred into 9 mL of 0.85% isotonic saline and poured onto Eosine Methylene Blue agar Petri dish plates and incubated at 44°C for 24 h. Plates showing growth of E. coli colonies (blue black with metallic sheen appearance) were sub-cultured onto Sorbitol MacConkey agar plates and incubated at 44°C for 24 h. Colonies that demonstrated a colourless appearance were isolated and re-cultured for pure colonies (Baron et al. 1994). Pure colonies were then serologically confirmed with E. coli prolex™ latex agglutination test kit (Oxoid, UK). One drop of E. coli O157:H7 antisera was dispensed onto a reaction card and a loop full of the pure colony of the test organism was added. This was then carefully emulsified into a smooth suspension. The card was carefully rocked in a circular motion. If agglutination occurred within 1 minute then the test organisms were considered positive for E. coli O157:H7. A similar reaction was carried out as a control using normal saline instead of the E. coli O157:H7 antisera. Quantifications were based on colony forming units (CFU) expressed per 100 g of lettuce.

Assessment of E. coli O157:H7 infection risk and DALYs

An integrated quantitative microbial risk assessment and DALYs approach was used to assess the E. coli O157:H7 infection risk, diarrhoeal disease morbidity and mortality and burden associated with the consumption of wastewater-irrigated lettuce salad. This was based on the following steps.

Hazard identification

The main hazard was E. coli O157:H7 in the ready-to-harvest, wastewater-irrigated lettuce. The E. coli serotype O157:H7 is regarded as a sub-group of enterohaemorrhagic verocytotoxin-producing E. coli associated with bloody diarrhoea (haemorrhagic colitis) and HUS (Su & Brandt 1993).

Exposure assessment

Occurrence of E. coli O157:H7 in ready-to-harvest lettuce: To account for variability and uncertainty in the level of E. coli O157:H7 in the lettuce, probability distribution functions (PDFs) were fitted to the wet and dry seasons’ E. coli O157:H7 data. The PDFs were fitted using the maximum likelihood estimation (MLE) method (Haas et al. 1999). The best fit PDF was obtained based on Akaike Information Criteria (AIC). Bootstrapping methods were used to obtain the uncertainties around the parameters of the PDFs.

Amount of lettuce consumed and exposure scenarios: The amount of lettuce consumed per single serving was obtained from a survey involving 270 street-food sellers and restaurants in Kumasi. Lettuce in ready-to-eat salad was weighed (Mettler balance, P-1200 (No. 903316)), PDFs were fitted to the weighed lettuce data, and the best fit PDF and bootstrapped uncertainty parameters were obtained using the MLE method (Haas et al. 1999). Two main exposure scenarios were considered in the risk assessment: (i) a worst-case scenario where there is no reduction in the level of E. coli O157:H7 in the wastewater-irrigated lettuce salad prior to consumption; and (ii) a best-case scenario where there is 0.5–2 log reduction of E. coli O157:H7 in wastewater-irrigated lettuce prior to consumption. The first scenario reflects the situation for most of the street foods where poor food safety practices prevail. The latter scenario is representative for high-class restaurants in the city where treatment of wastewater-irrigated lettuce using disinfectants (e.g., chlorine, salt solution, vinegar) is undertaken during salad preparation (Amoah et al. 2007).

The dose (D) of E. coli O157:H7 was obtained from the equation

\[ D = C_{\text{season}} \times 10^{-r} \times A \]  

(1)

where C is the concentration of E. coli O157:H7 in wastewater-irrigated lettuce salad in a given season (wet or dry); r is the reduction of E. coli O157:H7 on the salad (i.e., 0 for the worst-case scenario and log 0.5–2 for the best-case scenario); and A is the amount of lettuce salad consumed.

Dose–response (DR) assessment

It has been shown from outbreak studies and feeding trials that the beta-Poisson DR model best describes the dose(s) of E. coli O157:H7 ingested and the probability of infection.
The approximate form of the beta-Poisson DR model is given as (Furumoto & Mickey 1967)

\[ P_{\text{inf}} = 1 - \left( 1 + \frac{D}{\beta} \right)^{-\alpha} \]  

where \( P_{\text{inf}} \) is the probability of infection; \( D \) is the dose of \( E. coli \) O157:H7 ingested via lettuce salad; and \( \beta \) and \( \alpha \) are the DR parameters. In this study, the beta-Poisson DR model parameters derived for \( E. coli \) O157:H7 by Teunis et al. (2008) were used. To account for variability and uncertainty, a triangular probability distribution function was fitted to the \( \alpha \) and \( \beta \) parameters of the Teunis et al. (2008) DR model.

### Risk characterization

The \( E. coli \) O157:H7 infection resulting from a single consumption event of wastewater-irrigated lettuce was assessed. To account for variability and uncertainty separately in the risk estimates, a second-order Monte Carlo simulation was implemented. A description of the model parameters in the second-order Monte Carlo Simulation are presented in Table 1. The risk estimates accounted for both the wet and dry seasons expressed as the probability of infection per consumer per single consumption of lettuce salad. The second-order Monte Carlo risk models were constructed and run in R statistical software version 2.15.0 (www.r-project.org).

### Table 1

Summary of the parameters used in the risk assessment and DALYs estimations

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Unit</th>
<th>Probability distribution or assumption</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose of ( E. coli ) O157:H7 ingested (( D ))</td>
<td>CFU/g</td>
<td>( C_{\text{w wet season}} = \text{gamma} (\text{shape} = 0.052; \text{rate} = 0.00019) )</td>
<td>U &amp; V</td>
</tr>
<tr>
<td>( E. coli ) O157:H7 in irrigated lettuce (( C ))</td>
<td>Log g</td>
<td>( C_{\text{dry season}} = \text{gamma} (\text{shape} = 0.013; \text{rate} = 0.00025) )</td>
<td>V</td>
</tr>
<tr>
<td>Reduction in ( E. coli ) O157:H7 (( r ))</td>
<td>Uniform (0.5, 2)</td>
<td></td>
<td>U &amp; V</td>
</tr>
<tr>
<td>Amount of lettuce consumed per serving (( A ))</td>
<td>Lognormal (3.67; 0.19)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E. coli ) O157:H7 DR model</td>
<td></td>
<td>Parameters for the beta-Poisson model 3; ( \alpha = \text{Triang} (2.62 \times 10^{-4}; 0.373; 398.9) ) ( \beta = \text{Triang} (0.056; 39.71; 3.96 \times 10^{4}) )</td>
<td></td>
</tr>
<tr>
<td>Probability of infection (( P_{\text{inf}} ))</td>
<td></td>
<td>Beta-Poisson DR model</td>
<td>U &amp; V</td>
</tr>
<tr>
<td>Probability of illness (( P_{\text{ill}} )) with a certain symptom</td>
<td></td>
<td>( P_{\text{ill}} = P_{\text{inf}} \times 0.69^* )</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{\text{waterdiarr}} = P_{\text{ill}} \times 0.53^* )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{\text{blooddiarr}} = P_{\text{ill}} \times 0.47^* )</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>( P_{\text{HUS}} = P_{\text{blooddiarr}} \times 0.07^* )</td>
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<td></td>
<td></td>
<td>( P_{\text{ESRD}} = P_{\text{HUS}} \times 0.1^* )</td>
<td></td>
</tr>
<tr>
<td>Probability of fatality (( P_{\text{fatal}} ))</td>
<td></td>
<td>( P_{\text{fatal}} = P_{\text{blooddiarr}} \times 0.0003^* )</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{\text{fatal}} = P_{\text{HUS}} \times 0.17^* )</td>
<td></td>
</tr>
<tr>
<td>Severity weights for illness and fatality</td>
<td></td>
<td>( P_{\text{waterdiarr}} = 0.067^* )</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{\text{blooddiarr}} = 0.39^* )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{\text{HUS}} = 0.93^* )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{\text{fatal}} = 1^* )</td>
<td></td>
</tr>
<tr>
<td>Duration of illness</td>
<td>Days</td>
<td>( P_{\text{waterdiarr}} = 7 \text{ days}^* )</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{\text{blooddiarr}} = 12.2 \text{ days}^* )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{\text{HUS}} = 21^* )</td>
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</tr>
</tbody>
</table>

U, uncertainty; V, variability; C, calculated; gamma, gamma probability distribution function; Uniform, uniform probability distribution function; Lognormal, probability distribution function. Source: *This study; 2Amoah et al. (2007); 3Teunis et al. (2008); *Su & Brandt (1995); #Havelaar & Melse (2003).
Diarrhoeal disease burden

Diarrhoeal illness and mortality: Infections with E. coli O157:H7 can result in a wide range of symptoms and secondary complications. Given a probability of E. coli O157:H7 infection (\(P_{\text{inf}}\)), the probability of illness (morbidity) can be derived as

\[
P_{\text{ill}}(P_{\text{symp}}|D, \alpha, \beta) = \left(1 - \left(1 + \frac{D}{\beta}\right)^{-\alpha}\right) \times (P_{\text{symp}}) \tag{3}
\]

where the first part of the equation is \(P_{\text{inf}}\) and the second \(P_{\text{symp}}\) is the probability of an illness with a certain symptom or secondary complication resulting from the infection given a dose (\(D\)) of E. coli O157:H7 with DR parameters \(\alpha\) and \(\beta\).

Equation 3 can be expanded to obtain the probability of mortality (\(P_{\text{mort}}\)) as follows:

\[
P_{\text{mort}}(P_{\text{fatal}}|P_{\text{ill}}) = (P_{\text{ill}}) \times (P_{\text{fatal}}) \tag{4}
\]

where \(P_{\text{fatal}}\) is the probability of fatality given the occurrence of illness (\(P_{\text{ill}}\)) with a given symptom resulting from the consumption of a dose (\(D\)) of E. coli O157:H7.

To assess the illness (\(P_{\text{ill}}\)) and mortality (\(P_{\text{mort}}\)) associated with the consumption of E. coli O157:H7-contaminated lettuce salad, the E. coli O157:H7 disease transition model proposed by Havelaar & Melse (2003), with modifications, was followed. It was assumed that 31% of the infected consumers were asymptomatic (Su & Brandt 1995) while the rest were symptomatic. Of the symptomatic cases, 53% had watery diarrhoea (\(P_{\text{waterdiarr}}\)) and 47% bloody diarrhoea (haemorrhagic colitis) (\(P_{\text{blooddiarr}}\)). A case-fatality ratio of 0.03% was applied to cases with bloody diarrhoea (Havelaar & Melse 2003) while those cases with mild watery diarrhoea were expected to fully recover. Among the bloody diarrhoea cases, 7% later had HUS (Su & Brandt 1995) and 10% of the HUS cases developed an end-stage renal disease (ESRD) (Havelaar & Melse 2003). The mortality associated with the acute phase of HUS was assumed to be approximately 17% (Fitzpatrick et al. 1991; Havelaar & Melse 2003). The use of this high mortality rate was to account for the relatively poor health services in Kumasi.

Disability-adjusted life years: DALYs estimates were made to assess the burden of E. coli O157:H7 related diarrhoeal disease and mortality estimates derived from the previous section. DALYs were estimated using the equation of Murray (1994) as follows:

\[
\text{DALYs} = \text{YLLs} + \text{YLDs} \tag{5}
\]

where YLL is years of life lost due to mortality and YLD is years lived with a disability with weighing factor between 0 and 1 for the severity of the disability or disease. To derive the YLLs and YLDs for the E. coli O157:H7-related diarrhoeal disease and mortality, the following equations were used:

\[
\text{YLLs}[r, K, \beta] = \frac{KC_r^{a_0}}{(r + \beta)^2} \left\{ e^{-(r+\beta)(L+a)}[-(r+\beta)(L+a) - 1] - e^{-(r+\beta)a}[-(r+\beta)a - 1]\right\} + \frac{1-K}{r} (1-e^{-rL}) \tag{6}
\]

\[
\text{YLDs}[r, K, \beta] = D \left\{ \frac{KC_r^{a_0}}{(r + \beta)^2} \left\{ e^{-(r+\beta)(L+a)}[-(r+\beta)(L+a) - 1] - e^{-(r+\beta)a}[-(r+\beta)a - 1]\right\} + \frac{1-K}{r} (1-e^{-rL}) \right\} \tag{7}
\]

where \(K = \) age weighting modulation factor; \(C = \) constant; \(r = \) discount rate; \(a = \) age of death; \(\beta = \) parameter from the age weighting function; \(L = \) standard expectation of life at age \(a\). In this study, the age cohort 25–29 was used in the DALYs estimation. This cohort represents the highest proportion of consumers of wastewater-fed vegetables in urban Ghana (Seidu & Drechsel 2010). The severity weights for watery and bloody diarrhoea were taken as 0.067 and 0.39, respectively; and that of HUS was 0.93 (Havelaar & Melse 2003). Deaths resulting from diarrhoea, HUS and ESRD have a severity index of 1. A standard life expectancy of 65 years was used (Ghana Statistical Service 2010). Irrespective of the age group, mild diarrhoea and bloody diarrhoea were assumed to last 7 days and 12.2 days, respectively (Su & Brandt 1995). The HUS cases were estimated to last 21 days (Havelaar & Melse 2003). The DALY models were constructed and run in Microsoft Excel®.
RESULTS

Occurrence of *E. coli* O157:H7 in wastewater-fed lettuce and amount of lettuce salad consumed

Figure 1 shows the frequency distribution of *E. coli* O157:H7 in the wet and dry seasons. The occurrence of *E. coli* O157:H7 was low in the wastewater-fed lettuce, particularly in the dry season. The likelihood of a lettuce sample being positive for *E. coli* O157:H7 was 28% (30 out of 107 samples) and 5% (4 out of 89 samples) in the wet and dry seasons, respectively. Among the PDFs fitted to the *E. coli* O157:H7 occurrence data, the gamma PDF was the best fit for both the wet season (shape = 0.052; rate = 0.00019; AIC = 404.67) and dry season (shape = 0.013; rate = 0.00025; AIC = 363). Figure 2 shows the fitted PDFs and the bootstrapped parameters of the gamma PDF for the wet season (shape = 0.052 (95% CI: 2.9 x 10^{-2}–0.128); rate = 0.00019 (95% CI: 8.76 x 10^{-5}–8.9 x 10^{-4}) and dry season (shape = 0.013 (95% CI: 2.98 x 10^{-2}–1.3 x 10^{-1}); rate = 0.00025 (95% CI: 9.1 x 10^{-5}–8.9 x 10^{-4})).

Figure 3 shows the amount of lettuce salad consumed per serving as fitted with the lognormal PDF (Inμ = 3.67; Inσ = 0.19) and bootstrapped parameters (Inμ = 3.67 (95% CI: 3.64–3.69); Inσ = 0.19 (95% CI: 0.18–0.22)) of the PDF.

*E. coli* O157:H7 infection risk, diarrhoeal disease and DALYs

Table 2 presents a summary of the estimated *E. coli* O157:H7 infection risk, diarrhoeal disease morbidity and mortality and disability adjusted life years (DALYs) associated with the consumption of wastewater-fed lettuce in Kumasi, Ghana. Consumers of wastewater-irrigated lettuce salad were more likely to be infected with *E. coli* O157:H7 in the wet season than in the dry season. In the wet season, the one-time *E. coli* O157:H7 infection risk was 1.7 x 10^{-1} (95% CI: 0.02–0.39) for the worst-case scenario and 4.2 x 10^{-2} (95% CI: 0.0013–0.177) for the best-case scenario. In the dry season, the *E. coli* O157:H7 infection risks were 1.8 x 10^{-2} (95% CI: 0.0002–0.0810) for the worst-case scenario and 2.05 x 10^{-3} (95% CI: 7.63 x 10^{-6}–1.36 x 10^{-2}) for the best-case scenario. The variability and uncertainty of the risk estimates derived from the second-order Monte Carlo simulation under the different seasons and scenarios are presented in Figure 4.

*E. coli* O157:H7-related diarrhoeal morbidity and mortality

In the wet season, the diarrhoeal disease morbidity per consumer per single serving was 0.12 (95% CI: 0.014–0.269) for the worst-case scenario and 0.028 (95% CI: 0.00089–0.12213) for the best-case scenario (Table 2). The estimated mortalities resulting from the morbidity cases per serving were 8.25 x 10^{-5} (95% CI: 9.6 x 10^{-6}–1.9 x 10^{-4}) and 2 x 10^{-5} (6.28 x 10^{-7}–8.6 x 10^{-5}) for the worst-case and best-case scenarios, respectively, in the wet season. In the dry season, the estimated morbidities per consumer per single serving for the worst-case and best-case scenarios were...
respectively 0.012 (95% CI: 0.000138–0.05589) and 0.0014 (95% CI: 5.26×10⁻⁶ – 9.4×10⁻³), respectively. In the same season, the corresponding diarrhoeal mortalities for the worst-case and best-case scenarios were 8.69×10⁻⁶ (95% CI: 9.6×10⁻⁸–3.9×10⁻⁵) and 9.9×10⁻⁷ (95% CI: 3.68×10⁻⁹–6.6×10⁻⁶), respectively.

**Figure 2** | Level of *E. coli* O157:H7 in wastewater-irrigated lettuce in the wet (a) and dry (b) seasons fitted with the gamma probability distribution function and the bootstrapped parameters of the distribution.

**Figure 3** | Lognormal probability distribution fitted to the amount of lettuce salad consumed and the bootstrapped parameters of the distribution.
**Table 2** Predicted infection risk, diarrhoea disease case and disability adjusted life years (DALYs) for the O157:H7-contaminated lettuce salad in Kumasi, Ghana

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Wet season</th>
<th>Dry season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Infection risk</td>
<td>Diarrhoea mortality</td>
</tr>
<tr>
<td></td>
<td>(mean 95% CI)</td>
<td>(mean 95% CI)</td>
</tr>
<tr>
<td>Worst-case scenario</td>
<td>1.7 × 10⁻³</td>
<td>1.2 × 10⁻²</td>
</tr>
<tr>
<td></td>
<td>(1.4 × 10⁻³–3.9 × 10⁻³)</td>
<td>(1.6 × 10⁻²–5.6 × 10⁻²)</td>
</tr>
<tr>
<td>Best-case scenario</td>
<td>4.2 × 10⁻³</td>
<td>1.2 × 10⁻²</td>
</tr>
<tr>
<td></td>
<td>(3.9 × 10⁻³–6.6 × 10⁻³)</td>
<td>(2.2 × 10⁻²–3.4 × 10⁻²)</td>
</tr>
</tbody>
</table>

In the wet season the DALYs were 2.8 × 10⁻³ (95% CI: 3 × 10⁻⁴–6.5 × 10⁻³) and 7 × 10⁻⁴ (95% CI: 2.2 × 10⁻⁵–2.96 × 10⁻³) for the worst-case and best-case scenarios, respectively (Table 2). In the dry season the DALYs were 3 × 10⁻⁴ (3 × 10⁻⁶–1.3 × 10⁻³) and 3.4 × 10⁻⁵ (95% CI: 1.2 × 10⁻⁷–2.3 × 10⁻⁴) for the worst-case and best-case scenarios, respectively (Table 2).

**DISCUSSION**

The study shows that the occurrence of *E. coli* O157:H7 in wastewater-irrigated lettuce was seasonally dependent, with potential determinants including precipitation, temperature and humidity. On average, wastewater-fed lettuce collected from the farms was nearly six times (28% in wet season compared to 5% in the dry season) as likely to be contaminated with *E. coli* O157:H7 in the wet season as in the dry season. In the wet season, run-offs from animal farms and grazing sites adjacent to the farms are a potential source of *E. coli* O157:H7 contamination of the irrigation water. Also, almost all positive farms used chicken manure, a source of *E. coli* O157:H7, as a soil ameliorant (Griffin & Tauxe 1991; Griffin 1995). *E. coli* O157:H7 can survive longer in manure-amended soils (Kudva et al. 1998; Gagliardi & Karns 2000; Islam et al. 2004) and even longer in the wet season when the soil is either moist or wet (Solomon et al. 2002). Islam et al. (2004) demonstrated that *E. coli* O157:H7 in compost could survive for more than 5 months after application to the soil; and can contaminate the leaves of low-growing vegetables such as lettuce in the event of rainfall through soil splashes. The survival of *E. coli* O157:H7 on the leaves of lettuce is also likely to be longer in the wet season due to favourable environmental conditions (e.g., temperature and humidity) compared to the dry season. Temperature is an important determinant of the persistence of pathogens in the environment. The average temperature across the study sites was lower in the wet season (25.2–31.5 °C) than in the dry season (29.5–37.6 °C). The effect of temperature and humidity on the survival of *E. coli* O157:H7 as a function of season was recently
demonstrated (Oliveira et al. 2012). Oliveira et al. (2012) found that *E. coli* O157:H7 was more persistent on lettuce leaves in the fall when the humidity and temperature were 10 °C and 82%, respectively, and less persistent in the spring when humidity and temperature were 17 °C and 62%.

The study has shown that wastewater-irrigated farms are contributing to the transmission of *E. coli* O157:H7 with associated diarrhoeal disease and secondary complications (i.e., HUS and ESRD) in the city of Kumasi. Under the worst-case scenario in the wet season, the *E. coli* O157:H7 infection risk was $1.7 \times 10^{-1}$ per single consumption of wastewater-irrigated lettuce. This is about 6 log greater than the World Health Organization (WHO) tolerable diarrhoeal disease infection risk of $2.7 \times 10^{-7}$ per consumer per day ($\sim 10^{-4}$ per consumer per year) (WHO 2006). The wet season worst-case scenario *E. coli* O157:H7 infection risk resulted in 0.12 diarrhoeal disease cases per consumer per exposure, which is comparable with the diarrhoeal disease prevalence of 0.8–1.3 per person per year for developing countries with a potentially dire economic consequence (Mathers et al. 2002). The relatively high *E. coli* O157:H7 infection risk and accompanying DALYs has implications for the local economy and health systems of the city in particular. Currently, there are no epidemiological data on the incidence and cost of *E. coli* O157:H7-related diseases in Ghana in general, and Kumasi in particular. However, studies from the United States suggest that *E. coli* O157:H7-related diseases could have a devastating impact on
the local economy. Mead et al. (1999) estimated that US$405 million was lost annually through E. coli O157 (STEC) diseases related to food or other sources in the United States. Another estimate from the United States revealed that the average cost of E. coli O157:H7-related disease can range from US$26 for individuals who did not obtain medical care to US$5.2 million for cases that were hospitalized after developing HUS and ESRD (Frenzen et al. 2005). Based on Frenzen et al.’s (2005) study, the social and economic costs will be too prohibitive in the event that consumers of wastewater-irrigated lettuce salad in Kumasi develop HUS and ESRD. For those consumers suffering from kidney failure, the treatment options are kidney transplant or dialysis. The costs of paying for thrice-weekly dialysis would be unaffordable for the vast majority of consumers in Kumasi if they needed to pay out of their own pocket (Callegari et al. 2013). This seriously questions the continuous use of wastewater for vegetable irrigation given that the existing irrigation and farm practices lead to the contamination of vegetables with E. coli O157:H7.

From the foregoing information, the most critical question that policymakers should address is how to ensure that wastewater use in urban vegetable production does not result in significantly high economic and public health burdens. Several on-farm and post-harvest risk interventions have been piloted in Kumasi and other cities in Ghana to reduce the health risk (including diarrhoeal disease cases) associated with wastewater irrigation. These include on-farm interventions such as drip irrigation (Keraita et al. 2008a), irrigation cessation (Keraita et al. 2007), use of simple filters (Keraita et al. 2008a), sedimentation ponds (Keraita et al. 2008b) and post-farm interventions such as vegetable disinfection (Amoah et al. 2007). On-farm interventions such as drip irrigation, irrigation cessation and simple filtration have been effective in the reduction of faecal coliforms on wastewater-irrigated lettuce, and yet have proven difficult to implement due to economic reasons and farmers’ perceptions of health risk. In the short to medium term, these on-farm interventions are not likely to be implemented by farmers without a comprehensive enforcement backed by effective local guidelines and regulations. At the same time, additional efforts should be made towards improving post-harvest handling practices in the kitchens of street-food vendors and restaurants. For example, the study shows that a 0.5–2 log reduction in E. coli O157:H7 in the wastewater-irrigated lettuce would reduce the wet season worst-case diarrhoeal disease cases by a little over 90%.

In Ghana, surface disinfection of lettuce with salt solution is widely practised by street-food sellers and restaurants. Chlorine and vinegar are also used, but sparingly, because food sellers consider them to be expensive (Amoah et al. 2007). While the efficacy of salt solution and vinegar in the removal of E. coli O157:H7 on vegetables has not been documented in the literature, studies have reported a 1.5–2 log reduction of E. coli O157:H7 on vegetables (Beuchat 1999; Keskinen et al. 2009; Al-Nabulsi et al. 2014). Beuchat (1999) showed that the treatment of lettuce with 200 ppm chlorine solution or deionized water was effective in removing E. coli O157:H7 from lettuce. However, chlorine disinfection may prove ineffective if E. coli O157:H7 internalized in the vegetables is not significantly exposed to the active disinfectant agent, as has been demonstrated in several studies. E. coli O157:H7 can be internalized into lettuce through roots (Solomon et al. 2002; Erickson et al. 2010), attach inside stomatal pores (Seo & Frank 1999) and invade interior tissues via cut leaf edges (Kazue & Frank 2000; Erickson et al. 2010). Internalization of E. coli O157:H7 can render the surface treatment of lettuce with disinfectants such as chlorine ineffective (Kazue & Frank 2000). For example, a study showed that treatment of E. coli O157:H7 internalized in iceberg lettuce with 300 and 600 ppm chlorine solutions resulted in reductions of less than 1 log (Niemira 2008). Irradiation has been found to be more effective in the reduction of E. coli O157:H7 internalized in the tissues of lettuce. Niemira (2008) found a 5 log reduction of E. coli O157:H7 in iceberg lettuce treated with 1.5 kGy of irradiation. Nthenge et al. (2007) also showed that E. coli O157:H7 in the leaf tissue of lettuce was effectively removed by gamma irradiation while 200 ppm aqueous chlorine had no effect. Electrolyzed oxidizing water for the removal of E. coli O157:H7 on vegetables has also been demonstrated to be more effective than chlorine (Keskinen et al. 2009). These alternative disinfectants are relatively expensive and are not currently available to the vast majority of food-sellers and restaurants in Kumasi. It is therefore important that food sellers are introduced to less costly but effective disinfection measures. The introduction of any disinfection measure has to be
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