Risk factor analysis of diarrhoeal disease incidence in faecal sludge-applying farmers’ households in Tamale, Ghana
Razak Seidu, Owe Löfman, Pay Drechsel and Thor Axel Stenström

ABSTRACT
This study assesses the effect of risk factors and their inter-related mediation on diarrhoeal disease incidence in households applying faecal sludge in agricultural fields in Tamale, Ghana. Risk factors were assigned to three inter-related blocks: distal socio-economic, proximal public and domestic domains. The study involved 1,431 individuals living in 165 faecal sludge-applying households followed bi-weekly for 12 months. The incidence rate of diarrhoeal disease in the sludge-applying households was 1.09 (95% CI: 0.78–1.23) diarrhoeal episodes per person year at risk. Risk factors for diarrhoeal disease transmission in the public domain included sludge drying time (population attributable fraction (PAF) of 6%) and distance covered to collect water (PAF = 18%). The main distal socio-economic risk factor was wealth status (PAF = 15%). In the domestic domain, the risk factor significantly associated with diarrhoeal disease transmission was, not washing hands with soap after defecation (PAF = 18%). About 17% of the effect of sludge drying time (including distance to water facilities) was mediated by the domestic domain risk factors. The study recommends risk management strategies in sludge-applying households that address public and domestic domain risk factors in addition to specific farm level interventions.

Key words | diarrhoea, faecal sludge application, mediation, risk factors, Tamale Metropolitan Area

INTRODUCTION
Human excreta use in agriculture has been practised for centuries, particularly in Far East countries like China (World Health Organization [WHO] 2006). Although the practice has many benefits, it is associated with significant health risks that tend to erode its benefits if not undertaken in a safe manner. Health risks often associated with human excreta application in agriculture are helminthiasis and other gastro-enteric infections (Blumenthal & Peasey 2002).
In settings where the agricultural application of excreta is practised, disease transmission is mainly the consequence of several risk factors including those related to direct contact with excreta during application in the field (Blumenthal & Peasey 2002; WHO 2006). Risk factors in the public (e.g. water and sanitation) and domestic (e.g. food hygiene practices) may also contribute directly to diarrhoeal disease risk in excreta-applying households. In addition, risk factors such as the demographic and socio-economic status of the household may indirectly contribute to diarrhoeal disease. These risk factors can be categorised into distal and proximal risk factors, of which the distal factors (e.g. wealth status) are mediated through causal pathways involving the proximal factors (e.g. direct use of excreta) (Cairncross et al. 1996).
Understanding the effects of these factors and their inter-relationships is critical for the development of effective interventions to mitigate gastro-intestinal infections. In the context of excreta use in agriculture, distal factors such as the socio-economic status of households (e.g. wealth status, literacy rate) may be mediated by proximal public domain factors (e.g. access to water and sanitation facilities; use of excreta) and domestic domain factors (e.g. room...
occupancy) in the pathway to diarrhoeal disease transmission. Risk factor analysis of gastro-intestinal diseases associated with the application of excreta have accounted for the relative importance of different public and domestic domain risk factors using single multivariate models, focusing e.g. on the relationship between wastewater irrigation and gastro-intestinal infections. Single multivariate models are not able to capture the mediation proportions (MP) of the distal and proximal risk factors in the pathway to disease transmission (Victoria et al. 1997). This masquerades the inter-relationship between the public and domestic domain risk factors as well as their relative contribution to disease transmission. This shortcoming can be addressed by developing a conceptual framework that specifies how different distal and proximal risk factors of diarrhoeal disease transmission are inter-related. Based on the conceptual framework, the specific effects of different risk factors, as well as their associated mediated proportions, can be assessed using hierarchical effect decomposition models (Victoria et al. 1997; Ditlevsen et al. 2005).

In this study, a hierarchical effect decomposition model was applied to assess the public and domestic domain risk factors of diarrhoeal disease transmission in households applying faecal sludge in the Tamale Metropolitan Area (TMA) of Northern Ghana. The aims of the study are two-fold: (i) to identify the most important risk factors of diarrhoeal disease transmission in the sludge-applying households; and (ii) to assess the inter-relationships (MP) between the risk factors.

MATERIALS AND METHODS

Study area

The study was conducted in the TMA (9°18′–9°26′ N, 1°15′ E–1°23′ W) (Figure 1) of Northern Ghana which includes the city of Tamale and about 30 surrounding villages. TMA has a population of 293,900 with a growth rate of 2.5%. For several decades, some farmers in the larger Metropolitan area have used faecal sludge from onsite sanitation installations as their preferred soil ameliorant for crop production. Crops cultivated in the sludge fields include cereals, legumes and to a lesser extent vegetables.
(excluding all kinds of leafy vegetables eaten uncooked). Faecal sludge collected by farmers is dried on the farm and incorporated into the soil. A detailed description of the sludge application practices is presented elsewhere (Cofie et al. 2005; Seidu & Stenström 2012a).

**Study design and data collection**

The study was a closed cohort involving 165 faecal sludge-applying agricultural households in the TMA. The households were drawn from two peri-urban areas of the Metropolis where faecal sludge application in agricultural fields has been practised for several decades. A total of 1,431 individuals lived in these households. General characteristics of the sludge-applying households were obtained using semi-structured questionnaires. These characteristics included personal information of the individual members of the households such as age, sex, literacy level and occupation. Also, information related to households’ ownership of certain items, room occupancy, access to water and sanitation facilities, and sludge treatment practices was collected. In addition to the general household characteristics, an observational survey was conducted in each household using an open-ended questionnaire. In this survey, information on food preparation and storage facilities, water collection and storage facilities, presence of pets and animals in the household compound, garbage and/or faeces in the household compound, soap for hand washing, characteristics of the floors of sleeping rooms, and sludge application practices among others, were observed and documented. The characteristics of a particular household were assigned to individuals in that household.

A pre-coded diarrhoeal disease incidence questionnaire was used to record bi-weekly diarrhoeal disease episodes on the 1,431 individuals from February 2008 to March 2009. Individuals were allowed to withdraw. Additional information on diarrhoeal episodes with respect to duration and characteristics (e.g. watery or bloody) was collected. A diarrhoea episode was defined as three or more loose (or watery) stools within 24 hours, regardless of other gastrointestinal symptoms (Baqui et al. 1991), and without the influence of a purgative (or medication). Two independent episodes were separated by at least three diarrhoea-free days (Baqui et al. 1991). An episode of diarrhoea lasting 14 days or more was classified as persistent (WHO 1988). Diarrhoea episodes with blood were classified as severe. The diarrhoeal episodes information for infants and children was collected from their mothers.

All data were collected by trained fieldworkers. Prior to the data collection, a written purpose of the study was read in the local language to all the household heads and informed consent was obtained from them. The study instruments and methods were also reviewed and approved by the Ethics Committee of the University for Development Studies, Tamale, Ghana.

**Conceptual framework and statistical analysis**

Statistical analysis was undertaken based on the conceptual framework presented in Figure 2. The framework specifies the general hypothesis underpinning how diarrhoeal risk factors in sludge-applying households are grouped into blocks, the inter-relationships between the blocks and the pathway along which these blocks affect diarrhoeal disease. This framework is similar to others applied in Brazil to assess risk factors of childhood diarrhoeal disease incidence (Barreto et al. 2007; Ferrer et al. 2008; Genser et al. 2008). Diarrhoeal disease risk factors in the sludge-applying households were broadly grouped into distal and proximal. The proximal risk factors were further grouped into public and domestic domain factors. This resulted in three inter-linked blocks of risk factors: (i) distal (ii) proximal public domain; and (iii) proximal domestic domain. The inter-relationship between the three blocks was informed by an extensive literature search while the inclusion of variables in each block was based on information gathered from the household survey.

Following the conceptual framework, a hierarchical effect decomposition approach was used to quantify the effect of risk factors on diarrhoea (Victoria et al. 1997; Ditlevsen et al. 2005). By this approach, the direct and indirect mediated effects of the blocks were estimated. Descriptive analysis was carried out to examine the distribution of the risk factors in each block. Following this, a univariate analysis was conducted on the risk factors to identify which ones were significantly associated with diarrhoeal disease in the sludge-applying households. Significant risk factors from the univariate analysis (p ≤ 0.1) were entered into an intra-block multivariate model and analysed using mixed effect Poisson
regression models. Diarrhoeal disease clustering in households and individuals was accounted for by random coefficients in the mixed effect Poisson models with a gamma distribution (Rabe-Hesketh & Skrondal 2008). Significant variables (p ≤ 0.1) selection in the intra-block was conducted using a backward stepwise selection procedure. From the intra-block analysis, multivariate relative risks (RR) were obtained. All significant (p ≤ 0.1) variables retained in the intra-block multivariate models were included in an inter-block multivariate analysis. To assess the mediation effects (inter-relationships) of the blocks, an inter-block multivariate analysis was undertaken. The inter-block multivariate analysis involved a sequence of mixed effects Poisson regression models. The sequence started with model A, accounting for block I variables (distal), followed by model B, accounting for block I and block II variables (i.e., distal and proximal public domain risk factors) and finally model C accounting for blocks I, II and III variables (i.e., distal, proximal public and proximal domestic domain risk factors). Further the multivariate adjusted inter-block estimates of population attributable fraction (PAF) were calculated from the RR of both exposed subjects and the entire study population. The PAF was estimated using the formula: \( P_e \frac{(R_R - 1)}{1 + P_e (R_R - 1)} \), where \( P_e \) is the proportion of exposed group and \( R_R \) is the relative risk associated with the risk factor (Rothman & Greenland 1998). All models were adjusted for confounding by age (0–4; 5–14; ≥15) and gender.

By comparing the effect estimate before and after adjusting for the next block in the hierarchy of the inter-block multivariate analysis an estimate of how much the effect of the block has been mediated by the block on the pathway (i.e., the MP) was obtained (Victoria et al. 1997; Ditlevsen et al. 2005). The MP were obtained from the adjusted and unadjusted multivariate PAF according to the formula: \( \text{MP} = \frac{(\text{unadjusted PAF} - \text{adjusted PAF})}{\text{unadjusted PAF}} \times 100 \) (Genser et al. 2008). All statistical analyses were conducted using STATA (version 10; STATA Corporation, College Station, TX, USA).

**Figure 2** Conceptual framework of how different blocks of risk factors affect diarrhoeal disease incidence in sludge-applying farm households.
RESULTS AND DISCUSSION

Results

Diarrhoea incidence and characteristics

The 1,431 individuals from the sludge-applying households were followed for 489,465 person days at risk. During the follow-up period, 1,356 diarrhoeal disease episodes were recorded. This resulted in 1.09 (95% Confidence Interval [CI]: 0.78–1.23) diarrhoeal disease episodes per person year at risk. Children in the sludge-applying households recorded the highest incidence of diarrhoeal disease. Children ≤4 years had 2.9 (95% CI: 2.25–3.66) diarrhoeal disease episodes per person year at risk compared with 1.22 (95% CI: 0.92–1.52) episodes per person year for the 5–14 year age group and 0.59 (95% CI: 0.36–0.82) episodes per person year for the ≥15 age groups, respectively. The mean duration of a diarrhoea episode was 3.2 days (range: 1–18 days). Ten diarrhoeal episodes were persistent and occurred mainly (60% (n = 8)) in household members aged ≤14 years. Of the total diarrhoeal disease episodes recorded, 88 were severe. This resulted in 0.06 severe diarrhoeal disease episodes per person year at risk. About 30% of the severe diarrhoeal episodes occurred in children ≤4 years. There was no significant difference in diarrhoeal incidence between the male and female members of the households. The incidence of diarrhoeal disease was high in the warm dry season 1.04 (95% CI: 0.61–1.45) compared to the wet season 0.99 (95% CI: 0.73–1.24). However, this was not statistically significant.

Diarrhoeal disease risk factors

The univariate and intra-block multivariate analyses of risk factors associated with diarrhoeal disease incidence are presented in Tables 1 and 2 respectively. The univariate analysis presented in Table 1 revealed that distal risk factors such as wealth status, literacy of mothers and fathers and housing type were associated with diarrhoeal disease risk. Individuals from sludge-applying households with a lower wealth status were more likely (RR = 1.18, 95% CI: 0.94–1.49) to report diarrhoeal disease than those from households with higher wealth status. Also, individuals from sludge-applying households with a lower literacy of mothers and fathers were more likely to report diarrhoeal disease. Children aged ≤4 years and those living in traditional housing were at a higher risk of diarrhoeal disease.

Table 1 | Univariate analyses of potential risk factors associated with diarrhoeal disease in sludge-applying households in the Tamale Metropolitan Area, Ghana (N = 1,431)

<table>
<thead>
<tr>
<th>Block I: Distal Factors</th>
<th>N (%)</th>
<th>RR (95% CI)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Literate mother</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>99</td>
<td>1.10 (0.32–3.81)</td>
<td>0.069</td>
</tr>
<tr>
<td>Yes</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Literate father</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>8</td>
<td>0.87 (0.64–1.19)</td>
<td>0.386</td>
</tr>
<tr>
<td>No</td>
<td>92</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Housing type</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traditional</td>
<td>44.12</td>
<td>1.10 (0.89–1.25)</td>
<td>0.487</td>
</tr>
<tr>
<td>Modern</td>
<td>55.88</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Wealth status</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>18.33</td>
<td>1.18 (0.94–1.49)</td>
<td>0.175</td>
</tr>
<tr>
<td>Average</td>
<td>29.56</td>
<td>1.19 (0.92–1.53)</td>
<td>0.144</td>
</tr>
<tr>
<td>High</td>
<td>52.11</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Community standpipe pipe</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>66.96</td>
<td>1.66 (1.39–1.98)</td>
<td>0.000</td>
</tr>
<tr>
<td>Yes</td>
<td>33.04</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Distance covered to fetch water</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥500 m</td>
<td>47.61</td>
<td>1.63 (1.43–1.85)</td>
<td>0.000</td>
</tr>
<tr>
<td>≤500 m</td>
<td>52.39</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

(continued)
households living in traditional housing units were more likely ($RR = 1.10$, 95% CI: 0.32–3.81) to report diarrhoeal disease than those living in modern housing units. An increased diarrhoeal disease risk was also associated with sludge-applying households where either the mother or father was an illiterate. In the intra-block multivariate
analysis (Table 2), the independent predictors of diarrhoeal disease transmission in the distal socio-economic block were wealth status and housing type.

In the public domain univariate analysis presented in Table 1, individuals from sludge-applying households whose source of drinking water was unprotected dug-out ponds were more likely to report diarrhoeal disease ($RR = 1.66$, $95\% CI: 1.39–1.98$) than those drinking from a community stand pipe. Members of households walking 500 m or more to collect water were more likely ($RR = 1.63$, $95\% CI: 1.43–1.85$) to report diarrhoeal disease than those walking less than 500 m. In terms of the sanitation risk factors within the public domain, individuals from sludge-applying households practising open defecation had an increased risk of diarrhoeal disease compared to those using communal ventilated improved pit latrines. Drying sludge for not more than 14 days prior to incorporation into the soil was associated with an increased risk of diarrhoeal disease compared to 90 days or more of sludge drying. In the intra-block multivariate analysis (Table 2) of the public domain risk factors, the only factors that remained significantly associated with diarrhoeal disease risk ($p < 0.1$) were distance covered to collect water, faecal sludge drying times and access to a communal standpipe.

In the domestic domain block of risk factors (Table 1), drinking untreated water was significantly associated with diarrhoeal disease risk. Also, not washing hands with soap after defecation was significantly associated with diarrhoeal disease risk. The diarrhoeal disease risks were also high for individuals who ate food prepared outside the home environment and those who did not cover leftover food. Individuals from sludge-households that cleaned their cooking utensils the following day after eating had an increased risk of diarrhoeal disease. Keeping pets and animals in the household compound also increased diarrhoeal disease risk. Also, the presence of faeces and garbage in a sludge-applying household compound increased the diarrhoeal disease risk. Individuals from households where members engaged in sludge application and had no protective clothes (e.g. gloves, nose-masks, boots etc) had an increased risk of diarrhoea ($RR = 1.05$, $95\% CI: 0.83–1.34$). Sleeping on uncedmented floors was also associated with increased diarrhoeal disease risk ($RR = 1.14$, $95\% CI: 0.85–1.51$) and so was living in a crowded room. In the intra-block multivariate analysis (Table 2), the independent predictors of diarrhoeal disease outcome of the domestic domain were drinking untreated water, keeping pets and not washing hands with soap after defecation.

### Important risk factors and mediation proportions

Based on the PAFs derived in the inter-block mixed effect Poisson models (Table 3), the public domain block of risk factors (distance to water facilities and sludge drying time) was the most important determinant of diarrhoeal disease in the sludge-applying households. This was followed by the domestic domain risk factors (hand washing with soap after defecation) and distal socio-economic (wealth status) blocks respectively. The combined PAFs of the public domain block of risk factors was 15%, the domestic domain risk factors was 18% and the distal socio-economic block was 9%.

### Table 3

Population attributable fractions of diarrhoeal disease for blocks of risk factors based on reduced inter-block mixed effect Poisson regression models ($N = 1,431$)

<table>
<thead>
<tr>
<th>Block</th>
<th>Risk Factor</th>
<th>PAF (%)</th>
<th>$RR$ (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (Distal)</td>
<td>Wealth Status</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>18.33</td>
<td>1.18 (0.94–1.49)</td>
<td>9</td>
</tr>
<tr>
<td>Average</td>
<td>29.56</td>
<td>1.19 (0.92–1.53)</td>
<td>6</td>
</tr>
<tr>
<td>High</td>
<td>52.11</td>
<td>$1$</td>
<td></td>
</tr>
<tr>
<td>II (Public Domain)</td>
<td>Distance Covered to Fetch Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq$500 m</td>
<td>47.61</td>
<td>1.63 (1.43–1.85)</td>
<td>18</td>
</tr>
<tr>
<td>$&lt;500$ m</td>
<td>52.39</td>
<td>$1$</td>
<td></td>
</tr>
<tr>
<td>III (Domestic Domain)</td>
<td>Faecal Sludge Application (Days of Drying)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\leq$14</td>
<td>46.68</td>
<td>1.28 (1.04–1.59)</td>
<td>6</td>
</tr>
<tr>
<td>21–30</td>
<td>21.55</td>
<td>1.19 (0.72–1.98)</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>11.63</td>
<td>1.04 (0.69–2.01)</td>
<td></td>
</tr>
<tr>
<td>$\geq$90</td>
<td>20.13</td>
<td>$1$</td>
<td></td>
</tr>
</tbody>
</table>

*Sum of PAFs of significant variables ($p < 0.1$).
domain block was 24% accounted for by distance covered to water sources (18%) and sludge drying times (6%). Not washing hands with soap after defecation (PAF = 18%) was the main contributing risk factor of diarrhoeal disease transmission in the domestic domain of the sludge-applying households. In the distal socio-economic domain, the main risk factor was the wealth status of the households (PAF = 15%). Analysis of the inter-relationships of the different blocks of risk factors showed that 86% of the PAF of the socio-economic block was mediated; 33% by the public domain block and 53% by the domestic domain block. Also, 17% of the PAF of the public domain block of risk factors was mediated by the domestic domain block.

Discussion

A major finding of this study was the dominance of risk factors other than sludge application in the pathway to diarrhoeal disease transmission in the sludge-applying households. This sharply contrasts findings made in other studies involving wastewater use in agriculture. In this study, the main significant sludge application related risk factor (sludge drying time) contributed 6% of the diarrhoeal disease incidence in the sludge-applying households (Table 3). This is low, compared to the PAFs of diarrhoeal disease incidence associated with exposure to untreated wastewater in Mexico (PAF = 17–35%) and Vietnam (PAF = 35%) (Blumenthal et al. 2001; Trang et al. 2007). Compared to the wastewater irrigation practices in Vietnam and Mexico where farmers are in direct contact with raw wastewater with high loads of pathogens, farmers in Tamale are potentially exposed to relatively low loads of pathogens due to the use of traditional sludge drying methods. Seidu & Stenström (2022a) found that traditionally, most farmers spread faecal sludge in the field to dry during the dry season months of November to April when the temperature can reach 39 °C. Raw sludge spreading is done using mechanical suction trucks, thus limiting farmers’ exposure to pathogens in only the dried sludge. The average *Escherichia coli* concentration in sludge dried for 30 days or more was <10^2 Most Probable Number (MPN) of *E. coli/g TS* (Seidu & Stenström 2022a). The incorporation of dried sludge into the soil is also undertaken mainly with traditional hoes further reducing direct contact with the dried sludge.

This study confirms the important role sludge treatment and use of protective clothes play as a barrier against diarrhoeal disease in sludge-applying households. The study revealed that drying sludge for 90 days or more reduced the risk of diarrhoea in sludge-applying households. The use of protective clothes also reduced the risk of diarrhoeal disease, although this effect was not significant (Table 1). The use of protective clothes as a barrier against disease transmission has been challenging. From a farm observation survey, farmers engaged in sludge handling inconsistently used protective clothes (Seidu & Stenström 2022a); and thus were more likely to transfer pathogens from the farm domain (public) to the domestic domain. In a crossover study among 20 farmers from the sludge-applying households, significant contamination of the fingers of farmers using gloves during sludge handling was found (Seidu & Stenström 2022b). This shows that the use of protective clothes cannot always be a reliable option for reducing diarrhoeal disease risk.

Another major finding of this study was the increased risk of diarrhoeal disease among children not directly involved in sludge application. This confirms the important role other risk factors within the public and domestic domains play in the transmission of diarrhoeal diseases in the sludge-applying households. Distance to water facilities (public domain) and hand washing with soap after defecation (domestic domain) were the two most important risk factors of diarrhoeal disease transmission in the sludge-applying households (Table 3). Distance to water facilities may have a direct bearing on the quality of drinking water and the quantity of water available for personal hygiene purposes in the sludge-applying households. Adequate water for personal hygiene practices among farmers such as hand washing, washing of clothes and bathing after farm work is vital if the transfer of pathogens to children in the home environment is to be reduced. These personal hygiene practices can be grossly affected if sludge-applying households have to cover longer distances to collect water. In one study, hand washing among mothers was substantially constrained in households that had to cover more than 1 km to collect water ( Cairncross 1997).

A major strength of this study is the application of a hierarchical effect decomposition model to disentangle the
effects and MP of risk factors associated with diarrheal disease transmission in sludge-applying households. This allowed an estimation of the degree to which sludge application-related risk factors are potentially mediated by other factors in the pathway to diarrheal disease to be ascertained. This is a departure from other studies conducted in the past where the contribution of wastewater or excreta to diarrheal disease was estimated without accounting for the proportion of that contribution mediated by other factors. By applying the hierarchical effect decomposition model, the study has shown that about 17% of the effect of sludge application (including distance to water facilities) on diarrheal disease was mediated by the domestic domain risk factors. This shows that even though sludge application may contribute to diarrheal disease in sludge-applying households, a proportion of that contribution is accounted for through other risk factors within the domestic domain.

This study has some limitations that need to be stressed. To start with, the study did not account for some important risk factors implicated for diarrheal disease transmission. For instance, the study did not account for malnutrition, which is an important risk factor of diarrheal disease incidence among children in developing countries (Trang et al. 2007; Genser et al. 2008). Furthermore, no microbial analysis was carried out on the potential agents of the diarrheal diseases reported in this study. Studies in Northern Ghana have identified viral infections especially rotavirus as the main cause of diarrhoea among children (Armah et al. 2001, 2003; Binka et al. 2005; Reither et al. 2007). In Vietnam, rotavirus was also identified as the main cause of diarrhoea among pre-school children from households using untreated wastewater in agriculture and aquaculture (Hein et al. 2007). However, among adults engaged in wastewater-fed agriculture and aquaculture in Vietnam, pathogenic gastro-enteric bacteria (mainly diarrhoeagenic *E. coli*) were the most common cause of diarrhoea (Trang et al. 2007). Also, the study did not account for vectors such as houseflies that may contribute to the transmission of diarrheal disease. Furthermore, the bi-weekly visits employed in this study could have resulted in an underestimation of the reported diarrheal episodes. A comparative analysis of longitudinal diarrheal disease studies revealed that more episodes were likely to be recorded in studies involving more frequent visits than those with less frequent visits (Bern et al. 1992).

The hierarchical effect decomposition model used in this study is also not without limitations. In this approach estimates of the direct effects can only be obtained when there is no confounding at the level of the intermediate variable (Robins & Greenland 1992). In our conceptual framework efforts were made to consider and group all risk factors into meaningful blocks. Thus, it was unlikely that other unobserved factors are associated with both an intermediate block and diarrheal disease incidence.

**CONCLUSIONS**

In this study, a hierarchical effect decomposition model was implemented to assess the effect of risk factors associated with diarrheal disease incidence in households applying faecal sludge in the surroundings of Tamale in Northern Ghana. The risk factors were assigned to three inter-related blocks: distal socio-economic, proximal public domain and proximal domestic domain. Sludge drying time in the proximal public domain was associated with diarrheal disease incidence in the sludge-applying households. However, this contributed the least to diarrheal disease transmission in the sludge-applying households compared with other risk factors. The most important risk factors of diarrheal disease transmission in the sludge-applying households were wealth status in the distal socio-economic, distance to water facilities in the proximal public domain and not washing hands with soap after defecation in the proximal domestic domain. About 17% of the effect of sludge application related risk factors (including distance to water facilities) was mediated by the domestic domain risk factors. The study recommends risk management strategies in sludge-applying households that addresses public and domestic domain risk factors in addition to specific farm level interventions.

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