Do domestic animals contribute to bacterial contamination of infant transmission pathways?

Formative evidence from Ethiopia

Sophie Budge, Paul Hutchings, Alison Parker, Sean Tyrrel, Tizita Tulu, Mesfin Gizaw and Camila Garbutt

ABSTRACT

Child stunting is associated with poor water, sanitation and hygiene (WASH), partly due to the effect of infection on intestinal nutrient absorption. WASH interventions, however, show little effect on growth. A hypothesis is that bacterial contamination of hands and floors from domestic animals and their faeces, and subsequent ingestion via infant hand-to-mouth behaviours, may explain this. This formative study used microbial testing and survey and observational data from 20 households in Ethiopia to characterise principle bacterial transmission pathways to infants, considering WASH facilities and practices, infant behaviours and animal exposure. Microbial swabbing showed the contamination of hands and floor surfaces from thermotolerant coliform bacteria. Animal husbandry practices, such as keeping animals inside, contributed significantly (all \( p < 0.005 \)). There was no evidence that latrine facilities mitigated contamination across infant (\( p = 0.76 \)) or maternal (\( p = 0.86 \)) hands or floor surfaces (\( p = 0.36 \)). This small study contributes to the evidence that animal faeces are an important source of domestic bacterial contamination. The results imply that interventions aiming to reduce pathogen transmission to infants should think beyond improving WASH and also consider the need to separate infants and animals in the home. Intervention studies will be required to determine whether this reduces infant infection and improves linear growth.

Key words | animal husbandry, contamination, malnutrition, sanitation, WASH

ABBREVIATIONS

HAZ height-for-age (z-score)
IYC infants and young children
TTC thermotolerant coliform
WASH water, sanitation and hygiene
HEW Health Extension Worker
CFU colony-forming units

INTRODUCTION

Stunting, water, sanitation and hygiene (WASH) and infection

Linear growth failure, or stunting, defined as a z-score (an age- and sex-normalised measure of child height in units of standard deviations) of less than −2, remains highly prevalent among low-income countries. Despite having fallen on a global level, stunting still affects around one in five children (UNICEF and WHO 2019) and remains a key public health issue, both in terms of infant morbidity and mortality and in loss to national economic productivity (The World
Bank 2006; Martorell et al. 2010; Black et al. 2013; UNICEF and WHO 2019). Defining the precise causes of stunting remains elusive. While an inadequately diverse and nutrient-dense diet (Black et al. 2008) likely affects growth outcomes, supplementary and complementary feeding interventions may only improve stunting by a height-for-age z-score (HAZ) of around 0.7 (Dewey & Adu-Afarwuah 2008) – far from the average discrepancy of −2.0 in parts of sub-Saharan Africa (Victora et al. 2010). Diarrhoeal incidence, another factor correlated with undernutrition (Scrimshaw & Suskind 1976), also does not appear to explain a large proportion of the stunting burden: it is estimated that eliminating diarrhoea within the first 2 years of life would increase length by a HAZ score of only 0.13 (Richard et al. 2013). Given this marginal impact, it is apparent that other aetiological factors remain which have not yet been addressed to tackle early growth faltering.

Stunting is commonly observed in regions with poor water, sanitation and hygiene (WASH), supporting an underlying role of exposure to pathogenic bacteria and infection (Humphrey 2009; Ahmed et al. 2014). Certain pathogenic strains, which are widespread across low- and middle-income countries (Marquis et al. 1990; Lin et al. 2013; Ngure et al. 2013) and appear linked to stunted growth, include faecally associated Campylobacter (Harvey et al. 2003; Oberhelman et al. 2006; Headey & Hirvonen 2016), Cryptosporidium (Guer rant et al. 1999; Kotloff et al. 2013), Giardia (Kosek 2017) and pathogenic Escherichia coli (Steiner et al. 1998; Ngure et al. 2013). Although not well described, increased prevalence of these enteropathogens in healthy infants is associated with growth faltering (Checkley et al. 1997; Lee et al. 2013), even in the absence of other clinical insults like diarrhoea (Korpe & Petri 2012; Prendergast & Humphrey 2015; MAL-ED Network Investigators 2017). A quantitative framework which estimated the relative impact on stunting from different causes found infectious disease to be a significant contributory factor across global regions (Mosites et al. 2017). Preventing infection has, therefore, become an important focal point for WASH interventions addressing infant growth.

The five main faecal–oral routes of transmission are described in the ‘F diagram’ (fluids, fingers, fields, flies and food) – proposed some 60 years ago as an important map of causes of enteric infection (Wagner & Lanoix 1958). Fundamental to WASH research and programming, the diagram underpins WASH interventions to prevent infectious disease via both primary barriers (sanitation) and secondary barriers (water treatment and handwashing), which should block pathogen transmission. However, several recent, large trials which have assessed the effect of either an individual component or an individual and combined components of WASH across different study arms have demonstrated little impact on infant health, or a significant reduction in environmental faecal contamination (Clasen et al. 2014; Patil et al. 2015; Luby et al. 2018; Null et al. 2018; Humphrey et al. 2019). This remained the case even in combination with a nutrition programme (Clasen et al. 2014; Patil et al. 2015; Luby et al. 2018; Null et al. 2018; Humphrey et al. 2019). Following largely insignificant results across the different study designs and settings, researchers have concluded that such interventions, while necessary, were perhaps not sufficient in coverage to show noteworthy improvements in growth (Arnold et al. 2018). Perhaps, more importantly, these trials may have neglected to address, in particular, the main pathogen transmission pathways specific to infants and young children (IYC), having not considered the age-related behaviours which alter infection risks – as well as sources of faecal contamination other than human.

**WASH interventions and infant-specific behaviours and risks**

While WASH interventions, following the seminal F diagram, have traditionally focussed on improving latrine facilities, communal and household water supply and adult hygiene practices (ACF and UNICEF 2017), for IYC different needs and behaviours, create additional exposure to pathogens (Ngure et al. 2013; Morita et al. 2017). That is, developmental behaviours, such as crawling and the touching, mouthing and sucking of objects from frequent hand-to-mouth activity, mean that primary transmission pathways differ from adults and exposure risk is increased (ACF and UNICEF 2017; Kwong et al. 2019). This risk is higher across low-income countries where, while crawling and playing, IYC may come into contact with contaminated soil, faeces and enteric pathogens which are brought inside the home (Ngure et al. 2013; Reid et al. 2018). Faecal indicator bacteria and associated pathogens have been detected in soil (Pickering et al. 2012),...
and hand-to-mouth contact appears to result in significantly higher faecal intake in IYC than consumption of stored water (Mattioli et al. 2015). While direct ingestion of faeces is more rare, IYC frequently place soil in their mouth or put their hands in their mouths after touching soil (Ngure et al. 2015; Ercumen et al. 2017; Bauza et al. 2018; Kwong et al. 2019), meaning that hand recontamination is likely (Kwong et al. 2019). Both direct and indirect consumption are associated with diarrhoea, markers of infection and inflammation and growth failure in infants (Shivoga & Moturi 2009; George et al. 2015a, 2015b). While pathogenic bacteria of both human and animal origin can cause diarrhoea, even with improvements in sanitation these associations remain (Ercumen et al. 2017), suggesting that other external sources of faecal contamination are not illustrated in the original F diagram and considered in interventions.

In lower-income countries, domestic animals – usually livestock and poultry (WHO 2012; Ercumen et al. 2017) – are often not contained or separated from the household environment (Penakalapati et al. 2017), and animal faecal contamination appears widespread across the home (Boehm et al. 2016; Penakalapati et al. 2017). Recently, studies using molecular techniques have shown animal faecal markers in soil from the outside yard, household floor and infant hands (Boehm et al. 2016; Harris et al. 2016), and animal presence has been associated with higher levels of faecal contamination across multiple pathways, including soil (Ercumen et al. 2017) and contaminated food (Parvez et al. 2017). Both quantitative molecular techniques (Mattioli et al. 2015) and microbial source tracking (Parvez et al. 2017; Penakalapati et al. 2017) have shown a high burden of animal faecal contamination in living areas, particularly of hands and soil, which appears more prevalent than human contamination (Penakalapati et al. 2017). However, interventions underpinned by the F diagram have largely focussed on removing human faeces, with few objectives to remove animal faeces or reduce exposure. Such interventions that are limited in scope may miss animal contamination as a critical risk factor (also of importance given the differing pathogens present in animal faeces that cause enteric infection and present different risks to health) alongside not acknowledging the transmission pathways particular to IYC, like contaminated hands and soil. Considering the high prevalence of animal faeces and faecal contamination around the home (Ngure et al. 2013; Headey & Hirvonen 2016; Penakalapati et al. 2017), the behaviours which expose IYC to faeces and the associations with lower HAZ scores (Bukenya & Nwokolo 1991; George et al. 2015a, 2015b; Headey & Hirvonen 2016), animal faecal contamination of the domestic environment is an issue particularly significant to IYC in lower-income countries which may be stalling the progress of interventions to improve infant health. This may explain the failure of improved WASH infrastructure and facilities to reduce infectious disease and improve IYC health outcomes. Figure 1 illustrates the exposure pathways through which IYC are commonly and frequently exposed to, and ingest, pathogenic bacteria within the home (Budge et al. 2019). Where the dashed lines constitute the original ‘F diagram’, the figure illustrates how the original diagram does not consider specific infant behaviours (boxes in bold), nor the contribution of animal faeces to domestic contamination, but the integral relationship with those three components and microbial ingestion.

It follows that an improved understanding of the key sources of contamination and principal faecal–oral transmission pathways to IYC is necessary to understand the risk of infection to infants. Further evidence toward this may support and inform initiatives which are attempting to address sectoral integration to improve infant health such as the BabyWASH coalition (ACF and UNICEF 2017). In order to inform a larger trial intending to address pathogen transmission to infants, this small formative study sought (i) to quantify thermostolerant coliform (TTC) bacterial burden across infant-related environmental pathways (infant and caregiver hands, domestic floor surface) in rural Ethiopian households, (ii) to assess how the presence of animals within the household, household sanitation and key hygiene practices may affect levels of TTC contamination and (iii) to understand if and how these environmental transmission pathways within the home influence and impact one another through cross-contamination.

MATERIALS AND METHODS

Study sites and sampling frame

Formative research is intended as an initial part of the process of a larger study design and can use both qualitative and
quantitative methods to provide data for research teams to plan interventions or further data collection. While formative research is critical to designing and delivering interventions or programmes which are efficient and effective, it is early-phase data not powered to detect differences between groups (Gittelsohn et al. 2006). As such, this study must be interpreted in this context – it is intended to provide indicative evidence on a hypothesis but is not sufficiently powered to provide conclusive evidence in this area. This formative study was conducted in the Sidama zone, Southern Nations, Nationalities, and Peoples (SNNPR) region, Ethiopia as the geographical outreach area of the non-governmental organisation People In Need. The study took part in the month of May, which in the region is a mostly dry period with some afternoon rainfall. From the six woredas (districts) in the zone, 16 kebeles (neighbourhoods) were grouped into peri-urban ($n = 6$) or rural ($n = 10$). A simple random sampling method was used, whereby kebeles within the People In Need intervention area were listed, given a number and using a lottery method, eight kebeles were selected at random. From these eight kebeles, 20 households which included an infant aged 12–24 months old and not engaged in any other research with People In Need were selected. This involved communication with a Health Extension Worker (HEW) local to the kebele who was familiar with the ages of infants in the area. The final sample size was 20 infants ($n = 20$). Households were visited on one single occasion. A separate single location for piloting the study was chosen in the same manner and not included in the final sampling frame.

Figure 1 | Age-specific pathways and contributing sources by which infants are exposed to and ingest pathogenic bacteria within the home. Where the dashed lines constitute the original 'F diagram', the figure illustrates how the original diagram does not consider specific infant behaviours (boxes in bold), nor the contribution of animal faeces to domestic contamination, but the integral relationship with those three components and microbial ingestion. Adapted alongside the 'F diagram', as published by Wagner & Lanoix (1958).
Survey and infant observation period

A survey was designed to assess sanitation facilities, handwashing practices, animal presence, livestock husbandry and diarrhoea prevalence and duration of diarrhoeal episodes (where to avoid reporting bias, researchers asked caregivers for the frequency of loose or watery stools over the past 7 days and subsequently applied World Health Organization criteria) (Baqui et al. 1999). This was administered alongside a 1-hour observation period which noted infant hand-to-mouth behaviours and general sanitary conditions. During this, a pre-tested semi-structured survey tool was used to record every object that was either moulded or touched by the infant, where moulding was defined as an infant putting fomites or fingers into their mouths whether swallowed or not. This semi-structured tool was calibrated to capture some of the underemphasised key pathogen transmission pathways in infants. As illustrated in Figure 1, this is also well described by the ‘modified F diagram’ published by the Water, Sanitation and Hygiene Partnerships and Learning for Sustainability (WASHPaLS) consortium (Ngure et al. 2017), which illustrates additional key pathways specific to infants – namely geophagy and direct faecal ingestion. After entering into the home, primary introductions with the caregiver and the consent process, a fieldworker conducted the survey with the help of the local HEW. Concurrently, the primary researcher conducted the 1-h observation period of the infant. This included moulding and exploratory behaviours. Other observations included infant interaction with others, open defecation practices, general sanitation and hygiene, animal presence and husbandry. Observations of animal faeces and other hygiene markers were also visually assessed by the researcher, including cleanliness of caregiver and infant hands, which were visually inspected for visible dirt on the palms and underneath nails. General infant cleanliness was also noted by observing visible dirtiness of infants’ clothing and skin.

Microbiological analysis

Microbial samples were collected during the same visit as the survey in order to minimise social desirability bias and changes in behaviour. Nineteen of 20 households were sampled due to one baby asleep in the caregivers’ arms during the observation period. Following the survey and observation period, swabs were taken of infant and caregiver hands and a weighed sample of floor material (soil, dirt) within crawling reach of the infant was also collected from 18 households. For each sample approximately 1.0 g (weighed to the nearest 0.01) was collected using a sterile scoop and put into Whirl-Pak® 710 mL bags containing a buffer solution of 100 mL of bottled water with Ringer’s solution ¼ strength tablets and 0.1% v/v Tween® 20. It should be re-emphasised that this methodology could not distinguish between TTC of human or animal origin. Faeces were observed within the homes but were not sampled. Hand swabs used a similar methodology as described by Ngure et al. (2013) who found replicable results and is described briefly as follows. Hand swabs were collected using commercially available environmental sponge sampling kits (Whirl-Pak® Speci-Sponge® Environmental Surface Sampling Bags, Sigma-Aldrich, UK) which were pre-moistened with the same buffer solution previously described. Sponges swabbed both sides of both the caregivers’ and infants’ hands (palm, back of hand and in-between fingers). After swabbing, sponges were returned aseptically to the bag. Bags were sealed and transported in a cool-box for microbiological analysis within 6 h. All samples were analysed for TTC counts with a DelAgua single incubator using the water filtration method (DelAgua Water Testing Ltd 2015). Membrane Lauryl Sulphate Broth was pipetted on 0.45 μm 25 mm gridded cellulose nitrate membranes (DelAgua, UK) to grow TTC. Samples were incubated overnight for 16–18 h at 44 °C. To control for potential contamination in field laboratory conditions, a blank sample was incubated with every other set of samples. At the end of data collection, only one blank sample was found to be contaminated during sample processing.

Data analysis

Means for bacteria counts from swabs were calculated as TTC colony-forming units (CFU) per hand (TTC CFU/hand). Bacterial populations from the solid samples were calculated as TTC colony-forming units per dry gram (TTC CFU/dry g). Anonymised survey data were entered into a tablet using KoBoToolbox (Harvard Humanitarian Initiative, Massachusetts, USA) into preconfigured fields. Data
were downloaded into Microsoft Excel and coded for descriptive analysis and then transferred and further analysed using SPSS statistical software version 22.0 (IBM, New York, USA). Boxplots showed associations between infant and caregiver hand TTC CFU count, floor surface sample CFU count and associated variables. An unpaired t-test tested the difference in sample means of TTC count between vectors for statistical significance.

**Ethics**

Infants and their caregiver were visited in the home between the hours of 10:00–12:00 pm and 14:00–16:00 when the infant was most likely to be awake and playing. Households were visited unannounced to avoid researcher bias. However, at the start of the household visit, free and informed consent of the participants was obtained. To do this, the study was introduced by the field team and the HEW, and an informed consent statement was read to the caregiver in their first language of Amharic or Sidamigna (Sidamo). Fieldworkers tested the caregivers' understanding of consent by asking them questions regarding the study or the consent process, and explained data were anonymised. The survey was written in English, translated to Amharic by local fieldworkers and verbally translated into Sidamo by a local HEW. The study protocol was approved by an institutional Committee for the Protection of Human Participants (Cranfield University Research Ethics Committee; CURES/4955/2018).

**RESULTS**

**Survey results**

The WASH survey asked questions regarding infant characteristics, diarrhoea prevalence and episode duration (as described), latrine ownership and use, handwashing and animal husbandry practices. Briefly, most houses had a pit latrine either with a slab (40%) or without (30%). The remainder (20%) had no toilet at all (assumed to openly defecate) or used the toilet of a neighbour (10%). Only five (25%) households had a specific place to wash their hands; of those, all households had water available, but only three (15%) had soap (in two instances visual inspection indicated the soap was likely not used). Seventy per cent of households raised animals of some kind, with the most common chickens (93%) and cattle (71%). When asked where animals lived during the day, only one household reported that their animals lived outside enclosed in an area, with the rest kept outside either unenclosed or living inside with the family, suggesting that animals were mostly uncontained. One hundred per cent of households reported that during the night animals lived inside with the family. Regarding diarrhoea prevalence, three infants (15%) were reported to have experienced three or more loose stools within a 24-h period; across these infants, the reported mean duration of a diarrhoeal episode was 3.3 days. Table 1 illustrates these findings along with general hygiene characteristics of the infant's environment.

**Infant observation period results**

Nineteen infant–caregiver pairs were observed for 20 h during the infant observation period. Infants were frequently observed to mouth their own hands (a mean of 31 times over 1 h), or to mouth those of their caregiver (mean of 21 times over 1 h), which in the majority of instances were both visibly dirty (90% and 86%, respectively). Throughout the observation, infants would typically have nothing to play with other than a plastic bottle, which may explain why infants were observed to frequently suck their hands or those of their caregiver. Animal faeces were directly ingested by two infants, and the floor surface material was also picked up and directly entered into the infants' mouths on seven occasions.

Table 1 details hygiene characteristics as noted during the observation. In 50% of households, there were faeces visible on the floor (usually from chickens as the predominant livestock) and almost half of all infants were visibly dirty (often naked from the waist down and dirty). On four occasions, the infant crawled near-visible pools of urine and/or faeces. Animals, most commonly cattle or chickens, were often in the house during the observation and were rarely separated from the living area other than by a rudimentary wooden beam. Thus, animals tended to occupy the same space as the infant and were frequently around them at play.
Samples from the inside floor surface showed the highest bacterial count with a mean TTC CFU/dry g of 76.5 (1.88 log_{10}). The higher count in the floor sample may reflect the typical presence of animals inside as well as the common occurrence of animal faeces. High counts in the domestic floor sample are significant, given the sample was collected within crawling reach of the infant and was observed to enter the infants’ mouths and contaminate their hands. Infant hand contamination showed a slightly higher mean count than those of their caregiver (mean TTC CFU/hand 33.3 (1.52 log_{10}) versus 23.6 (1.37 log_{10}), respectively) (p < 0.005, data not shown). This is unsurprising in a context where infants were frequently crawling on the floor and touching and mouthing objects, which were usually visibly dirty (Table 1). The relationship between key vectors and transmission pathways, as measured by microbial testing, is presented in Figure 2. The p-values presented are from a t-test that assessed any statistically significant differences between TTC CFU counts on hands and between floor surface samples and key transmission pathways. The data, illustrated by the striking differences in the box plot figures, indicate that levels of TTC were much greater in households than raised livestock and where livestock were kept indoors. Infants and caregivers who lived in a house which raised animals showed a significantly higher hand TTC CFU count than those who did not (Figure 2, graphs 3A [p < 0.005] and 3B [p < 0.005]), and the floor surface TTC CFU count was also higher in these households (Figure 2, graph 3C, p = 0.006). Similarly, graphs 4A, 4B and 4C show CFU animals living inside during the day were significantly related with an increased CFU count on both infant and caregiver hands and in floor surface samples. In contrast, from the data, it appears that owning a handwashing facility did not reduce TTC CFU count on hands (Figure 2, graphs 1A [p = 0.57] and 1B [p = 0.38]); nor for floor surface (graph 1C [p = 0.68]). A similar observation can be made for whether the household owned a latrine (Yes) or openly defecated (No) (graphs 2A, 2B and 2C), where owning a latrine was not related to a reduced hand CFU count for infant or caregiver hand (p = 0.76 and 0.86, respectively), nor for floor surface samples (p = 0.36).

Study limitations

This study presents some limitations. Firstly, the small sample size in this study of 20 infants/households would not have comprehensively captured variability in TTC contamination across pathways, which likely varies considerably. As is noted elsewhere (Navab-Daneshmand et al. 2018), high variability in contamination across pathways and vectors requires a large sample size to provide good statistical power. However, the results are emphasised as formative evidence and do support the primary hypothesis regarding the diversity of contamination across pathways and animals as a contributor to TTC contamination.

**Table 1** General characteristics of the home environment and specific hygiene characteristics as reported from survey data and as noted during the infant observation period

| Characteristic (survey)                          | n   | %  |
|-------------------------------------------------|-----|----|
| Rural                                           | 14  | 70 |
| Infant male sex                                 | 14  | 70 |
| Diarrhoea within the last 7 days                | 3   | 15 |
| Mud house                                       | 15  | 75 |
| Mud floor                                       | 18  | 90 |
| Open defaecation                                | 4   | 20 |
| Share neighbour’s toilet                        | 2   | 10 |
| Pit latrine without slab                        | 6   | 30 |
| Pit latrine with slab                           | 8   | 40 |
| Specific handwashing station                    | 5   | 25 |
| Water available                                 | 5   | 25 |
| Soap available                                  | 3   | 15 |
| Raises animals                                   | 14  | 70 |

**Hygiene characteristics (observed)**

| Characteristic                                      | n   | %  |
|----------------------------------------------------|-----|----|
| Flies on baby                                      | 12  | 60 |
| Mud house                                          | 15  | 75 |
| Mud floor                                          | 18  | 90 |
| Animal faeces visible on the floor                 | 10  | 50 |
| Baby visibly dirty                                 | 9   | 45 |
| Baby crawled near urine/faeces                    | 4   | 20 |
| Any animal in the house                            | 12  | 60 |
| Cattle in the house                                | 5   | 25 |
| Goats or sheep in the house                        | 2   | 10 |
| Chickens in the house                              | 10  | 50 |

**Microbiological data**

Samples from the inside floor surface showed the highest bacterial count with a mean TTC CFU/dry g of 76.5 (1.88 log_{10}). The higher count in the floor sample may reflect the typical presence of animals inside as well as the common occurrence of animal faeces. High counts in the domestic floor sample are significant, given the sample was collected within crawling reach of the infant and was observed to enter the infants’ mouths and contaminate their hands. Infant hand contamination showed a slightly higher mean count than those of their caregiver (mean TTC CFU/hand 33.3 (1.52 log_{10}) versus 23.6 (1.37 log_{10}), respectively) (p < 0.005, data not shown). This is unsurprising in a context where infants were frequently crawling on the floor and touching and mouthing objects, which were usually visibly dirty (Table 1). The relationship between key vectors and transmission pathways, as measured by microbial testing, is presented in Figure 2. The p-values presented are from a t-test that assessed any statistically significant differences between TTC CFU counts on hands and between floor surface samples and key transmission pathways. The data, illustrated by the striking differences in the box plot figures, indicate that levels of TTC were much greater in households than raised livestock and where livestock were kept indoors. Infants and caregivers who lived in a house which raised animals showed a significantly higher hand TTC CFU count than those who did not (Figure 2, graphs 3A [p < 0.005] and 3B [p < 0.005]), and the floor surface TTC CFU count was also higher in these households (Figure 2, graph 3C, p = 0.006). Similarly, graphs 4A, 4B and 4C show CFU animals living inside during the day were significantly related with an increased CFU count on both infant and caregiver hands and in floor surface samples. In contrast, from the data, it appears that owning a handwashing facility did not reduce TTC CFU count on hands (Figure 2, graphs 1A [p = 0.57] and 1B [p = 0.38]); nor for floor surface (graph 1C [p = 0.68]). A similar observation can be made for whether the household owned a latrine (Yes) or openly defecated (No) (graphs 2A, 2B and 2C), where owning a latrine was not related to a reduced hand CFU count for infant or caregiver hand (p = 0.76 and 0.86, respectively), nor for floor surface samples (p = 0.36).
Association with an increase in infant and caregiver hand and floor surface sample TTC CFU count with specific hygiene characteristics. From top left: (1) Relationship between if the household had a specific handwashing facility ($n = 5$) with increased TTC CFU count for: (1A) infant hands ($p = 0.57$), (1B) caregiver hands ($p = 0.38$) and (1C) floor surface sample ($p = 0.68$); (2) Relationship between if the household owned a latrine (Yes) ($n = 16$) or openly defecated (No) ($n = 4$) with increased TTC CFU count for: (2A) infant hands ($p = 0.76$), (2B) caregiver hands ($p = 0.86$) and (2C) floor surface sample ($p = 0.36$); (3) Relationship between if the family raised animals ($n = 14$) with increased TTC CFU count for: (3A) infant hands ($p < 0.005$), (3B) caregiver hands ($p < 0.00$) and (3C) floor surface sample ($p = 0.006$); and (4) Relationship between if animals lived inside during the day ($n = 13$) and increased TTC CFU count for: (4A) infant hands ($p < 0.005$), (4B) caregiver hands ($p < 0.005$) and (4C) floor surface sample ($p = 0.04$).
Secondly and relatedly, it was not possible to determine the origin of TTC bacteria. As such, it is possible that the bacteria detected in animal-rearing households were of human origin. However, given the lack of human faeces observed within homes versus the high prevalence of animal faeces, and the correlation between animal-rearing households and TTC counts across different measures, we have confidence in supporting the theory describing a link between animal practices and environmental contamination. This is also backed up by broader studies (Ngure et al. 2014; Schriewer et al. 2015; Ercumen et al. 2017). Thirdly, the presence of TTCs indicates the presence of faecal contamination but cannot directly quantify the burden of pathogens that cause enteric infection. Fourthly, due to a lack of facilities, soil moisture content was not measured. This limits the ability to compare results between soil samples of different moisture content, as well as across studies, and should be a methodological consideration in further research. Lastly, this study only provides part of the picture of total infection risks to IYC. While hands and floors are key transmission pathways (Davis et al. 2018), contaminated food (Parvez et al. 2011) and water (Barnes et al. 2018) also constitute important pathways, of which we did not measure contamination. A broader study that seeks to measure each of these and assesses additive effects would be a productive route for extending this research.

DISCUSSION

This formative study found faecal contamination common across different transmission pathways in rural Ethiopian households with high sanitation access, contributing to a growing evidence base that improved sanitation access alone is not enough to improve overall environmental hygiene (Ercumen et al. 2017; Barnes et al. 2018). The contamination of caregiver and infant hands and domestic floor surface samples with TTCs suggests that IYC are frequently exposed to faecal pathogens through transmission pathways which are intrinsically linked. Through normal exploratory and hand-to-mouth behaviours, frequent contact with dirty floors meant that infant hands themselves became vectors for the transmission of faecal microbes, corroborating research found in similar settings (Ngure et al. 2013; Ercumen et al. 2017; Bauza et al. 2018; Reid et al. 2018). In this study, 35% of infants directly ingested soil over the 1-h period. Only a few other studies have sought to correlate high levels of hand-to-mouth behaviours and direct and indirect floor surface material ingestion. In rural Bangladesh, 25% of children aged 3–18 months old directly ingested soil during a 5-h observation (Kwong et al. 2016); in another study, in rural Ghana, 28% of children aged 6–36 months old reportedly ingested soil a median of 14 times in the past week (Bauza et al. 2018). Ingestion of floor surface materials by IYC is of concern giving the growing number of studies linking ingestion with negative health outcomes, such as diarrhoea (Yeager et al. 1991; Shivoga & Moturi 2009), and both enteric dysfunction from infection and linear growth failure (George et al. 2015a, 2015b).

Regarding the reliability of the testing method, the CFU counts captured in this study are a similar magnitude to others with similar methodologies, including a recent study in urban Harare which reported a mean 1.62 log10 CFU/g in soil (per dry gram) and a mean 1.52 log10 CFU/hand before handwashing (Navab-Daneshmand et al. 2018). An earlier study in a Tanzanian community with improved, non-networked water supplies found a mean E. coli count of 3.1 log10 CFU, but over two hands (Pickering et al. 2010). Although in many settings the original source of contamination is not clear, strong evidence supports a relationship between domestic animal ownership and residual contamination from faeces (Marquis et al. 1990; Reid et al. 2018) and animal presence is associated with high levels of faecal contamination across multiple pathways (Ercumen et al. 2017; Parvez et al. 2017). These results suggest that faecal contamination of different transmission pathways is related, with the presence of animal faeces as the common contamination factor – supported by this study by the strong difference in the CFU count in households with animals (Figure 2, graphs 3–4). Due to the small number of sampled households, it was not possible to determine differences in bacterial contamination across floor types, which may point to a wider need for improved housing. However, other research has found no association with floor material (mud or concrete), the amount and frequency of infant soil ingestion and diarrhoeal episodes (Bauza et al. 2018), suggesting an independent contamination factor. In this study, where animals (particularly poultry) were present in most
households, their presence likely led to floor contamination regardless of flooring type. In another study in Zimbabwe, floor surface contamination could not be explained by household-level WASH factors, but households with animals showed significantly higher concentrations of *E. coli* (Navab-Daneshmand et al. 2018). In this study, poultry was likely a key factor in contamination levels due to their common presence in the home – of concern given demonstrated associations between poultry faeces, diarrhoea (Yeager et al. 1999; Zambrano et al. 2014) and poor growth (Headey et al. 2017).

In this study, even in households with a latrine (improved or other) contamination was still common, suggesting that even with sufficient sanitation infrastructure the presence of animals within the home may propagate contamination. In one study in Bangladesh, while households with fewer contaminated toys and objects were those with high latrine coverage and WASH infrastructure (Torondel et al. 2015), the absence of animals was highlighted as a possible noteworthy factor to low levels of contamination (Penakalapati et al. 2017). In this study, it is possible that latrines were not being used and open defecation was practised, although the likelihood of latrine use, determined via spot check if the path was trodden and if faeces were present, suggested they were. Owning a specific handwashing facility was not common here, but even where facilities existed contamination remained. This may be due to poor handwashing practices (soap was observed to be unused on three occasions); however, it is possible that even where good hygiene behaviours exist, if the environment is continually contaminated by an external source contamination, transmission and infection will not decrease (Curtis et al. 2000; Langford et al. 2011). Studies have shown that even after handwashing, *E. coli* count on hands, possibly from human and animal contamination of dirt and sand (Pickering et al. 2012; Lupindu et al. 2015), can increase 2–3 log_{10}CFU within minutes of resuming normal activity (Pickering et al. 2011; Ram et al. 2011; Devamani et al. 2014). Furthermore, Barnes et al. (2018) found that despite high coverage of improved water sources, two-thirds of households in Kenya had drinking water contaminated with *E. coli* at point-of-use, which was significantly correlated with animal ownership and the presence of animal waste in the home. It is worth bearing in mind that poor water quality within the home influences not only personal and domestic hygiene but also the safety of food, propagating whole environment contamination and further reducing the capacity for domestic and personal hygiene and food safety. Parvez et al. (2017) found an increase in *E. coli* count in complementary foods in houses where mothers transferred food and fed infants with their hands, along with animal presence in the compound. Ercumen et al. (2017) found significantly higher levels of *E. coli* in food in compounds where animals lived – primarily increased by the presence of poultry. It, therefore, stands to reason that if other external sources of contamination from animals are not considered, all pathways will remain contaminated and bacterial transmission to infants may not be reduced – regardless of improvements in sanitation.

Notwithstanding this study does not suggest that animal husbandry should be restricted, as it remains critical for socio-economic development – especially in lower-income countries. Indeed, studies have found both non-significant and protective effects from domestic animal husbandry, for example, through the nutritional benefit of consuming animal products. A cross-sectional study in Nigeria found a significant protective effect against diarrhoea linked with animal exposure (rate ratio 0.8, 95% CI: 0.7–0.9), although confounding by other factors was suspected (Huttly et al. 1987). An analysis of cross-sectional datasets from Ethiopia, Kenya and Uganda found a negligible beneficial effect of household livestock ownership on child stunting prevalence (Mosites et al. 2015). In another study in Kenya, greater household livestock ownership at the baseline was not related to the baseline infant HAZ score (Mosites et al. 2016). What seems apparent is that while livestock ownership may provide benefits in terms of nutrition and economic development, these benefits must be utilised and capitalised on and at the same time are not without risk. The ways in which households and their livestock interact and share space vary from setting to setting and in the absence of integrated WASH, nutrition and agriculture programmes, it is possible that the close proximity of livestock may be of detriment to the health of IYC. This research advocates that further research within the WASH field should consider animal husbandry practices and work more closely (i) with the agricultural sector to better understand how exposure and transmission risks differ across settings and (ii) with nutrition experts to understand how
risk might be mitigated. This may be especially pertinent for certain animals. In this study, in corroboration with findings in Bangladesh (Ercumen et al. 2017), Zimbabwe (Ngure et al. 2013), Peru (Marquis et al. 1990) and Zambia (Reid et al. 2018), poultry was the most common animal found within the home; poultry faeces are often found inside near the playing infant and are frequently ingested along with soil (Yeager et al. 1991; Ngure et al. 2013; Reid et al. 2018). Due to their mobility and the difficulty with which their faeces are noticed, small animals like poultry may pose a greater risk to infants.

CONCLUSION

Although the evidence presented here is of a small sample, results support the growing body of evidence which suggests that WASH interventions must address animal faecal contamination across the domestic environment: a ‘total environmental hygiene’ approach, which fully addresses multiple sources of contamination. Increased attention should be placed not only on WASH infrastructure and quality but also on addressing barriers from widespread faecal contamination to overall improved hygiene on a much wider level. Similarly to another recent study (Kwong et al. 2019), this study did not observe human faeces within the home and suggests that faecal contamination from animals may be a primary limitation in WASH interventions, which tend to focus on that of humans. Further interventions, which aim to improve infant growth by addressing contamination, are likely to benefit from considering certain common animal husbandry practices, such as keeping animals indoors during the day and night, and the need to separate IYC from animals. If not considered, in this setting and other similar settings, it is possible that WASH interventions may not interrupt faecal–oral transmission of bacteria and pathogens to IYC. Similarly, if interventions targeted towards IYC are predicated on health grounds, effects may be limited when animals share household space. While new, more targeted programmes such as the ‘Baby WASH’ initiative may reduce infant zoonotic transmission and diarrhoea, large-scale interventions must focus on controlling animal faecal pathogen transmission and limiting infant exposure. These findings alongside similar, larger studies may aid policymakers to better understand the contribution of specific risk factors and transmission pathways within the home and in the allocation of resources to infant-focussed WASH interventions that aim to improve growth.

REFERENCES

ACF and UNICEF 2017 WASH’ Nutrition: A Practical Guidebook. ACF International, Paris.
Ahmed, T., Auble, D., Berkley, J. A., Black, R., Ahern, P. P., Hossain, M., Hsieh, I., Ireen, S., Arabi, M. & Gordon, J. I. 2014 An evolving perspective about the origins of childhood undernutrition and nutritional interventions that include the gut microbiome. Annals of the New York Academy of Sciences 1332 (1), 22–38. doi:10.1111/nyas.12487.
Arnold, B. F., Null, C., Luby, S. P. & Colford Jr., J. M. 2018 Implications of WASH benefits trials for water and sanitation – authors’ reply. The Lancet Global Health 6 (6), e616–e617. doi:10.1016/S2214-109X(18)30229-8.
Baqui, A. H., Black, R. E., Yunus, M., Hoque, A. R., Chowdhury, H. R. & Sack, R. B. 1991 Methodological issues in diarrhoeal diseases epidemiology: definition of diarrhoeal episodes. International Journal of Epidemiology 20(4), 1057–1063. doi:10.1093/ije/20.4.1057.
Barnes, A. N., Anderson, J. D., Muma, J., Mahmud, Z. H. & Cumming, O. 2018 The association between domestic animal presence and ownership and household drinking water contamination among peri-urban communities of Kisumu, Kenya. PLoS ONE 13 (6), e0197587. doi:10.1371/journal.pone.0197587.
Bauza, V., Byrne, D. M., Trimmer, J. T., Lardizabal, A., Atiim, P., Asigbee, M. A. K. & Guest, J. S. 2018 Child soil ingestion in rural Ghana – frequency, caregiver perceptions, relationship with household floor material and associations with child diarrhoea. Tropical Medicine and International Health 23 (5), 558–569. doi:10.1111/tmi.13055.
Black, R. E., Allen, L. H., Bhatta, Z. A., Caulfield, L. E., de Onis, M., Ezzati, M., Mathers, C. & Rivera, J. 2008 Maternal and child undernutrition: global and regional exposures and health consequences. The Lancet 371 (9608), 243–260. doi:10.1016/S0140-6736(07)61690-0.
Black, R. E., Victora, C. G., Walker, S. P., Bhatta, Z. A., Christian, P. & de Onis, M. 2013 Maternal and child undernutrition: overweight in low-income and middle-income countries. The Lancet 382 (9890), 427–451. doi:10.1016/S0140-6736(13)60937-X.
Boehm, A. B., Wang, W., Ercumen, A., Shea, M., Harris, A. R., Shanks, O. R., Kelty, C., Ahmed, A., Hayat Mahmoud, Z., Arnold, B. F., Chase, C., Vollmann, C., Colford, J. M., Luby, S. P. & Pickering, A. J. 2016 Occurrence of host-associated faecal markers on child hands, household soil, and drinking water in rural Bangladeshi households. Environmental Science and Technology Letters 3 (11), 393–398. doi:10.1021/acs.estlett.6b00382.
Environmental enteric dysfunction and child stunting.

Nutrition Reviews 77 (4), 240–253. doi:10.1093/nutrit/nuy068.

Bukenya, G. B. & Nwokolo, N. 1991 Compound hygiene, presence of standpipe and the risk of childhood diarrhoea in an urban settlement of Papua New Guinea. International Journal of Epidemiology 20 (2), 534–539. doi:10.1093/ije/20.2.534.

Checkley, W., Gilman, R. H., Epstein, L. D., Suarez, M., Diaz, J. F., Cabrera, L., Black, R. E. & Sterling, C. R. 1997 Asymptomatic and symptomatic cryptosporidiosis: their acute effect on weight gain in Peruvian children. American Journal of Epidemiology 145 (2), 156–163. doi:10.1093/oxfordjournals.aje.a009086.

Clasen, T., Boisson, S., Routray, P., Torondel, B., Bell, M., Cumming, O., Ensink, J., Freeman, M., Jenkins, M., Odagiri, M., Ray, S., Sinha, A., Suar, M. & Schimdt, W.-P. 2014 Effectiveness of a rural sanitation programme on diarrhoea, soil-transmitted helminth infection, and child malnutrition in Odisha, India: a cluster-randomised trial. The Lancet Global Health 2 (11), e645–e653. doi:10.1016/S2214-109X(14)70307-9.

Curtis, V., Cairncross, S. & Yoni, R. 2000 Review: domestic hygiene and diarrhoea – pinpointing the problem. Tropical Medicine and International Health 5 (1), 22–32. doi:10.1046/j.1365-3156.2000.00512.x.

Davis, E., Cumming, O., Aseyo, R. E., Muganda, D. N., Baker, K. K., Mumba, J. & Dreibelbis, R. 2008 Oral contact events and caregiver hand hygiene: implications for fecal-oral exposure to enteric pathogens among infants 3–9 months living in informal, peri-urban communities in Kisu, Kenya. International Journal of Environmental Research and Public Health 15 (2), e192. doi:10.3390/ijerph15020192.

DelAgua Water Testing Ltd 2015 DelAgua Portable Water Testing Kit. User Manual Version 5.0.

Devamani, C., Norman, G. & Schmidt, W.-P. 2014 A simple microbiological tool to evaluate the effect of environmental health interventions on hand contamination. International Journal of Environmental Research and Public Health 11 (11), 11846–11859. doi:10.3390/ijerph11111846.

Dewey, K. G. & Adu-Afarwuah, S. 2008 Systematic review of the efficacy and effectiveness of complementary feeding interventions in developing countries. Maternal and Child Nutrition 4 (SI), 24–85. doi:10.1111/j.1740-7790.2007.00124.x.

Ercumen, A., Pickering, A. J., Kwong, L. H., Arnold, B. F., Parvez, S. M., Alam, M., Sen, D., Islam, S., Mullmann, C., Chase, C., Ahmed, R., Unicomb, L., Luby, S. P. & Colford, J. M. 2017 Animal feces contribute to domestic fecal contamination: evidence from E. coli measured in water, hands, food, flies, and soil in Bangladesh. Environmental Science & Technology 51 (15), 8725-8734. https://doi.org/10.1021/acs.est.7b01710.

George, C. M., Oldja, L., Biswas, S., Perin, J., Lee, G. O., Kosek, M., Sack, B. R., Shahnawaz, A., Haque, R., Parvin, T., Azmi, I. J., Bhuyian, S. I., Talukder, K. A. & Faruque, A. G. 2015a Geophagy is associated with environmental enteropathy and stunting in children in rural Bangladesh. American Journal of Tropical Medicine and Hygiene 92 (6), 1117–1124. doi:10.4269/ajtmh.14-0672.

George, C. M., Oldja, L., Biswas, S., Perin, J., Lee, G. O., Kosek, M., Sack, B. R., Shahnawaz, A., Haque, R., Parvin, T., Azmi, I. J., Bhuyian, S. I., Talukder, K. A., Mohammad, S. & Faruque, A. G. 2015b Fecal markers of environmental enteropathy are associated with animal exposure and caregiver hygiene in Bangladesh. American Journal of Tropical Medicine and Hygiene 95 (2), 269–275. doi:10.4269/ajtmh.14-069.

Gittelsohn, J., Steckler, A., Johnson, C. C., Pratt, P., Grieser, M., Pickrel, J. & Staten, L. K. 2006 Formative research in school and community-based health programs and studies: ‘State of the Art’ and the TAAG approach. Health Education and Behavior 33 (1), 25–39. doi:10.1177/1090198015282412.

Guerrant, D. I., Moore, S. R., Lima, A. A., Patrick, P. D., Schorling, J. B & Guerrant, R. L. 1999 Association of early childhood diarrhoea and cryptosporidiosis with impaired physical fitness and cognitive function four-seven years later in a poor urban community in Northeast Brazil. American Journal of Tropical Medicine and Hygiene 61 (5), 707–713. doi:10.4269/ajtmh.1999.61.707.

Harris, A. R., Pickering, A. J., Harris, M., Doza, S., Islam, M. S., Unicomb, L., Luby, S., Davis, J. & Boehm, A. B. 2016 Ruminants contribute fecal contamination to the urban household environment in Dhaka, Bangladesh. Environmental Science and Technology 50 (9), 4642–4649. doi:10.1021/acs.est.5b06282.

Harvey, S. A., Winch, P. J., Leontsini, E., Torres Gayoso, C., López Romero, S., Gilman, R. H. & Oberhelman, R. A. 2003 Domestic poultry-raising practices in a Peruvian shantytown: implications for control of Campylobacter jejuni-associated diarrhea. Acta Tropica 86 (1), 41–54. doi:10.1016/S0001-706X(03)00006-8.

Headey, D. & Hirvonen, K. 2016 Is exposure to poultry harmful to child nutrition? An observational analysis for rural Ethiopia. PloS ONE 11 (8), e0160590. doi:10.1371/journal.pone.0160590.

Headey, D., Nguyen, P., Kim, S., Rawat, R., Ruel, M. & Menon, P. 2017 Is exposure to animal feces harmful to child nutrition and health outcomes? A multicountry observational analysis. American Journal of Tropical Medicine and Hygiene 96 (4), 961–969. doi:10.4269/ajtmh.16-0270.

Humphrey, J. H. 2009 Child undernutrition, tropical enteropathy, toilets, and handwashing. The Lancet 374 (9694), 1032–1035. doi:10.1016/S0140-6736(09)60950-8.

Humphrey, J. H., Mduduzi, N., Mbuya, N., Ntuzino, R., Moulton, L. H., Stoltzfus, R. J., Ravengwa, N. V., Mutasa, K., Majo, F., Mutasa, B., Mangwadu, G., Chassokela, C. M., Chigumira, A., Chakewka, B., Smith, L. E., Tielsch, J. M., Jones, A. D., Manges, A. R., Maluccio, J. A. & Prendergast, A. J. 2009 Independent and combined effects of improved water, sanitation, and hygiene, and improved complementary feeding, on child stunting and anaemia in rural Zimbabwe: a cluster-randomised trial. Lancet Global Health 7 (1), e132–e147. https://doi.org/10.1016/S2214-109X(18)30374-7.
Hutty, S. R., Blum, D., Kirkwood, B. R., Emeh, R. N. & Feachem, R. G. 1987 The epidemiology of acute diarrhoea in a rural community in Imo State, Nigeria. Transactions of the Royal Society of Tropical Medicine and Hygiene 81 (5), 865–870. doi:10.1016/0035-9203(87)90055-1.

Korpe, P. S. & Petri, W. A. 2012 Environmental enteropathy: critical implications of a poorly understood condition. Trends in Molecular Medicine 18 (6), 328–336. doi:10.1016/j.molmed.2012.04.007.

Kosek, M. N., MAL-ED Network Investigators 2017 Causal pathways from enteropathogens to environmental enteropathy: findings from the MAL-ED birth cohort study. EBio Medicine 18, 109–117. doi:10.1016/j.ebiom.2017.02.024.

Kotloff, K. L., Nataro, J. P., Blackwelder, W. C., Nasrin, D., Farag, T. H., Panchalingam, S., Wu, Y., Sow, S. O., Sur, D., Breiman, R. F., Faruque, A. S. G., Zaidi, A. K. M., Saha, D., Alonso, P. L., Tamboura, B., Sanogo, D., Onwuchekwa, U. & Manna, B. 2013 Burden and aetiology of diarrhoeal disease in infants and young children in developing countries (the Global Enteric Multicenter Study, GEMS): a prospective case-control study. The Lancet 382 (9888), 209–222. doi:10.1016/S0140-6736(13)60844-2.

Kwong, L. H., Ercumen, A., Pickinger, A. J., Unicomb, L., Davis, J. & Luby, S. P. 2016 Hand- and object-mouthing of rural Bangladeshi children 3–18 months old. International Journal of Environmental Research and Public Health 13 (6), e563. doi:10.3390/ijerph13060563.

Kwong, L. H., Ercumen, A., Pickinger, A. J., Unicomb, L., Davis, J. & Luby, S. P. 2019 Age-related changes to environmental exposure: variation in the frequency that young children place hands and objects in their mouths. Journal of Exposure Science & Environmental Epidemiology. doi:10.1038/s41370-019-0115-8.

Langford, R., Lunn, P. & Panter-Brick, C. 2011 Hand-washing, subclinical infections, and growth: a longitudinal evaluation of an intervention in Nepal slums. American Journal of Human Biology 23 (5), 621–629. doi:10.1002/ajhb.21189.

Lee, G., Pan, W., Peñato, Yori, P., Paredes Olortegui, M., Tilley, D., Gregory, M., Oberhelman, R. B., Bandha Chavez, C. & Kosek, M. 2015 Symptomatic and asymptomatic Campylobacter infections associated with reduced growth in Peruvian children. PLoS Neglected Tropical Diseases 7 (1), e2036. doi:10.1371/journal.pntd.0002036.

Lin, A., Arnold, B. F., Alfreen, S., Goto, R., Mohammad, T., Huda, N., Haque, R., Raquib, R., Unicomb, L., Ahmed, T., Colford Jr, J. M. & Luby, S. P. 2013 Household environmental conditions are associated with enteropathy and impaired growth in rural Bangladesh. American Journal of Tropical Medicine and Hygiene 89 (1), 130–137. doi:10.4269/ajtmh.12-0367.

Lin, A., Aronld, B. F., Unicomb, L., Asfar, S., Winch, P. J., Stewart, C. P., Begum, F., Hussain, F., Benjamin-Chung, J., Leontsini, E., Naser, A. M., Parvez, S. M., Hubbard, A. E., Lin, A., Nizame, F. A., Jannat, K. & Ercumen, A. 2018 Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Bangladesh: a cluster randomised controlled trial. The Lancet Global Health 6 (3), e302–e315. doi:10.1016/S2214-109X(17)30490-4.

Lupindu, A. M., Dalsgaard, A., Msolle, P. F., Ngowi, H. A., Mtambo, M. M. & Olsen, J. E. 2015 Transmission of antibiotic-resistant Escherichia coli between cattle, humans and the environment in peri-urban livestock keeping communities in Morogoro, Tanzania. Preventive Veterinary Medicine 118 (4), 477–482. doi:10.1016/j.prevetmed.2014.12.005.

MAL-ED Network Investigators 2017 Relationship between growth and illness, enteropathogens and dietary intakes in the first 2 years of life. BMJ Global Health 2 (4), e000370. doi:10.1136/bmjgh-2017-000370.

Marquis, G. S., Ventura, G., Gilman, R. G., Porras, E., Miranda, E., Carbajal, L. & Penta, M. 1990 Fecal contamination of shanty town toddlers in households with non-corralled poultry, Lima, Peru. American Journal of Public Health 80 (2), 146–149. doi:10.2105/ajph.80.2.146.

Martorell, R., Horta, B. L., Adair, L., Stein, A. D., Richter, L., Fall, C. H. D., Bhargava, S. K., Dey Biswas, S. K., Perez, L., Barros, F. C., Victora, C. G. & Consortium on Health Orientated Research in Transional Societies Group 2010 Weight gain in the first two years of life is an important predictor of schooling outcomes in pooled analyses from five birth cohorts from low- and middle-income countries. Journal of Nutrition 140 (2), 348–354. doi:10.3945/jn.109.112300.

Mattioli, M., Davis, J. & Boehm, A. B. 2015 Hand-to-mouth contacts result in greater ingestion of feces than dietary water consumption in Tanzania: a quantitative fecal exposure assessment model. Environmental Science and Technology 49 (3), 1912–1920. doi:10.1021/es505555f.

Morita, T., Perin, J., Oldjia, L., Biswas, S., Sack, B. R., Ahmed, S., Haque, R., Bhuyian, N. A., Parvin, T., Bhuyian, S. I., Akter, M., Talukder, K. A., Shahnaj, M., Faruque, A. G. & George, C. M. 2017 Mouthing of soil contaminated objects is associated with environmental enteropathy in young children. Tropical Medicine and International Health 22 (6), 670–678. doi:10.1111/tmi.12869.

Mosites, E. M., Rabinowitz, P. M., Thumbi, S. M., Montgomery, J. P., Palmer, G. H., May, S., Rowhani-Rahbar, A., Neuhouser, M. L. & Walson, J. L. 2015 The relationship between livestock ownership and child stunting in three countries in Eastern Africa using national survey data. PLoS ONE 10 (9), e0136686. doi:10.1371/journal.pone.0136686.

Mosites, E., Thumbi, S. M., Otiang, E., McElwain, T. F., NJenga, M., Rabinowitz, P. M., Rowhani-Rahbar, A., Neuhouser, M. L., May, S., Palmer, G. H. & Walson, J. L. 2016 Relations between household livestock ownership, livestock disease, and young child growth. Journal of Nutrition 146 (5), 1118–1124. doi:10.3945/jn.115.229561.

Mosites, E., Dawson-Hahn, E., Walson, J., Rowhani-Rahbar, A. & Neuhouser, M. L. 2017 Piecing together the stunting puzzle: a framework for attributable factors of child stunting. Paediatrics and International Child Health 37 (3), 158–165. doi:10.1080/20469047.2016.1230952.
Navab-Daneshmand, T., Friedrich, M. N. D., Gächter, M., Montealegre, M. C., Mlambo, L. S., Nhawiwa, T., Mosler, H.-J. & Julian, T. R. 2018 *Escherichia coli* contamination across multiple environmental compartments (soil, hands, drinking water, and handwashing water) in urban Harare: correlations and risk factors. *American Journal of Tropical Medicine and Hygiene* 98 (3), 803–813. doi:10.4269/ajtmh.17-0521.

Ngure, F., Humphrey, J., Mbuya, M., Majo, F., Mutasa, K., Gova, M., Mazarura, E., Chasekwa, B., Prendergast, A. J., Curtis, V., Boor, K. J. & Stoltzfus, R. J. 2015 Formative research on hygiene behaviors and geophagy among infants and young children and implications of exposure to fecal bacteria. *American Journal of Tropical Medicine and Hygiene* 89 (4), 709–716. doi:10.4269/ajtmh.12-0568.

Ngure, F. M., Reid, B. M., Humphrey, J. H., Mbuya, M. N., Pelto, G. & Stoltzfus, R. J. 2014 *Water, sanitation, and hygiene* (WASH), environmental enteropathy, nutrition, and early child development: making the links. *Annals of the New York Academy of Sciences* 1308 (1), 118–128. doi:10.1111/nyas.12330.

Ngure, F., Rosenbaum, J., Albert, A., Khush, R., Israel, M., Jenkins, M. & Brown, J. 2015 *Water, Sanitation, and Hygiene Partnerships and Learning for Sustainability* (WASHPALS). *Toward a Review Environment for Infants and Young Children: A Review of the Literature*. Tetra Tech, Arlington, VA.

Null, C., Stewart, C. P., Pickering, A. J., Dentz, H. N., Arnold, B. F., Arnold, C. D., Benjamin-Chung, J., Clasen, T., Dewey, K. G., Fernald, L. C. H., Hubbard, A. E., Kariger, P., Lin, A., Luby, S. P., Mertens, A., Nyambane, G., Ram, P. K. & Colford Jr, J. M. 2018 Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Kenya: a cluster-randomised controlled trial. *The Lancet Global Health* 6 (3), e316–e329. doi:10.1016/S2214-109X(18)30005-6.

Oberhelman, R., Gilman, R., Sheen, P., Cordova, J., Zimic, M., Cabrera, L, Meza, R. & Perez, J. 2006 An intervention-control study of coralling of free-ranging chickens to control *Campylobacter* infections among children in a Peruvian periurban shantytown. *American Journal of Tropical Medicine and Hygiene* 74 (6), 1054–1059. doi:10.4269/ajtmh.2006.74.1054.

Parvez, S. M., Kwong, L., Rahman, M. J., Ercumen, A., Pickering, A. J., Ghosh, P. K., Rahman, Z., Das, K. K., Luby, S. P. & Unicom, L. 2015 *Escherichia coli* contamination of child complementary foods and association with domestic hygiene in rural Bangladesh. *Tropical Medicine and International Health* 22 (5), 547–557. doi:10.1111/tmi.12849.

Patil, S. R., Arnold, B. F, Salvatore, A. L., Briceno, B., Ganguly, S., Colford Jr, J. M. & Gertler, P. J. 2015 The effect of India’s total sanitation campaign on defecation behaviors and child health in rural Madhya Pradesh: a cluster randomized controlled trial. *PLoS Medicine* 11 (8), e1001709. doi:10.1371/journal.pmed.1001709.

Penakalapati, G., Swarthout, J., Delahoy, M. J., McAlliley, L., Wodnik, B., Levy, K. & Freeman, M. C. 2017 Exposure to animal feces and human health: a systematic review and proposed research priorities. *Environmental Science and Technology* 51 (20), 11537–11552. doi:10.1021/acs.est.7b02811.

Pickering, A. J., Davis, J., Walters, S. P., Horak, H. M., Keymer, D. P., Mush, D., Strickfaden, R., Chynoweth, J. S., Liu, J., Blum, A., Rogers, K. & Boehm, A. B. 2010 *Hands, water, and health* : fecal contamination in Tanzanian communities with improved, non-networked water supplies. *Environmental Science and Technology* 44 (9), 3267–3272. doi:10.1021/es903524.m.

Pickering, A. J., Julian, T. R., Mamuya, S., Boehm, A. B. & Davis, J. 2011 Bacterial hand contamination among Tanzanian mothers varies temporally and following household activities. *Tropical Medicine and International Health* 16 (2), 233–239. doi:10.1111/j.1365-3156.2010.02677.x.

Pickering, A. J., Julian, T. R., Marks, S. J., Mattioli, M. C., Boehm, A. B., Schwab, K. J. & Davis, J. 2012 Fecal contamination and diarrheal pathogens on surfaces and in soils among Tanzanian households with and without improved sanitation. *Environmental Science and Technology* 46 (11), 5736–5743. doi:10.1021/es300022c.

Prendergast, A. J. & Humphrey, J. H. 2015 Stunting persists despite optimal feeding: are toilets part of the solution? *Nestle Nutrition Institute Workshop Series* 81, 99–110. doi:10.1159/0003565807.

Ram, P. K., Jahid, I., Halder, A. K., Nygren, B., Islam, M. S., Granger, S. P., Molyneaux, J. W. & Luby, S. P. 2011 Variability in hand contamination based on serial measurements: implications for assessment of hand-cleansing behavior and disease risk. *American Journal of Tropical Medicine and Hygiene* 84 (4), 510–516. doi:10.4269/ajtmh.2011.10-0299.

Reid, B., Orgle, J., Roy, K., Pongolani, C., Chileshe, M. & Stoltzfus, R. 2018 Characterizing potential risks of fecal–oral microbial transmission for infants and young children in rural Zambia. *American Journal of Tropical Medicine and Hygiene* 98 (3), 816–823. doi:10.4269/ajtmh.17-0124.

Richard, S. A., Black, R. E., Gilman, R. H., Guerrant, R. L., Kang, G., Lanata, C. F., Mølbak, K., Rasmussen, Z. A., Sack, R. B., Valentiner-Branth, P. & Checkley, W. 2013 Diarrhea in early childhood: short-term association with weight and long-term association with length. *American Journal of Epidemiology* 178 (7), 1192–1198. doi:10.1093/aje/kwt094.

Schriefer, A., Odagiri, M., Vuertz, S., Misra, P. R., Panigrahi, P., Clasen, T. & Jenkins, M. W. 2015 Human and animal fecal contamination of community water sources, stored drinking water and hands in rural India measured with validated microbial source tracking assays. *American Journal of Tropical Medicine and Hygiene* 93 (5), 509–516. doi:10.4269/ajtmh.14-0824.

Scrimshaw, N. S. & Suskind, R. M. 1976 Interactions of nutrition and infection. *Dental Clinics of North America* 20 (3), 461–472.

Shivoga, W. A. & Moturi, W. N. 2009 Geophagia as a risk factor for diarrhoea. *The Journal of Infection in Developing Countries* 3 (2), 94–98. doi:10.3855/jidc.35.
Steiner, T. S., Lima, A. A., Nataro, J. P. & Guerrant, R. L. 1998
Enteroaggregative Escherichia coli produce intestinal
inflammation and growth impairment and cause interleukin-
8 release from intestinal epithelial cells. Journal of Infectious
Disease 177 (1), 88–96. doi:10.1086/513809.

The World Bank 2006 Repositioning Nutrition as Central to
Development: A Strategy for Large-Scale Action – Overview
(English). Directions in Development, Washington, DC.

Torondel, B., Gyekye-Aboagye, Y., Routray, P., Boisson, S.,
Schmidt, W. & Clasen, T. 2015 Laboratory development and
field testing of sentinel toys to assess environmental faecal
exposure of young children in rural India. Transactions of the
Royal Society of Tropical Medicine and Hygiene 109 (6),
386–392. doi:10.1093/trstmh/trv023.

UNICEF and WHO 2019 Joint Child Malnutrition Estimates 2019
Edition – Interactive Dashboard. Available from: https://
data.unicef.org/resources/joint-child-malnutrition-estimates-
interactive-dashboard (accessed 14 May 2018).

Victora, C. G., de Onis, M., Hallal, P. C., Blössner, M. &
Shrimpton, R. 2010 Worldwide timing of growth faltering:
revisiting implications for interventions. Pediatrics 125 (3),
e473–e480. doi:10.1542/peds.2009-1519.

Wagner, E. & Lanoix, J. 1998 Excreta Disposal for Rural Areas and
Small Communities, Vol. 39. World Health Organization,
Geneva, Switzerland.

WHO 2012 Animal Waste, Water Quality and Human Health.
IWA Press, London.

Yeager, B. A., Lanata, C. F., Lazo, F., Verastegui, H. & Black, R. E.
1991 Transmission factors and socioeconomic status as
determinants of diarrhoeal incidence in Lima, Peru. Journal
of Diarrhoeal Disease Research 9 (3), 186–193.

Zambrano, L. D., Levy, K., Menezes, N. P. & Freeman, M. C. 2014
Human diarrhea infections associated with domestic animal
husbandry: a systematic review and meta-analysis.
Transactions of the Royal Society of Tropical Medicine and
Hygiene 108 (6), 313–325. doi:10.1093/trstmh/tru056.

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