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# Risk factors and transmission pathways to infection and malnutrition in infants in Ethiopia: Implications for WASH programming

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‘When we try to pick out anything by itself, we find it hitched to everything else in the Universe.’

- John Muir, *My First Summer in the Sierra*

## Abstract

In certain lower-income regions, poor infant health outcomes remain a key concern. These include diarrhoea and infection which can impede development. Water, sanitation and hygiene (WASH) interventions should block faecal-oral transmission and prevent infection from pathogenic organisms. However, interventions have focused on containing human faeces whilst overlooking the burden from domestic animals. Interventions also often neglect the age- and behaviour-related pathways to infection and are so not adequately tailored to mitigate it. This thesis sought to better understand the risk factors and transmission pathways to infant infection in Ethiopia and how a household playspace (HPS) might reduce this. Multiple methods were employed. Initially, a literature review examined the contribution of domestic animals to infant infection, malnutrition and household contamination. Following, two phases of formative fieldwork used environmental and clinical sampling, anthropometry, survey, and observational data to identify specific risk factors and transmission pathways contributing to infection in rural Ethiopian households. Important was the effect of keeping animals inside on maternal and infant hand and floor contamination (all $p<0.005$), and with infant stools positive for *Campylobacter* ($p=0.027$, OR 3.5). WASH facilities did not reduce contamination ($p=0.76$) nor the odds of infection ($p>0.5$). Concurrent fieldwork involved the design and build of an HPS to block key transmission pathways. Through a multi-stage, participatory design process, an HPS prototype was developed and trialled in a feasibility trial. This aimed to determine the feasibility of a definitive trial. The trial demonstrated good acceptance and adherence among intervention households and multiple secondary benefits, including on maternal time burden and infant injury prevention. Through multiple stages, this thesis describes the impact of animal faecal contamination on domestic hygiene and infant infection risk and how a WASH intervention component might mitigate this. Future interventions must consider age-specific needs and the importance of overall domestic hygiene to improve infant health.



## Keywords

BabyWASH, Campylobacter, domestic animals, hygiene, infant health, infection, malnutrition, sanitation, WASH.

## Acknowledgements

Unlike many stories I heard before starting, I enjoyed (almost) every second of my PhD. However, it might have passed in a very different way were it not for many great people. This journey has been an utter privilege that has allowed me to travel, learn from and work with some truly brilliant humans.

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Ian – For so much laughter and letting me eat your food. You have an excellent mind and your faith in me is unshakeable.

Charlotte – So many miles and so much love, always right when I needed it – soul sister. Jamie – Where have 10 years gone? Luckily, we didn’t have to marry each other at 30. Ella – You said I would get here one day, and I did – sister from another mister.

*This thesis is dedicated to David: I would not be here were it not for your kindness.*

# Contents

## Tables

## Figures

## List of abbreviations

| | |
|---|---|
| CI | Confidence interval |
| CFU | Colony forming unit |
| ECD | Early child development |
| EED | Environmental enteric dysfunction |
| HAZ | Height-for-age (z-score) |
| HEW | Health Extension Worker |
| HPS | Household playspace |
| LAZ | Length-for-age (z-score) |
| LMIC | Lower-to-middle-income country |
| PIN | People In Need |
| q(PCR) | (quantitative) polymerase chain reaction |
| RCT | Randomised controlled trial |
| SDG | Sustainable Development Goal |
| SNNPR | Southern Nations, Nationalities, and Peoples' Region |
| TIPs | Trials by Improved Practice |
| TTC | Thermotolerant coliform |
| UNICEF | United Nations Children's Fund |
| WASH | Water, sanitation and hygiene |
| WAZ | Weight-for-age (z-score) |
| WLZ | Weight-for-length (z-score) |
| WHO | World Health Organization |

# 1 Introduction

## 1.1 Research background

Short-term growth in infancy and early childhood is a highly complex and non-linear process. Pioneering studies which measured infant frequently during the first 21 months of life suggested that growth is episodic rather than periodic[1] – described as a 'saltation and stasis' model. Here, 'saltation' refers to sudden growth events and 'stasis' the variable intervals of no growth.[2] These early models showed that when assessed weekly, incremental gains in length were between 0.5 to 2.5 cm (saltation) punctuated by seven- to 63-day intervals of no growth (stasis).[1] The process, illustrated in **Figure 1**, is described as 'discontinuous and intermittent',[3] with high variability in the amount and timing of growth between individuals.[2,3]

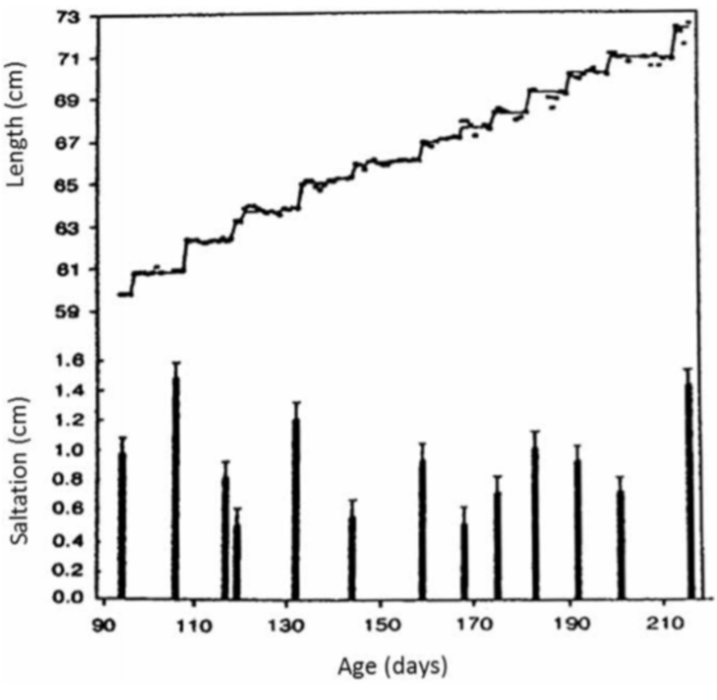


Figure 1. Saltation and stasis growth model.[2]

The model applied to daily measurements of total body length in one infant (top panel) identifies a discontinuous, stepwise pattern of growth.[1] Incremental growth saltations greater than measurement error (bottom panel) form the steps in the graph.[3]

Despite high variation in individual growth, during the foetal period and the first few years of life, growth overall is very similar across different geographical areas – that is, if mothers' nutritional and health needs are met and if infants are raised in 'unconstrained conditions'.[4] These environmental factors – amongst others, such as feeding practices, water, sanitation and hygiene (WASH) frequency of infections and access to healthcare – are therefore major determinants of growth in the first thousand days.[5] Thus, worldwide, millions of children do not achieve their linear growth potential because of suboptimal health conditions, nutrition and care. Linear growth failure in early childhood is the most prevalent form of undernutrition worldwide.[6] Global prevalence of linear growth failure has reduced by almost half from 1990 (40%) to 2019 (21%), However, an estimated 144 million children under five are 'stunted'[6]: that is, with a height- or length-for-age z-score (HAZ, LAZ) below -2 (more than two standard deviations (SD) below the population median).[7] Further, there is an even greater proportion of infants and young children who do not reach this cut off but who still fail to achieve adequate linear growth.[8] Studies have associated (but often cannot prove causality between[8,9]) childhood growth failure with lower IQ and school performance, overall poverty and a later higher risk of chronic diseases, including diabetes, heart disease, and stroke.[10–12] Due to these long-term effects, linear growth failure may hold implications for the developmental potential and human capital of whole nations.[13] Thus it rightly remains a pressing public health concern. **Figure 2** shows data from the India National Family Health Survey and illustrates that compared with the World Health Organisation Child Growth Standards, the entire LAZ and HAZ z-score distribution is shifted left – indicating that all children (not only those -2 SD below the median, were affected by some degree of growth failure.[14]

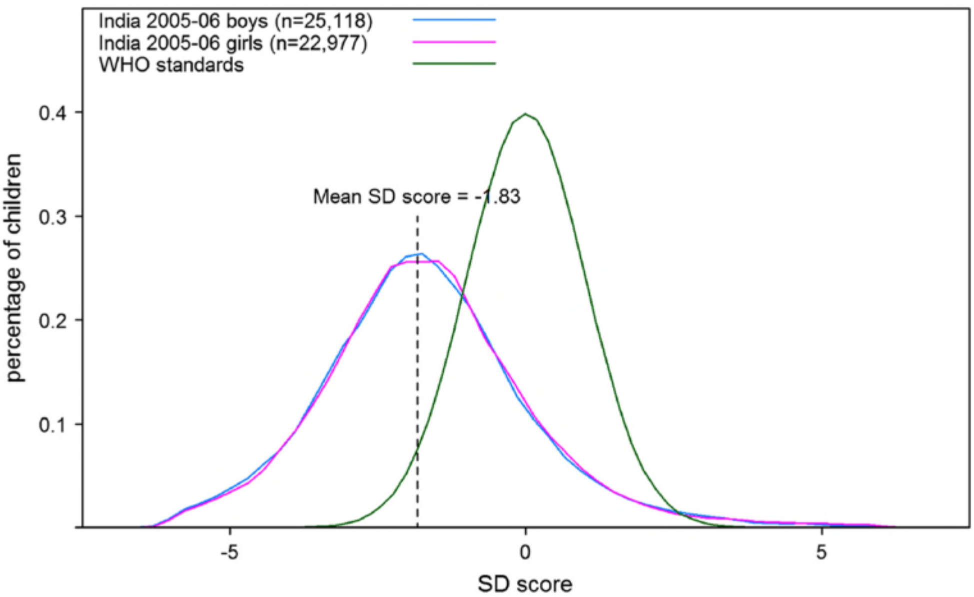


Figure 2. SD score distribution for length-for-age/height-for-age of Indian children compared with the WHO Child Growth Standards. In de Onis M and Branca F, 2016.[14]

Epidemiological studies are clear that suboptimal breastfeeding, poor complementary feeding practices and micronutrient deficiencies are key determinants of linear growth failure.[13,15] However, the most efficacious interventions only demonstrate improvements in HAZ z-scores of around 0.3: that is, following interventions stunted infants regain only about a third of the height deficit. This may be because the *average* growth deficit is already -2.0 (stunting) by 24 months among African and Asian children.[12,16] However in some countries (such as India), growth failure occurs even among well-fed children[12] and thus over time it has become clear that nutritional interventions are only one part of the solution to linear growth failure.[17]

Early research described metabolic and immune associations with poor health outcomes, and it was widely accepted that diarrhoea was one reason for stunting.[12] However, opinion differed widely as to whether diarrhoea was[18,19] or was not[20] the main causal factor. Later catch-up growth in children who experienced chronic diarrhoea questioned its impact on final height outcomes.[18] The relative contribution of diarrhoea remains controversial, and trials that reduce incidence do not necessarily result in improved growth.[21] However, infection is a clear co-factor in undernutrition. Early research in Central and South America and South Africa (reviewed in Keusch[22]) highlighted the interactions between nutrition, immunity, and infection – then advanced by Keusch[22] and Scrimshaw et al.[23] This research recognised and defined the synergistic, antagonistic, and cyclical relationships between infection, undernutrition, morbidity and mortality – described below in **Figure 3**. Essentially, this interaction occurs primarily from the decline in health following infection, where infants are underweight, weakened, and vulnerable to further infections. Here, insufficient dietary intake leads to weight loss, weakened immunity, cell mucosal damage, invasion by pathogenic bacteria, subsequent diarrhoea, nutrient malabsorption and ultimately impaired growth and development. Infants with infection also suffer loss of appetite (anorexia), a diversion of nutrients towards immune recovery and urinary nitrogen loss. These deficiencies lead to further damage of defence mechanisms,[23,24] and the cycle continues.

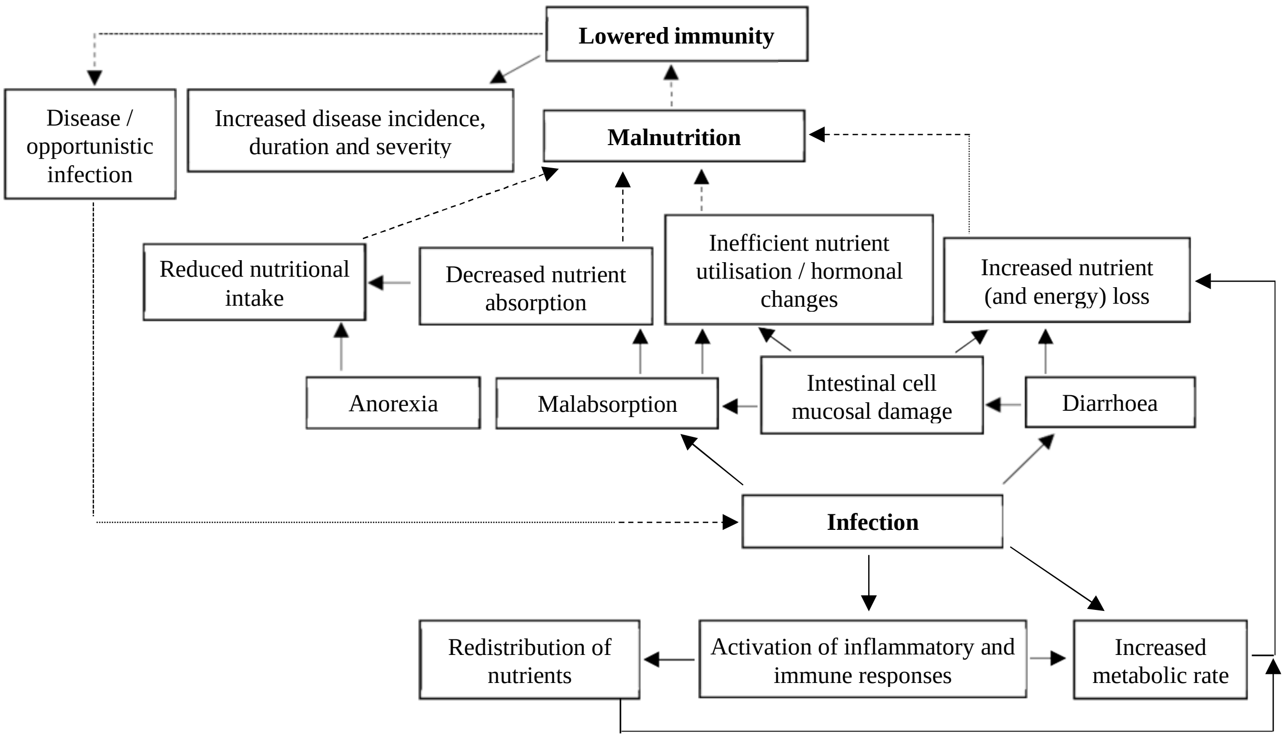


Figure 3. The synergistic, antagonistic relationship between infection, malnutrition, and lowered immunity. Based on research by Keusch[22] and Scrimshaw.[23]

## 1.2 WASH and linear growth

## 1.3 WASH interventions and infant infection and growth

Communicable disease (including infectious disease and diarrhoeal disease) related to insufficient and unsafe water and sanitation contribute significantly to morbidity and mortality across lower- to middle-income countries (LMICs).[25,26] They are classified as faecal-oral (water-borne and waterwashed), non-faecal-oral water-washed, water- based and water-related insect vector disease.[25] Improved quantity, quality and availability of water and sanitation alongside hygiene education provides a control strategy for these diseases. Considering the scope of what WASH can provide and the ‘definition’ of WASH as a framework, this involves primarily water supply, hygiene and sanitation. Water supply involves the supply of water for domestic purposes and drinking water but might (and arguably ought to) include the provision for irrigation or livestock, which ultimately affects domestic water quality.[27] Sanitation primarily refers to excreta disposal but, as per water supply, again might include other environmental health interventions such as solid waste management and surface water drainage which again will affect levels of faecal (and pathogen) contamination within the home. Hygiene refers to handwashing with soap at critical points, but which, as argued later, might encompass the safe and hygienic preparation of food as a potentially key transmission pathway. This traditional scope of WASH is the early paradigm illustrated by the Fdiagram[28] but which this thesis will later argue misses key risk factors and transmission pathways to infant infection and is thus limited by its very definition.

From the point of view of the effect on the disease burden, the main health benefit of WASH is a reduction in diarrheal disease via blocking waterborne, faecal-oral diseases. In LMICs during infancy and early childhood, diarrhoeal disease incidence is high – particularly in contexts with poor WASH. Further, the faecal-oral pathway constitutes one of the main transmission routes for pathogenic infection in infants.[29] This results from contact with faecal pathogens which is either direct (faecal ingestion) or indirect (contaminated food, hands, utensils, toys) and thus for infants most transmission occurs within the household. Contaminated water and hands are key transmission routes for infants in LMICs due to a lack of safe water and sanitation facilities.[29–30] Thus, WASH has a plausible role in preventing infection and WASH interventions which aim to block waterborne diseases and reduce faecal contamination of the home through containing human waste and improved hand hygiene should reduce infant faecal exposure to faecal-oral pathogens that cause disease. However, WASH interventions have not yet shown consistent protection of infants during critical stages of growth and development – as demonstrated by recent trials.[32–35] Much evidence does support the importance of WASH for normal linear growth.[36–40] In Bangladesh for example, infants who had access to clean drinking water, improved latrines and facilities for handwashing with soap had an approximate 50% increase in HAZ scores versus controls.[41] However, the evidence base for the effect of WASH on infant health is inconsistent. Recent large, randomised controlled trials include WASH Benefits (Bangladesh[32] and Kenya[33]), the Sanitation Hygiene Infant Nutrition Efficacy (SHINE) trial[34] and the Maputo Sanitation (MapSan) trial.[35] These trials are discussed in detail in Chapter 2. Essentially, all trials tested the independent and combined effects of improved infant feeding and household WASH on growth and diarrhoea outcomes. Briefly, across trials infant feeding modestly but significantly increased the mean LAZ score. However, WASH interventions alone had no effect on growth, and combining WASH with feeding had no additional benefit versus feeding alone.[42]

Effects varied by site and do not disprove the benefits of WASH for infant health. Yet, of note was the prevalence of enteric (gut) infections in intervention groups – typically ten times higher than in high-income countries.[42] Recent research describing links between infection and linear growth failure have aimed to identify the aetiology of diarrhoeal disease and specific enteropathogens.[43,44] There appears a consistent, predictable pattern of infection and co-infections from key pathogens which underlie a substantial burden of moderate-to-severe diarrhoea and later linear growth failure[43,44] and the burden of diarrhoeal mortality, as demonstrated in the prospective Global Enteric Multicenter Study (GEMS).[44] These include G*iardia,*[43,45] *Cryptosporidium,*[46,47] *enteroaggregative* and *enteropathogenic E. coli*[43,45,48] and *Shigella.*[49,50] Infections are characterised by a combination of high shedding rates and high transmissibility through multiple environmental pathways. The periodic disappearance and reappearance of these pathogens during infancy suggests chronic exposure to faecal contamination and related pathogens throughout this time.[51] Consistent low-level infection causes persistent illness (such as prolonged diarrhoea) and prevents recovery.[51,52]

### 1.4 The research gap

In LMICs, contamination of the home with enteric pathogens and other pathogenic organisms is extensive,[53–55] reaching infants through multiple transmission pathways. Understanding levels of faecal contamination (and the burden of enteric and other pathogenic organisms) across different faecal-oral transmission pathways and their sources can help highlight the principal routes that pose health risks.[56,57] However, such an ‘exposure profile’ approach might lead to further fragmentation of interventions which are not broad enough to significantly reduce the burden of pathogenic contamination. Another limitation of research which attempts to delineate these primary pathways is the fact that for different sectors of the population, different vulnerabilities change and increase risk. Thus, as mentioned, the F-diagram – whilst an excellent communication tool and useful heuristic to understand the main pathways of transmission (both for microbiological and behavioural endpoints) – does not adequately capture the broad transmission pathways which expose infants to pathogens. This is a further limitation of WASH interventions which are designed around the F-diagram; although they endeavour to reduce waterborne disease by way of blocking faecal-oral transmission of pathogens and thus reducing infant infection, they largely do not consider the age- and developmental-related behaviours which increase risk for certain pathways. That is, as defined earlier by the scope of WASH, most WASH interventions aim to improve drinking water, latrines and handwashing with soap. However, they miss other risk factors and transmission pathways, including key vectors, where faecal-oral pathogens are either indirectly or directly ingested during infant exploratory play and mouthing.[58] This includes toys or other items given to the infant, soil or dirt from domestic floors and human or animal faeces on the home floor.[58–61] What constitutes as a main transmission pathway may well also change with age – as the infant passes through the first thousand days, the dominant pathways and risk factors will change with different developmental stages. Age-related behaviours and associated risks might underlie links between certain animal husbandry practices and poor infant health outcomes. Essentially, focusing on few pathways and attempting to tackle the pathogen burden from an exposure profile approach may not substantially reduce overall pathogen prevalence nor capture certain pathways relating to more vulnerable populations.

Importantly, and central to the hypothesis of this thesis, is the significant contribution of animal faeces to the burden of domestic contamination. In LMICs, people frequently live in close proximity with livestock, usually not separated in living and sleeping quarters. Both humans and animals carry faeces and diverse microbes and pathogens into the home and into the immediate vicinity of infants.[62–64] Thus insufficient separation of animals and their faeces from the home environment can result in the ingestion of pathogens through direct and indirect contact[63] – increasingly documented.[27,58,64–69] While some key enteropathogens (such as rotavirus) have limited zoonotic (animal-human) transmission,[63,70] this thesis hypothesises that animal faeces may play an important role in the transmission of some of the key enteropathogens previously mentioned – many of which are zoonotic.[70] Increasing evidence links indoor cohabitation with increased faecal contamination of the home and thus with pathogenic organisms and adverse infant health outcomes.[58,64,71,72] However, such studies are rarely in relation to existing WASH facilities and use. Research is needed to further understand the additional contribution of domestic animal contamination to infant infection risk.

Further, despite the aim of WASH to block faecal-oral transmission, the scope of WASH rarely extends to the management of animals and their faeces. Although guidelines do exist which discuss wastewater and excreta, this does not approach animal management, where it only briefly touches on foodborne trematodes.[73] Further, other books in the field have summarised essential information on key zoonotic pathogens and their transmission, assessment, management and regulation[74,75] but do not specifically provide guidelines for WASH interventions. Sanitation interventions have focused primarily on the containment of human excrement and thus WASH interventions do not typically pay attention to, or do not indirectly address pathogens found in animal faeces that are transmitted via WASH-related pathways.[62] Animal management and contamination is not discussed in WHO Sanitation and Health guidelines[76] – despite the fact that several of these pathogens are related to WASH elements in terms of prevention and/or treatment.[62,77] Further, few studies have evaluated the potential of primary WASH barriers (e.g. sanitation facilities or infrastructure which addresses animal faecal waste, or animal husbandry practices which address faeces in the environment plus contamination of water sources) to reduce the burden of animal faeces on infecton.[62] This is an issue for trials aiming to improve infant health outcomes where growth effects may be mitigated, or by other risk factors such as indoor animal housing practices which increase contamination across floors and fomites.

Recently, the ‘BabyWASH’ approach was proposed as an additional component of early childhood development (ECD) programmes, with the aim of blocking faecal-oral exposure and related transmission pathways for infants.[78–80] Integrating WASH within maternal, new-born and child health (MNCH) and ECD, BabyWASH involves a set of WASH interventions focusing on pregnant women, babies, infants, and their caregivers. The approach aims to reduce bacterial the bacterial burden of living spaces where infants reside – primarily in play and feeding environments.[78–80] This may contribute greatly to reducing infection. Whilst a BabyWASH approach is important in identifying risk factors within the environment that pertain to infants, it might be argued that rather than providing another set of interventions to add to existing WASH programmes, what is needed is a more comprehensive WASH package that tackles pathogen contamination across the broader home environment – from an infant standpoint. This is important particularly where trials are predicated on infant health grounds. Regardless, the BabyWASH concept does highlight that *‘...no attention has been given to exploratory ingestion of soil and animal faeces that occurs in early childhood’* despite that a key BabyWASH activity is to separate animals within the home and to address animal faeces within infant play areas.[79,80] This highlights that traditional WASH approaches have failed to identify and implement solutions to overlooked risk factors to infants, such as infection from zoonotic pathogens. However, it also highlights the issue of fragmenting ‘aspects’ of WASH into further sectors (i.e. BabyWASH) which may not help the sector in designing and deploying necessarily extensive interventions (this is further addressed within the discussion).

Regardless, the issue of animal contamination is significant for WASH interventions which have largely focused on containing human faeces and have overlooked the management of that from domestic animals.[62,63] Thus it is prudent to discuss limitations of the WASH framework and the scope of WASH interventions this is not yet a formal consideration. Thus, this thesis sets out to test the hypothesis that within households in rural, subsistence agriculture communities in LMICs, a large burden of household contamination is from domestic animals. Further, it asks whether existing WASH facilities and use help to mitigate contamination and faecal-oral transmission and prevent infant infection, as well as the impact on WASH of domestic animals and infant behaviours in these contexts.

The BabyWASH concept recognises the contribution of infant behaviours to faecal-oral transmission of pathogenic organisms and thus infection.[80] However it also emphasises that requiring mothers (or caregivers) to devote more time to watching their infant to prevent soil and/or faecal ingestion may result in further burdening them where time constraints are already a concern.[80,81] Thus interventions that focus exclusively on hygiene behaviours may confer additional stress and may be inefficient at blocking faecal-oral transmission of pathogens. The few interventions aiming to reduce faecal exposure have mostly focused on corralling animals,[82,83] but which have not shown a reduction in infant infection. Therefore, as noted by other teams in this field,[82] it is pertinent to develop strategies that address infant faecal-oral transmission through a WASH framework and create an enabling environment for household hygiene, whilst not increasing maternal/caregiver workload.[81] An alternative to corralling chickens or other animals is to provide a designated household playspace (HPS) for infants. By acting as a barrier to key direct (hand-to-mouth faecal-oral ingestion) and indirect (mouthing of faecally-contaminated objects, soil, or household flooring) transmission pathways, a hygienic, walled HPS holds potential to help reduce infection. When mothers and caretakers understand the risks associated with ingesting soil and/or animal faeces, a protective HPS is valued and desirable[71,84,85] and mothers recognise the importance of keeping a child safe during play.[85] BabyWASH guidelines suggest ‘safe and clean play spaces: mats/plastic sheets and/or play yards [spaces]’ are a key hygiene-related activity for programmes aiming to reduce infection[56] and the WHO describes an HPS as a ‘critical’ intervention component within WASH scope.[86] Although some research efforts have investigated communal playspaces[71] or plastic models,[34,87] no other team or other implementing body within the WASH field has yet designed, developed or tested a playspace for inside the home which is safe, feasible and acceptable within local contexts in LMICs. Thus lastly, this thesis explores how an HPS, as one material component part of a wider WASH package, might help to prevent faecal-oral transmission and impact infection and diarrhoea.

## 1.5 Thesis aims and objectives

Thus the aim of this research was to understand the epidemiology of, and risk factors for, infection and malnutrition in infants in Ethiopia and to assess how a material intervention component might reduce incidence of infection in order to improve growth. Further, it sought to understand how the scope and definition of WASH may fail to account for these specific risk factors – including the age- and behaviour-specific needs of infants alongside the burden of contamination from domestic animals. Further, it hypothesised that an HPS could reduce infection and impact quality of life in rural subsistence agriculture households and an HPS may prove a feasible and efficacious material input as a component of a broader WASH intervention. To test these hypotheses and deliver against the main aim, the following objectives were set:

1. To review current evidence surrounding infant infection, malnutrition and environmental enteric dysfunction in relation to domestic animal husbandry

2. To identify specific risk factors and transmission pathways that contribute to infant infection in rural Ethiopian households

3. To better understand how domestic animals and household WASH facilities (ownership and use) affect contamination across different transmission pathways and infant infection risk, as well as the effect of domestic animal on WASH facilities

4. To design an HPS to reduce the risk of infection within rural subsistence agriculture households

5. To assess the potential for an HPS to reduce the risk of infection in such households, and to:

    a. Assess feasibility to inform a future definitive trial
    b. Describe effects on other livelihood-related outcomes

6. To discuss limitations of the WASH framework and the scope of WASH interventions to improve infant health outcomes considering the thesis findings.

**Table 1** and **Figure 4** below detail how the overall study aim and each objective was approached and answered.

Table 1. Table of thesis chapters according to research stage and thesis objective.

| **Risk factors and transmission pathways to infection and malnutrition in infants in Ethiopia: Implications for (Baby-)WASH programming and policy** | | | | | |
|---|---|---|---|---|---|
| **Chapter number** | **Paper number** | **Thesis objective** | **Chapter title** | **Research stage** | **Publication / status*** |
| 1 | - | - | Introduction | - | - |
| 2 | 1 | 1 | Review: Environmental enteric dysfunction | Literature review | Nutrition Reviews 2019; 77(4): 240–253 |
| 3 | 2 | 2/3 | Formative fieldwork phase 1: Do domestic animals contribute to bacterial contamination of infant transmission pathways? Formative evidence from Ethiopia | Fieldwork phase 1 | Journal of Water and Health 2019; 17(5): 655−669 |
| 4 | 3 | 2/3 | Formative fieldwork phase 2: Risk factors and transmission pathways associated with infant *Campylobacter* spp. prevalence and malnutrition: A formative study in rural Ethiopia | Fieldwork phase 2 | PLoS One 2020; 15(5): e0232541<br><br>With funding from Cranfield GCRF 2018-19 |
| 5 | 4 | 4 | Process fieldwork: Multisectoral participation in the development of a household playspace for rural Ethiopian households | Process fieldwork | American Journal of Tropical Medicine & Hygiene 2021; *In press.* |
| 6 | 5 | 5 | Formative fieldwork phase 3. A randomised controlled feasibility trial of a household playspace: The CAMPI study | Fieldwork phase 3 | PLOS Neglected Tropical Diseases 2021; *In press.* |
| 7 | - | 6 | Discussion | - | - |
| 8 | - | 6 | Conclusions and future work | - | - |

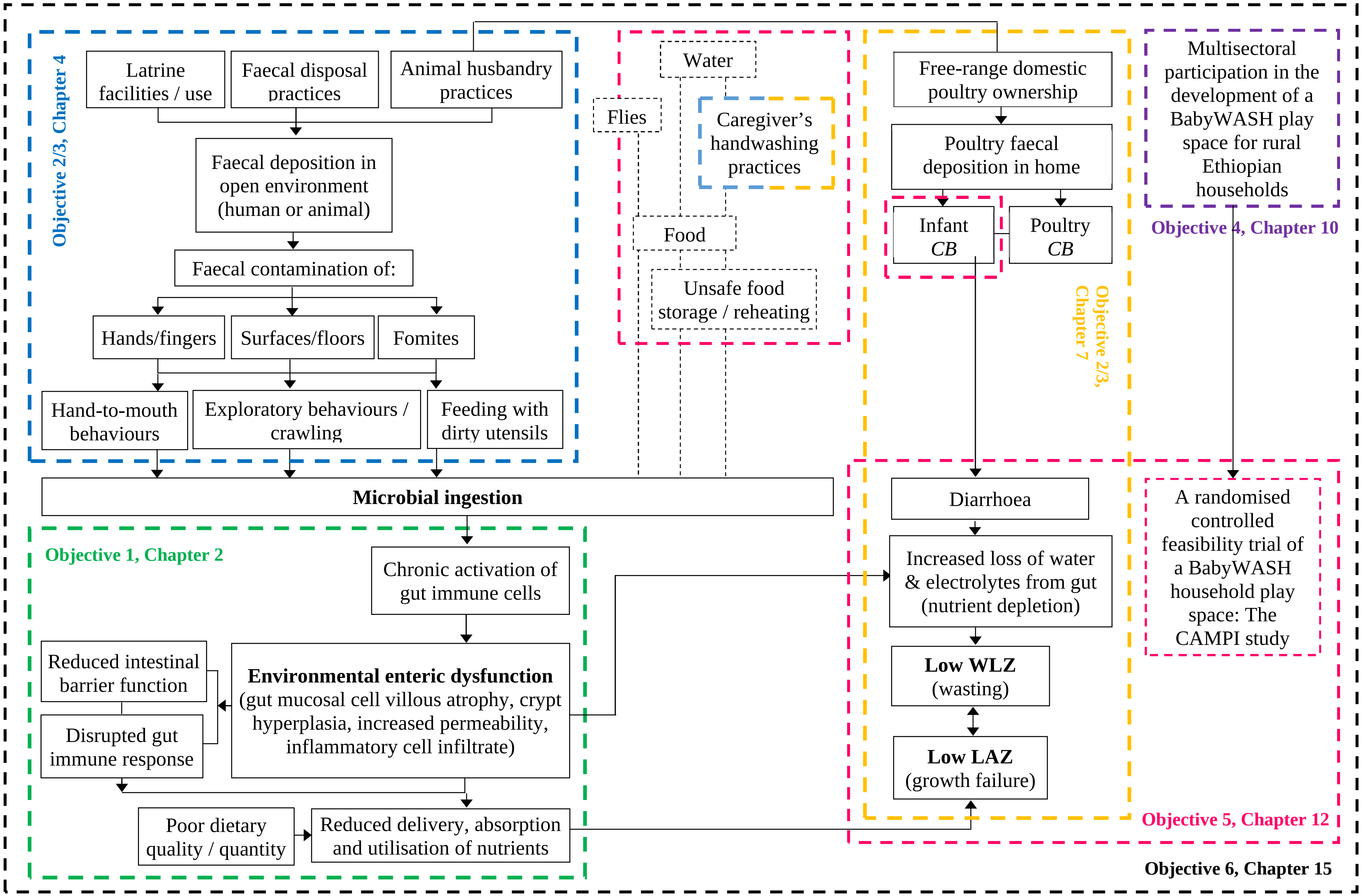


Figure 4. Diagram illustrating connections between thesis objectives and methodological components.

## 1.6 Chapter summaries

Evidence suggests that repeated infection in infancy results in histological changes in the small intestine: a subclinical condition known as environmental enteric dysfunction (EED).[88,89] EED appears the result of frequent, chronic, low-inoculum exposure to a range of pathogens[90,91]; it is almost uniform in infants living with poor WASH[89] and is linked to growth failure.[43,44,90,91] EED might constitute one of the primary pathways linking infection and inflammation, nutrient intake and metabolism with WASH and infant health outcomes.[90] **Chapter 2** reviews the existing literature for the proposed pathology and aetiology of EED in infants alongside considerations for nutrition and WASH interventions to improve growth. Considering the contribution of animals to domestic faecal contamination with related enteric pathogens, **Chapter 2** also discusses the relationship between domestic animal ownership and certain husbandry practices and infection, EED and poor health outcomes.

As a primary pathway to infant infection, there is a further need to characterise risks and identify the dominant pathways of faecal-oral exposure to enteric pathogens and other pathogenic organisms in infants.[56,57] However, this is understudied within the home, where within the first thousand days infants spend most of their time. A multiple methods approach is needed to assess the relative importance of different transmission pathways in highly contaminated environments. This must include a consideration of the age-related risk factors and behaviours which open risk. The first piece of formative fieldwork in this thesis (**Chapter 3**) aims to identify and describe primary sources of bacterial contamination and specific risk factors and transmission pathways which might contribute to infant infection in rural Ethiopian households (objective 2). Building on the research gap, **Chapter 3** also aims to describe how domestic animal husbandry practices and WASH facilities might increase or decrease infection risk (objective 3). Further, it estimates the effect of domestic animals on the effectiveness of WASH facilities (objective 3).

Among the pathogens where early infection is related to poor infant health is the *Campylobacter* subspecies, also zoonotic. *Campylobacter* infection and disease (Campylobacteriosis) is 'hyperendemic' in LMICs[92] and both older[68,92,93] and more recent work[95–97] implicates infection in reduced linear growth.[97] Prevalence appears 'remarkably high'[97] in the first thousand days with an increasing prevalence over the first year.[96]

Poultry are known reservoirs and bacterial shedding contaminates the home environment. Importantly, due to the smaller, more mobile nature of chickens versus other domestic animals, chicken faeces may be more prevalent in homesteads[58,69] and are often directly ingested during infant play.[58] Thus early infection with the pathogen due to close contact with poultry and other animal reservoirs (cows, sheep) may explain isolation of *Campylobacter* in infants.[92] However, little research has specifically isolated *Campylobacter* across WASH- and infant-related transmission pathways within the home, despite calls for its detection as an outcome in WASH trials.[49,95] Thus the second formative fieldwork in **Chapter 4** both builds on and narrows the initial fieldwork by focusing on *Campylobacter* infection and transmission pathways to infants in rural homes in Ethiopia (objective 2). The fieldwork also considers exposure to domestic animals and the effect on existing WASH facilities and use (objective 3). Further, the first formative fieldwork describes an important neglected transmission pathway to infants is that of floors: thus, this fieldwork also isolates *Campylobacter* from domestic floor samples to estimate infection risk.

The WASH sector must develop and test new strategies and material intervention components which reduce infant exposure to pathogens through the faecal-oral route. One possible solution is an HPS which aims to avoid key transmission routes of enteric pathogens and other pathogenic organisms to infants (via direct and indirect faecal-oral transmission). **Chapter 5** describes the design and development of an HPS using a multisectoral, participatory and evidence-based design process (objective 4). The process results in a final prototype design that is culturally acceptable, feasible, and integrated into the local rural context and which is produced at small scale alongside a local artisan.

Lastly, the final HPS prototype is tested in the Campylobacter-Associated Malnutrition Playspace Intervention (CAMPI) trial – a randomised, controlled feasibility trial (RCT). **Chapter 6** describes the trial and outcomes. As a feasibility trial, the trial primarily aims to establish the feasibility of a definitive RCT of an HPS in subsistence agriculture homes in rural Ethiopia (objective 5). The feasibility trial uses surveys validated during the previous two phases of formative research and the *Campylobacter* culture isolation and anthropometry methods piloted during fieldwork phase two.

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## 2 Review: Environmental enteric dysfunction

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### 2.1 Abstract

*In 2017, an estimated 1 in every 4 (23%) children aged < 5 years were stunted worldwide. With slow progress in stunting reduction in many regions and the realisation that a large proportion of stunting is not due to insufficient diet or diarrhoea alone, it remains that other factors must explain continued growth faltering. EED, a subclinical state of intestinal inflammation, can occur in infants across the developing world and is proposed as an immediate causal factor connecting poor sanitation and stunting. A result of chronic pathogen exposure, EED presents multiple causal pathways, and as such the scope and sensitivity of traditional WASH interventions have possibly been unsubstantial. Although the definite pathogenesis of EED and the mechanism by which stunting occurs are yet to be defined, this paper reviews the existing literature surrounding the proposed pathology and transmission of EED in infants and considerations for nutrition and WASH interventions to improve linear growth worldwide.*

### 2.2 Linear growth failure: a complex and prevalent condition

Linear growth failure, or stunting, is the most prevalent form of undernutrition worldwide. An estimated 149 million, or 21.9% of children under five worldwide are stunted,[1] defined by the World Health Organisation (WHO) as a height-for-age (HAZ) score less than −2.[2] Although the global prevalence of stunting has more than halved from 47% in 1985[3] in some of the poorer regions of the world, progress has been slow. In East Africa where there is the highest regional prevalence, 35% remain stunted – an estimated 24 million infants.[1] Whilst undernutrition in general is responsible for almost half of all child mortality,[4] stunting in particular bears other critical, long-term effects on both individuals and societies. The cumulative effects of the resulting impairments to cognitive and physical development and reduced productive capacity include lower levels of schooling, household per-capita expenditure and decreased national economic output.[5–7] A review describing the size of developmental loss from stunting estimated that over the course of a year, stunted individuals will earn an average 22% less than their non-stunted counterparts[8] (likely conservative), and a World Bank report estimating economic costs of stunting suggests a country's gross domestic product may be reduced as much as 3%.[7] As such, stunting is both a major cause and effect in the cycle of poverty, particularity given that women who were stunted themselves, or of low birth weight, are more likely to have stunted children[9]; both genetic and epigenetic research has demonstrated the phenomenon of transgenerational inheritance of environmental insults.[10] Child growth does demonstrate an element of plasticity (as seen through catch-up growth), however it is likely that the adaptive degree of that plasticity in response to environmental cues is also at least partly determined by epigenetic mechanisms.[10,11] This generational reproduction of stunting is a cycle that is difficult to break: however, key periods of growth from pregnancy through birth and childhood offer windows of opportunity for potential intervention.[12] To act now is critical to improve outcomes for multiple future generations. This review aims to summarise key factors which contribute to linear growth failure – in particular, those related to WASH and gut health. Principally, it explores the role of EED, household sanitation and differing exposure pathways in infants as critical factors underlying poor growth and the importance for interventions aiming to improve growth in children worldwide.

### 2.3 The pathogenesis of stunting

Throughout development, periods of growth occur in four interrelated phases: foetal, infant, childhood and pubertal. During these periods, actual spurts of growth are short, occurring during only 5% of a healthy infancy[13]: however, it is then when nutrient needs are highest, determining growth over the life-course. Maximal growth velocity is normally achieved between birth and six months,[12] a period also critical for long-term cognitive development.[14] From 6−24 months linear growth is determined,[15] and so in most developing countries this is when stunting is most prevalent as high nutritional demand from growth meets a nutrient-poor environment.[16] As such, inadequate nutrition from conception onward can cause irreparable damage through impaired physical and cognitive growth; this begins in utero from conception, the effect is sustained throughout pregnancy, and will continue to affect development for at least the first two years of life.[12,17] The first ‘thousand days’ has therefore been identified as a critical period in which to focus nutrition-specific and -sensitive interventions which aim to address both the immediate and underlying determinants of foetal and child nutrition and growth.[17,18]

An individual’s nutritional status during the first thousand days is dependent on a diverse range of interconnected factors, and as such determining the causes of stunting is complex. At the most basic level, stunting from undernutrition is the result of poor dietary intake and repeated infection,[19] but multiple underlying proximal and distal determinants mean establishing causality is difficult. Child undernutrition is caused not just by insufficient food quality and quantity, but also by poor care practices and lack of access to healthcare and social services. These determinants were first detailed in UNICEF’s conceptual framework of child undernutrition more than two decades ago[20] and has since evolved to capture new knowledge and evidence on the causes, consequences and impacts of undernutrition.[21] **Figure 5** details these immediate, underlying, and basic factors. The black arrows indicate how undernutrition throughout the lifecycle feeds back into underlying and basic causes, creating a vicious cycle of poverty and undernutrition. Also captured by the WHO Conceptual Framework on Childhood Stunting, the other distal, structural socioeconomic and political factors such as political stability and urbanisation also play a large role in stunting prevalence, having a long-term influence on malnutrition.[19] Along with the most proximal causes, including the quality and quantity of food and an individual’s digestive capacity and immunity,[12,22] therein lies a complicated network in which growth failure can occur. Such a multifaceted condition suggests that an adequate diet is necessary but not sufficient alone to ensure optimal child growth. Indeed, the majority of interventions to improve breastfeeding, complementary feeding, or nutritional supplementation have individually (and collectively) yielded large effects on survival improvements in HAZ have been mostly small,[16,23] with an estimated efficacy of +0.79 (z-score).[24] This is far from the median deficits seen across Sub-Saharan Africa of –2.0.[15] The inability of interventions to combat stunting highlight the complexity of the condition, and it is becoming clearer that other aetiological factors must be at play.

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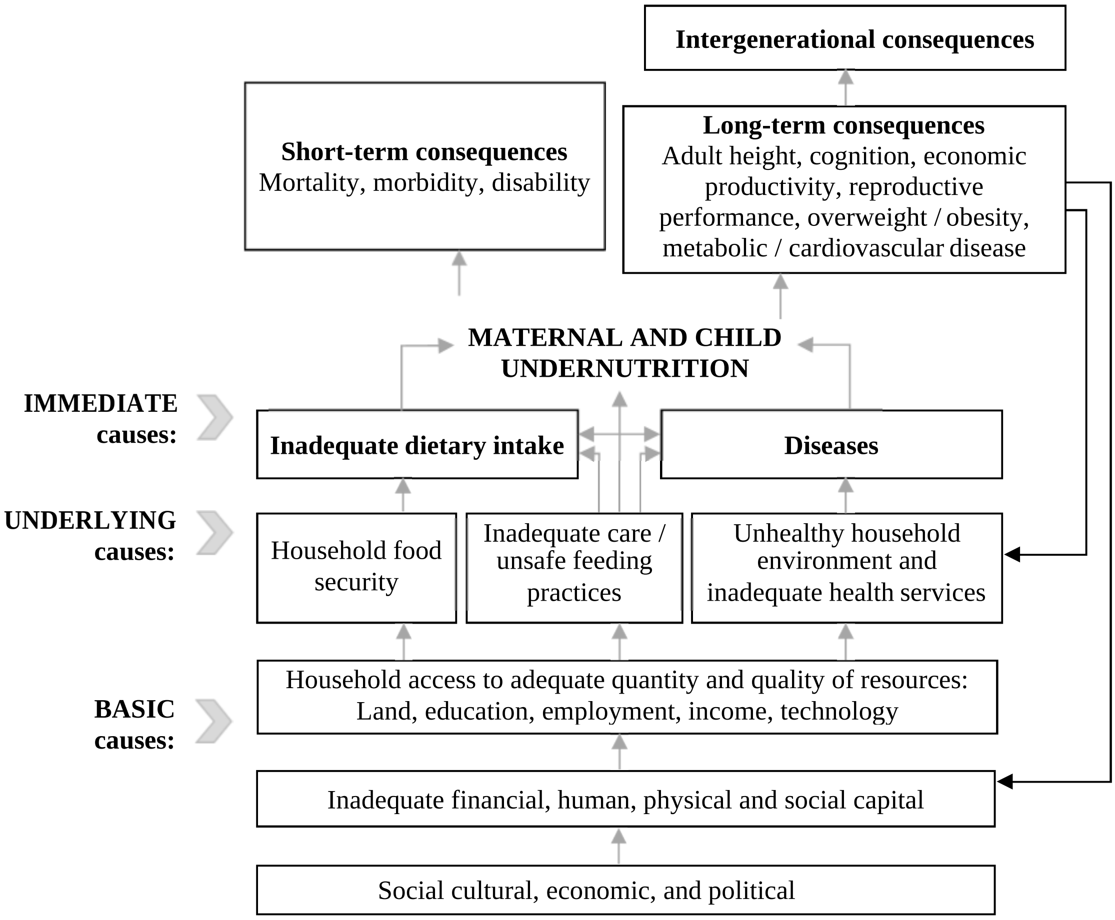


Figure 5. UNICEF conceptual framework of the determinants of child undernutrition. Adapted from UNICEF.[25]

## 2.4 The relationship between linear growth failure and water, sanitation, and hygiene

The failure of polarised interventions to reduce stunting may lie in the rationale that the three main underlying causes– namely poor quality and quantity of food, poor care practices and infectious disease – are either directly or indirectly related to inadequate WASH infrastructure and facilities.[18] The following sections aim to describe this relationship between linear growth failure and WASH and the reasons for the limited success of WASH interventions thus far to prevent stunting worldwide.

At the direct, biological level, three main pathways between poor WASH and stunting have been proposed: repeated diarrhoeal episodes, soil-transmitted infections (helminths) and EED.[18,25] The secondary, more indirect links between poor WASH conditions and nutritional status relate mainly to the broader socioeconomic environment: such as access and affordability of WASH services, distance from household to a water point, education and poverty.[18] These parameters, although highly open to confounding and thus more difficult to ascertain, are no less notable, affecting the possibility of a safe and clean living environment and reducing the available time an adult has to provide adequate childcare.[26] Moreover, poor access to WASH (or poor WASH)impacts child educational achievement, resulting in reduced working capital and worsened household food security – further perpetuating undernutrition, stunting, and the cycle of poverty.[27] As such, poor WASH conditions are now more clearly recognised as contributing to child stunting, and have increasingly become the focus of targeted interventions aimed at improving both global public health and child growth.

## 2.5 Intervening to improve linear growth

### 2.5.1 Water, sanitation, and hygiene interventions

The 2013 Lancet Series identified a set of 10 nutrition-specific interventions. It proposed, if scaled-up from the existing population coverage to 90%, these interventions could save an estimated 900,000 deaths in the 34 countries housing 90% of the world's stunted children. Resultantly, stunting prevalence would be reduced by one-fifth worldwide.[28] Whilst this is noteworthy, nutrition-sensitive interventions (not analysed in the report), including WASH, are possibly equally important for the reduction of undernutrition.[26,28] WASH interventions include a number of different programmes that could be grouped accordingly: water supply (improvements in water quantity and quality), sanitation (particularly safe disposal of faeces) and hygiene promotion / education (including hand washing, and food, personal and environmental hygiene).[18] Of the small but growing evidence base which supports the effect of WASH intervention on stunting reduction, results are mixed: Bhutta et al.[28] estimated that those at scale with 99% coverage would only reduce stunting prevalence by 2.5%. Some observational studies in different developing contexts have suggested a modest association with linear growth[29–32]; a study in Peru found a positive association between improved water sources and HAZ, an effect which was greater when the intervention was combined with improved sanitation facilities.[31] In India, a cross-sectional analysis of health surveys indicated that with reported optimal handwashing practices, stunting risk decreased.[29] Controlled trials report similar findings: a meta-analysis of five cluster- RCTs which assessed interventions in water and hygiene (but not sanitation) found a small but significant impact on HAZ (p=<0.05, mean difference 0.08, 95% CI 0.00–0.16).[26]

### 2.5.2 Water, sanitation, and hygiene interventions to reduce diarrhoea

Most commonly, WASH interventions aiming to address malnutrition have focused on reducing incidence of diarrhoea, as it is frequent in children who live in conditions of poor sanitation, and incidence during the first thousand days has shown some association with poor linear growth.[33–35] Indeed, symptomatic infection is common during the first years of life in low-income countries, where within the first thousand days infants suffer on average six to eight episodes of acute diarrhoea.[36] Observational studies have suggested that recurring diarrhoea or infection are associated with increased risk of stunting[35,37,38]: indeed, symptomatic infection is common during the first years of life in low-income countries, where within the first thousand days infants suffer on average six to eight episodes of acute diarrhoea.[36] In a pooled analysis of nine studies, the probability of stunting at two years increased by 2.5% per episode of diarrhoea, and 25% of all stunting in two-year olds was attributable to having five or more episodes of diarrhoea in the first thousand days.[35] A more recent study found a small difference in height at two years in the children who had experienced a ‘typical’ diarrhoea burden in the same time period.[34] However, other research suggests that the incidence of diarrhoea bears little significance on linear growth This is because between diarrhoeal episodes, the speed of growth can be higher than the average for that age, meaning ultimately catch-up growth is still achieved.[39] As such the relative contribution of diarrhoea to stunting and, resultantly the potential benefit of related WASH interventions is contentious. The Lancet Maternal and Child Undernutrition Series recently estimated that sanitation and hygiene interventions implemented with 99% coverage would reduce diarrhoea incidence by 30%, which would in turn decrease the prevalence of stunting by only 2.4%.[24]

Handwashing interventions, growing in evidence as a specific component of WASH, have shown similar results. A RCT of handwashing in Karachi found a protective effect against diarrhoea (64% lower incidence, 95% confidence interval [CI] 29−90),[40] but not against stunting[41]; this was also observed in a study in Nepal: although improved handwashing with soap reduced child diarrhoeal morbidity by 41% (p=0.023), there was no significant difference in change in growth between intervention and control p=0.76).[42] This was also demonstrated in results from the recent WASH Benefits trials[43] (one of several[44–47] trials which studied the effects of WASH on linear growth), where in Bangladesh handwashing showed the largest effect on diarrhoea reduction (0.60, 95% CI 0.45–0.80)[45] but in both study sites no significant impact on growth versus the control (Bangladesh p=0.169; Kenya p=0.478).[44,45]

Estimating the overall impact of sanitation on diarrhoeal disease also shows mixed (and mostly modest) results. A systematic review which pooled estimates for the effect of handwashing on diarrhoeal diseases gave a risk reduction of 40% (risk ratio 0.60, 95% CI 0.53–0.68), reduced to 23% (risk ratio 0.77, 95% CI 0.32–1.86) after adjustment for un-blinded studies.[48] A recent meta-analysis estimated that overall, improved sanitation was associated with only a 12% reduction in diarrhoea risk (odds ratio 0.88, 95% CI 0.83−0.92).[49] WASH Benefits Bangladesh indicated that versus the control, groups receiving a WASH intervention (excluding water) did experience a reduction in reported diarrhoea: however the effect in the combined intervention groups (water, sanitation, handwashing, and nutrition) was no larger.[45] A recent analysis by the Water, Sanitation, and Hygiene Partnerships and Learning for Sustainability (WASHPaLS) task force concluded that WASH interventions aimed at reducing diarrhoea show a mixed effect, with certain intervention categories seemingly more effective, such as improved water supply and point-of-use water treatment.[50] The report concluded that the effect of improved overall sanitation on diarrhoea is unclear, and whilst handwashing shows substantial efficacy in some contexts, effects are inconsistent and vary highly across settings.[50] Diarrhoea and stunting frequently coincide in an individual,[35,38] and this certainly indicates a level of gut disturbance. However, the heterogeneity of results amongst interventions and the small impact of diarrhoea reduction strategies suggests that diarrhoea along is not causing stunting, and there must be other contributory factors, which have so far not been addressed.

### 2.5.3 What has limited the success of water, sanitation, and hygiene interventions?

Despite reductions in child mortality over the last few decades and some improvements to linear growth, growth faltering and impaired neurodevelopment still persists in low- and middle-income countries, and poor WASH conditions remain connected to a significant proportion of morbidity and mortality in under-fives worldwide.[18] With such mixed results in a substantial body of research, it has been necessary to isolate other reasons for the continued prevalence of stunting and, given the complicated nature of the issue, to consider the issue more broadly. It is becoming clearer that WASH must be viewed more holistically, as ‘broadly encompassing the hygiene-related aspects of the physical and behavioural environment in which children are being raised’.[32] Thus the part-failure of WASH interventions to reduce stunting may lie in traditional design, which typically aim to reduce diarrhoea by standard improvements in sanitation, but may not consider other causative factors that sit within the wider etiological framework of stunting. Subsequently, this has meant taking into consideration the need for a more well-rounded intervention design. A recent experimental trial demonstrated that in a food-insecure region in Ethiopia, children gained +0.33 z-score in mean HAZ over five years if they lived in a WASH intervention area.[51] This, allowed for a protected water supply, sanitation education, soap use, handwashing practices, sanitary facility construction, domestic hygiene, separate housing of animals, and the maintenance of clean water.[51] The implication may lie in the completeness of the intervention, which also addressed the potential source of infection from animals. WASH programmes may therefore need to broaden to consider the wider sanitary environment and the implication for child growth: specifically, WASH must consider what factors are necessary aspects of an intervention to reduce the burden and risk of pathogen exposure in the domestic environment. The following sections address pathogen exposure as a primary causal factor in the pathway to stunting and implications for future WASH interventions that address sanitation within the home.

## 2.6 Environmental enteric dysfunction

### 2.6.1 The missing piece of the stunting puzzle?

The manifestation of stunting is the indication of disturbances to the healthy development of multiple bodily systems. Of specific interest is the disturbance of the immune system, where it appears certain subclinical alterations means stunting can occur even in the absence of obvious insults, such as diarrhoea.[52–54] One proposed cause for this is poor sanitary conditions, where chronic pathogen exposure leads to this subclinical shift in gut structure and function.[22,55] The resulting condition has been termed environmental or tropical enteropathy, or more recently environmental enteric dysfunction (EED)[56] – an apparently seasonal,[57] reversible[58] disorder marked by gut mucosal cell villous atrophy, crypt hyperplasia, increased permeability and inflammatory cell infiltrate.[52,55,59] It is not clear that EED is present at birth[60] but appears by infancy[61–63] across the developing world[53] and is possibly a key factor in reduced linear growth.

By way of process, it is proposed that chronic exposure to enteric pathogens drives T- cell mediated hyperstimulation of the gut immune system, which remains in an inflammatory, hyperimmune state.[52] This, an otherwise appropriate reaction, leads to the aforementioned structural changes in the gut and increased intestinal inflammation and permeability, resulting in disrupted gut immune response, reduced delivery, absorption and utilisation of nutrients and subsequently, nutritional deficiency.[55,64] Nutritional deficiency in turn impairs the renewal of epithelial tissue and the maturation and proliferation of intestinal cells and pancreatic β-cells,[52,64] and resultantly, linear growth faltering.[61,65–67] Concurrently, the low-grade inflammatory state associated with EED appears to inhibit endochondral ossification, thereby inhibiting bone growth and directly affecting height.[68] Epidemiological studies suggest that continuous exposure to enteric pathogens and other pathogenic organisms from faeces is one principal cause of EED, but it is still unclear how pathogens trigger the development of EED.[69] One proposed mechanism is small intestine bacterial overgrowth: a subclinical disturbance in numbers of bacterial colonisation in the upper gastrointestinal tract, small intestine bacterial overgrowth is observed in children in developing countries[70] and is associated with growth faltering.[71,72] Alternatively, it is suggested that chronic exposure to faecal and enteric pathogens may cause qualitative changes in gut microbiota[69]; studies in Bangladesh and Malawi demonstrated that microbiota immaturity correlated with both malnutrition and stunting.[73,74] Thus both quantitative and qualitative changes in gut function may contribute to EED – which also appear to commonly overlap.[69] With an aetiology in poor sanitation, non-symptomatic, subclinical effects independent of those of diarrhoea, and considering the uncertainty over the causal effect of diarrhoea on stunting,[39] it is proposed that the primary causal mechanism between poor WASH and stunting is not diarrhoea, but EED.[12,32] This is illustrated in **Figure 6** which describes the proposed pathway linking EED to stunting. If this is the case, stunting prevention will require a multisector approach which considers not only improved WASH, food quality and quantity and the reduction of acute illness, but which also addresses disruptions to immune function and gut stasis; i.e., which prevents the chronic gut inflammation and malabsorption as seen in EED by improved household sanitation.[75,76]

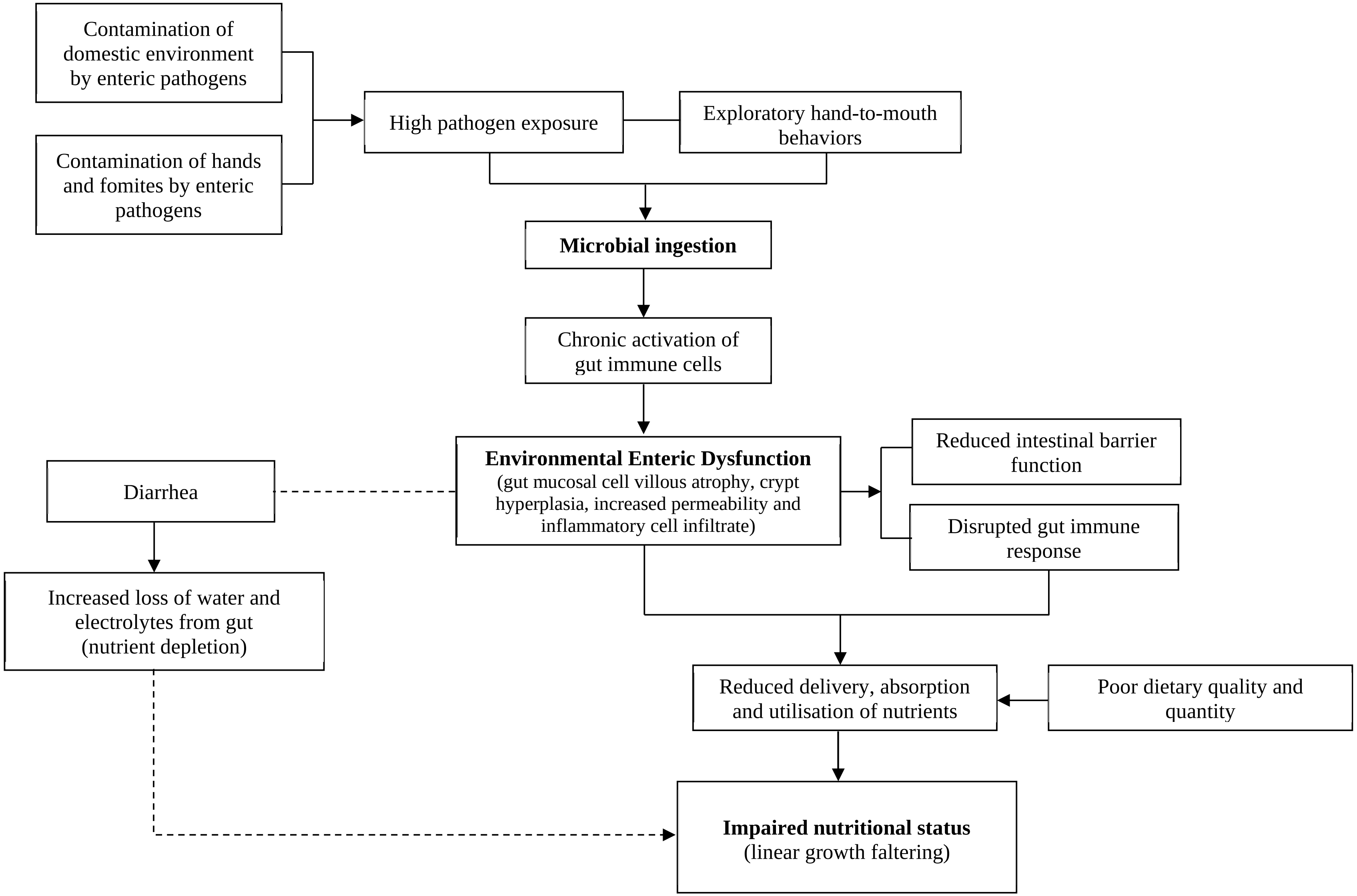


Figure 6. Proposed causal pathways linking environmental enteric dysfunction with linear growth faltering.

### 2.6.2 Enteric infection and linear growth

Stunted infants and young children with EED experience high rates of both symptomatic and asymptomatic enteric infection.[65,77] However, whilst it is not clear how an overstimulated immunity effects pathogen ingestion, in EED, colonisation and stunting appear to occur more often without any clinical effects[78] – even when diarrhoea does not[54,65] – or only in a small proportion of individuals. In Brazil for example, children with intestinal *E. coli* infection exhibited significant decline in height-for-age (p=<0.001), regardless of the presence or absence of diarrhoea.[79] Effects of the initial pathogenic infection may explain this. Gut permeability was observed in Bangladeshi children, where those from contaminated households had dramatically higher incidence of stunting and parasitic infection and worsened gut function than those from clean households.[80] In studies which examined growth in Gambian children, dietary sufficiency and diarrhoea were not associated with stunting, but measures of intestinal permeability explained 43% of linear growth.[62]

Specific microbes may also be responsible for the outcome on growth. Recent findings from the MAL-ED study indicated that the sample-based lactulose:mannitol ratio z- score tended to be higher (indicating increased permeability of the gut wall) in infants with pathogenic infection, particularly in those who tested for *Cryptosporidium* (mean 0.34) and *Giardia* (mean 0.20).[67] As detected in non-diarrhoeal stool samples, *Giardia* was directly associated with reduced linear growth.[67] Infection from *Cryptosporidium*, often isolated in animal faeces (although with variation in infectivity across species), has also been associated with linear growth failure; this was seen in Peru and Brazil, also independent of diarrhoea.[81,82] On the other hand, wide heterogeneity across studies does mean the relationship between microbial infection, EED and stunting is unclear, and the exact mechanism by which intestinal permeability and inflammation affect growth are uncertain.[83] The associations between various aspects of EED and stunted growth appear highly variable, conflicting and easily confounded[83] and as such, far more complicated than can be confidently asserted.

### 2.6.3 Enteric infection and nutritional status

It is suggested that stunting is a result of the gut disturbances from EED meeting limited dietary quality and quantity within the first thousand days, when nutritional needs are high.[12] Also, the effect of enteric infection and the associated subclinical disruptions seen in EED may limit responses to any dietary intervention[16,53]. This may explain the part-failure of nutritional supplementation alone to improve linear growth, as described in **Figure 6**. Hence, improving nutritional intake and breastfeeding practices has understandably been expected to mitigate such associated outcomes. However, although such interventions have largely helped to lower child mortality, they have not successfully prevented stunting, and effects seem mostly small.[16,24] Even nutritional interventions which have specifically aimed to reduce EED (such as with probiotics, antibiotics, or dietary supplements) appear to have little improved either EED or growth.[84] Certain breastmilk constituents, including sialylated oligosaccharides, are shown to enhance gut barrier function and may improve nutrient uptake,[85] and it has been demonstrated that early feeding behaviours are associated with biomarkers of EED.[86] Early breastfeeding initiation, pre-lacteal feeding, and infant feeding are associated with biomarkers of environmental However, whilst breastfeeding is arguably one of the most effective hygiene interventions,[18] impaired gut health has been observed in stunted infants still breastfeeding at eighteen months of age,[87] and early growth assessments in Gambian infants indicated persistent abnormalities in gut mucosa (and later growth faltering) in infants who were continuously breastfed.[62] Furthermore, studies have indicated that the average infant harbours two to four enteric pathogens at any one time, even during exclusive breastfeeding postpartum.[88,89] It seems likely that sustained breastfeeding and an improved diet may be able to lessen, but perhaps not overcome, the effects of enteric infection and EED on growth.

A recent retrospective cohort study assessed trends in growth of Gambian infants after four decades of intervention. In a setting where the community has received access to primary and antenatal care, improved WASH facilities, and screening and treatment of undernutrition, stunting halved over the study period from 1976 to 2012, from 57% to 30%.[76] However, given the unacceptably high prevalence of stunting remaining in the community,[90] it is apparent that the level of nutrition could not fully explain the burden. With noteworthy levels of structural gut disruption also noted within the same community,[91] it is suggested that the chronic inflammation characteristic of EED is likely a major contributory factor to the stall in progress to reduce stunting in this setting, where other potential risk factors were comprehensively addressed.[90] Increasing evidence of this kind suggests EED may bear a the strong effect in the stunting pathway.[92] A more focused intervention which specifically aims to reduce pathogen exposure and infection in infants during the first thousand days may more significantly improve linear growth.[67]

## 2.6 Pathogen exposure in infants

### 2.7.1 In consideration of the broader environment

The faecal-oral route of transmission as described in the 'F-Diagram' (fluids, fingers, fields, flies and food) was proposed some 60 years ago as an important map of causes of enteric infection.[93] An understanding of the principal faecal-oral transmission routes is critical, as the rational for intervening on stunting depends on the potential of each route to cause enteric-related disease and establish EED.[52] Importantly, for babies and infants these primary transmission pathways differ, given that their principal food and fluid is breastmilk, and exploratory behaviours, including crawling and the sucking and the mouthing of objects, create additional exposures to enteric pathogens.[94,95] Thus the following sections address pathogen exposure as it pertains to babies, routes of exposure in the domestic environment and what this might signify for future interventions aimed at reducing linear growth failure.

In developing settings, humans or animals that tread in faeces, or whom openly defecate, bring pathogens into the domestic vicinity of infants and babies,[32] who will often come into contact with faeces and contaminated objects and soil whilst crawling and playing.[29,95,96] The original F=diagram, although fundamental to WASH research and programming, was however developed to illustrate transmission routes from human excreta only, and did not consider the contribution to contamination from animals inside and around the home. From both animal and human faeces, potential pathways of exposure in infants to pathogens inside the home include unclean (i.e., pathogen- contaminated) floors, caregiver and infant hands, food, and fomites. **Figure 7** illustrates these exposure pathways in the domestic environment. The dashed lines integrate the traditional 'F-diagram', which does not specifically account for infant behaviours.

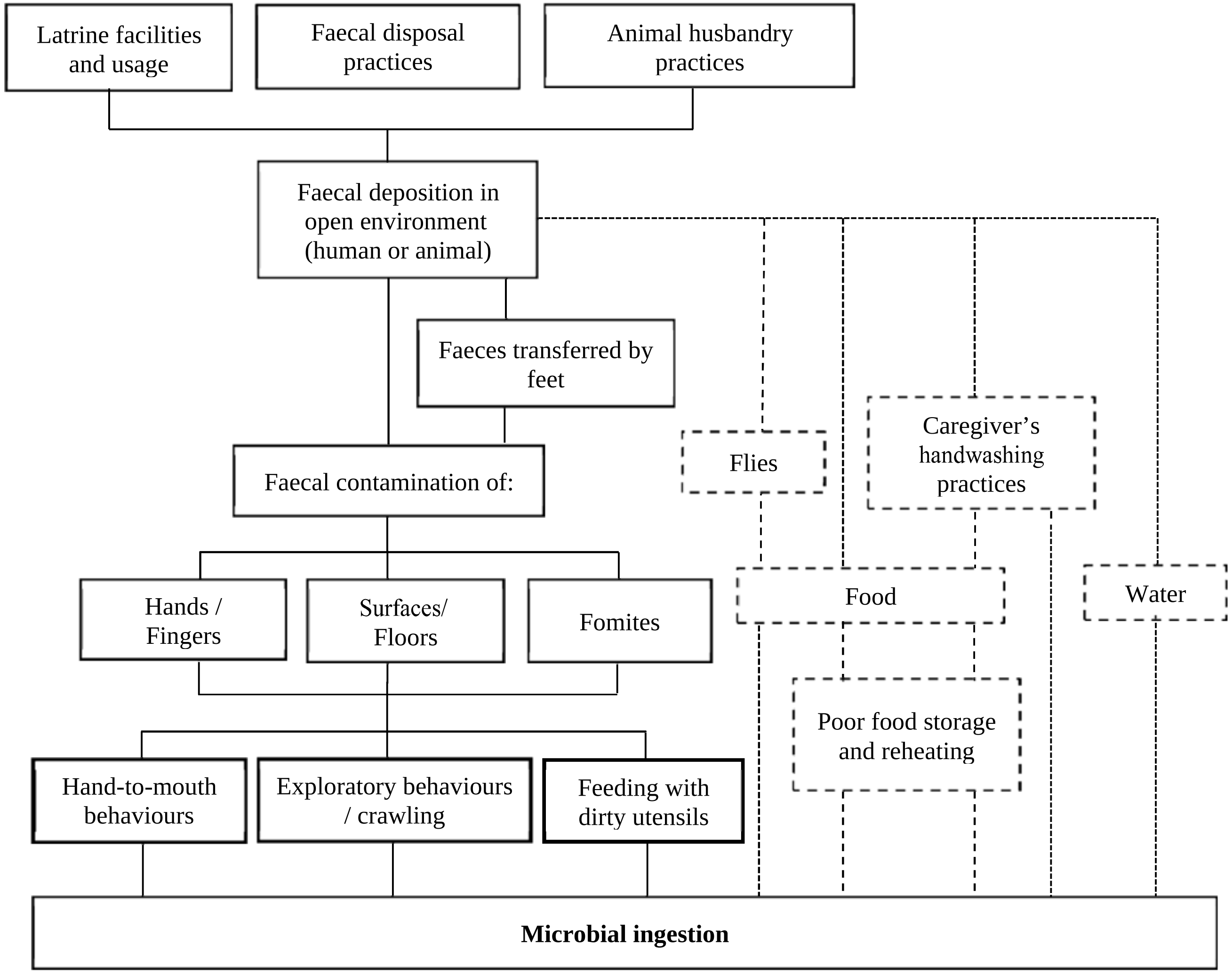


Figure 7. The common pathways by which infants are exposed to and ingest pathogens in the domestic environment.

The dashed lines integrate the traditional 'F-diagram',[93] which does not refer specifically to infant behaviours (thicker black boxes) but includes the multiple pathways by which infants are exposed to enteropathogens.

### 2.7.2 Routes of exposure to infants in the domestic environment

Faecal, and thus pathogenic, contamination of the domestic environment is common in the developing world, and thus infant ingestion of microbes appears widespread. Dirty, contaminated floors, where infants will typically sit to play and crawl, are common. In rural Zimbabwe, all soil samples collected within reach of a crawling infant were commonly, highly contaminated with *E. coli*, with counts 3- to 35-fold higher in soil than water.[95] Kitchen floor swabs also tested positive for *E. coli* in 82% of sites tested. In a second study in Zimbabwe, pathogenic *Clostridium difficile* was isolated in 37% of soil and 6% of water samples.[97] A study of twenty peri-urban Tanzanian households detected *E. coli* in samples across the household, with highest concentrations found in soil from the house floor (83%)[98] both general (70%) and human-specific (18%) faecal Bacteroidales were detected in samples, as well as pathogenic *E. coli*, *enterovirus*, and rotavirus genes. Another pathway, the contamination of fomites – items such as toys, bottles, feeding and cooking utensils – is an important route of exposure in infants, and serves as an indicator of faecal (and/or pathogenic) contamination at the household level. In Tanzania, Pickering et al.[98] found high levels of *E. coli* and *Enterococci* on plastic plates and cups and on children's toys; of all surface samples that harboured an *E. coli* pathotype gene, 62% were from cups and plates. In Huascar, a poor semi-urban community near Lima, 35% of sampled household objects, including infant bottle nipples, feeding bottles, spoons and can openers have tested for *E. coli*.[99] A third pathway is contaminated hands, both caregiver and infant, which is intrinsically linked to the surrounding level of contamination. In the aforementioned study in Zimbabwe, mothers' and infants' hands were contaminated in 50% and 13% of households respectively.[95] As an exposure route, hand contamination is difficult to determine in risk and origin as contamination is usually from animals and most studies do not specifically assess human-to-animal contact.[100] However, studies have found associations between increasing direct contact with animals and/or animal faecal contamination and poor health outcomes.[101–103]

### 2.7.3 Domestic contamination by animals, EED and linear growth

The issue of contamination from animals is significant.[100] In developing countries domestic animals – usually livestock[104] – are often not contained or separated from the household environment and the close proximity of animals to infants increases the pathogen load, as well as the likelihood of microbial ingestion.[105] In rural Zimbabwean infants, ingestion of soil and chicken faeces from the floor were identified as a key pathway for faecal-oral transmission of bacteria, whereby all faeces samples tested positive for *E. coli*.[97] In a different setting in rural Zimbabwe, animals, mostly poultry, occupied the kitchens of one-third of households and one-third had chicken faeces on the kitchen floor.[95] It seems inevitable that an unobserved playing infant, who by nature needs to explore the senses of taste and touch to learn, will eventually come into contact with pathogens; in the latter study, three infants ingested soil a mean of 11.3 times, and two infants ingested chicken faeces twice over a six-hour observational period.[95] An observational study in a poor, peri-urban shanty town in Lima measured the frequency with which infants were exposed to chicken faeces, and reported that faeces was ingested on average four times during a twelve-hour period.[106] Infants rarely had their hands washed after contact and often put their fingers in their mouths; as would be expected, faeces-to-hand and faeces-to-mouth episodes were highly correlated ($r = 0.94$).[106]

Several pathogens isolated from animal faeces are related to acute gastrointestinal symptoms in children.[107] With few studies which quantitatively address specific exposure pathways between animal faeces and child health and specific health risks, the causal network is not well outlined. However, cohabitation with animals has been associated with negative health outcomes, including stunting. In rural Bangladesh, children in households with animal pens in the sleeping area had significantly higher EED scores (from faecal markers) than those without (1.0 point difference,95% CI 0.13−1.88, $p<0.05$).[108] Households with fewer toys contaminated with *E. coli* were in villages with more than 50% toilet coverage, handwashing facilities with soap, no open defecation, safe disposal of child faeces, and no animals present in the household.[109] Among children in rural Malawi, animals sleeping in the same room was positively associated with EED,[66] and Ethiopian children in households where poultry were kept indoors overnight experienced reductions in growth.[110] In the aforementioned study in Ethiopia which managed to improve growth,[51] the broad extensiveness of the WASH infrastructure may have been key to reduced faecal contamination and pathogen exposure, but the lack of animals in the household and safe faeces disposal was possibly significant. Similarly, in a public sanitation programme in Mali in which linear child growth increased (but without a reduction in diarrhoea), intervention households were half as likely to have visible human faeces within the domestic setting, and animal faeces were less likely to be present.[111] These figures are not completely indicative of infection risk, and it is not always certain that the pathogen responsible is of animal origin. However, it appears substantial data demonstrate that animal faeces are a large contributor to levels of contamination in the home. Considering the common high contamination of enteric pathogens among the illustrated transmission pathways and the naturally high frequency of hand-to-mouth contact in infants, it is likely that animals are important sources of enteropathogens in the faecal-oral route of disease transmission, in the promotion of EED and ultimately linear growth failure.

### 2.7.4 Reducing pathogen contamination: A focus on animals

What might work best in terms of reducing pathogen exposure is unclear. Penakalapati et al. modified the traditional F-diagram to isolate specific ‘primary’ barriers aimed at reducing exposure to animal faeces. Of the seven interventions they found to purposely address animal control, the intervention was mostly ineffective.[100] Some studies even suggested that enclosing animals may increase the burden of pathogens by way of increased pathogen concentration; in these studies, infants continued to enter and handle the animals (particularly poultry), and experienced higher rates of *Campylobacter*-related diarrhoea than before animal separation.[110,112,113] Other efforts, including providing metal scoops for faeces removal resulted in minimal difference in faecal contamination from baseline in rural Bangladesh.[114] This was partly attributed to an inefficiency of the tool, but also the observation that domestic animals form such an integral part of rural livelihoods, that interventions might have greater impact by preventing infant exposure through means other than removing faeces alone. Similarly, another study which attempted to confine poultry was also unsuccessful, likely due to household preferences for free-range poultry and eggs and different cultural, structural, and economic barriers.[113]

Given the high prevalence of human and animal faeces around the home in developing countries, the potential for high concentrations of even non-pathogenic bacteria in the gut to cause EED,[115] and the clear association between the presence of animal faeces, EED[66,108] and lower HAZ scores,[108,110,116,117] animal exposure and animal faeces must be an important consideration in interventions which aim to reduce pathogen exposure. This is not often a feature of nutrition-sensitive WASH interventions, which have typically overtly focused on improving toilet facilities, water and water sources, and point-of-use water treatment. Furthermore, there is little indication that interventions are routinely geared towards reducing exposure to animal faeces.[26] This is of particular importance in rural settings, where animals, which are often kept in and around the domestic area, may be overlooked during intervention design – and where, indeed, stunting rates are high, often surpassing those of urban areas.

### 2.7.5 What does this mean for future interventions?

More evidence is needed on how chronic pathogen exposure over the first thousand days represents an important risk to ECD, furthermore, but itis likely that reducing stunting in the most resource-poor areas will require a solution which more substantially blocks exposure to infants. Whilst it might seem obvious that the risk of pathogen exposure should be a major consideration in intervention design, so far WASH programmes and ECD interventions, such as ‘The Essential Package’ from Save the Children and ‘Care for Child Development Package’ from the United Nations Children’s Fund (UNICEF), have not specifically tackled the pathogen burden encountered by babies and infants in their home and play environments.

Specifically, possibly due in part to insufficiently comprehensive and collaborative design, existing WASH interventions have not sufficiently addressed the relevant exposure pathways, and thus not protected young infants and children from ingesting faecal pathogens and microorganisms at critical stages of growth. Hygienic faecal disposal and handwashing with soap after faecal contact are primary preventions of faecal-oral transmission as they prevent contamination of the domestic environment. However, there are different transmission routes which must be considered in WASH intervention design which specifically pertain to infants – particularly contamination from animals of the household spaces in which young infants play and sleep, which appears to be more relevant during the first thousand days than contaminated drinking water.[32] The evidence exists (and is mounting) for strong associations between *E. coli* counts in soil from infant play areas, rates of diarrhoea and elevated levels of biomarkers associated with EED.[94] Other studies have found high levels of diarrhoeagenic *E. coli* on surfaces and objects which an infant regularly encounters as part of play, including toys and balls.[94,98,118] These exposure routes represent critical, undisrupted pathways, and a noteworthy gap for innovative, creative interventions and behavioural change programmes.

### 2.7.6 An infant-centred approach: Thinking outside the box

Given that each transmission pathway is closely linked to infant play and exploration, one proposed solution is the creation of an infant and young child playspace[96]: a clean, safe environment in which babies and infants can freely play which avoids key faecal bacteria and pathogen transmission routes. A specific, designated play area also allows for stricter control of hygiene and sanitation; given that mothers and caregivers in developing settings encounter multiple demands of day-to-day living which limit the time and attention available to their children,[32,119] for example they may miss the necessary instances for handwashing to reduce faecal contact. The provision of a sanitary space in which crawling infants can be left to explore offers the opportunity to interrupt main transmission routes, whilst providing an environment which is safe, practical, and conducive to infant growth and development. However, the possible efficacy of such a space is uncertain. WASHPaLS concluded in their report that the potential benefit of a playspace depends on a more thorough understanding of the protective biological effect against risk, and that in areas with high levels of contamination from enteric pathogenic or other pathogenic organisms, 'extended periods of protection on a mat or within a play yard may not be sufficient to prevent risk posed by even short periods of time'.[50] It has been argued that the importance of this lies in the importance of household level sanitation in predicting child health. Indeed, a recent study in Bangladesh comparing EED and stunting with household WASH status supports the view that this is more relevant to early growth than improvements in community sanitation.[80] However, WASHPaLS suggest that unless complete community sanitation coverage is reached (in order to achieve the desired 'herd effect'), improved sanitation at the household level may be insufficient to mitigate pathogen exposure and improve infant health.

## 2.7 Discussion

### 2.8.1 Moving forward: Clarifying pathways linking animal ownership to poor infant health outcomes

In their review, WASHPaLS note a clear finding that ‘Practitioners and researchers have underestimated potentially key pathways of disease transmission in Wagner & Lanoix’s 1958 “F-Diagram.”’[50] It is arguable that the greater oversight is that of the importance of animal faecal contamination and related pathogenic organisms, the burden of which may be greater and more critical in rural, poor areas where livestock and poultry husbandry are a mainstay. Necessary then to improving child growth and reducing exposure to enteric pathogens requires a focus on ‘field’ transmission routes relevant to infants and young children and a disruption of several, if not all, key risk pathways. This is outlined in **Figure 6** and **Figure 7.** Whilst the body of research suggests that the contribution of each exposure pathway to microbial ingestion and enteric infection may be highly context specific,[120] such a ‘pathway-specific approach’ may not be sufficient to substantially reduce pathogenic contamination into the home environment and may lead to a further ‘fragmenting’ of WASH interventions which do not encompass the broader environment. Whilst it is important to quantify the relative magnitude of exposure from pathogenic bacteria across each pathway and furthermore, how these effects vary by infant age, behaviour, and growth stages (that is, the change in risk as infant mobility changes), the focus should be on what sort of interventions can largely reduce the burden and overall exposure to the greatest effect. Results from WASH Benefits Kenya indicated that HAZ scores at two years were higher in the combined water, sanitation, handwashing, and nutrition intervention versus control (mean difference in score 0.16 [95% CI 0.05–0.27]).[44] The effect appeared significant ($p=0.004$) at two years after the intervention, when concurrently changing infant behaviours broadens routes of exposure. These findings highlight the importance of a specific WASH component to interventions as infants age, but one which also considers how exposure pathways and exposure risk change over time. Additional research is needed to understand the efficacy, uptake, constraints, and scale potential of different interventions to reduce pathogen exposure, including but not limited to clean play spaces, improved animal husbandry practices, and domestic sanitation (and indeed, more non-conventional approaches are certainly required). Research must explore the further benefits of these interventions when coupled with traditional WASH intervention measures, such as improved water supply and quality, improved toilets, and handwashing with soap, as well as the potential difference in effect between household- and community-level interventions. This together might constitute sufficient to reduce overall household contamination from pathogenic bacteria to a level that has clinically meaningful benefits for infant growth and development.

### 2.8.2 Moving forward: Challenges in the field

To progress this area of research, several key challenges present. The first is the measurement of a very complex, multi-causal change processes, and then isolating the factors which are making a difference (if any). Establishing cause and effect appears one of the most pertinent issues in clarifying the EED-stunting pathway, particularly as the primary contributory cause of EED is not yet established (and it is unlikely there is just one). Thus there is currently no ‘gold standard’, or established criteria for defining and measuring EED (although a histological examination via endoscopy and small intestinal biopsy may clarify), with the most widely accepted surrogate marker the lactulose:mannitol test, followed by serum and faecal biomarkers.[52] Thus of further necessity is the identification of a biomarker (or surrogate), or a range of biomarkers that are practical and affordable to collect and analyse in the field: not only to diagnose EED but to establish prevalence, and to quantify the effects of interventions of differing design and across varying settings.

Second is the challenge of delivering a baby-focused WASH intervention – if evidence accumulates that it is effective. The WASH sector faces challenges in delivering interventions which are effective, sustainable, and supported and upheld by the national political and bureaucratic environment.[121] Further complicating an already challenging area, the multifaceted nature of a baby-focused WASH intervention requires strong sector integration and holistic programming. The phenomenon of EED spans multiple discipline boundaries, so tackling it will require collaboration and research across diverse specialties, including WASH experts and nutritionists, public health professionals, gastroenterologists, paediatricians, and immunologists. Here barriers may present, which are not due to a lack of evidence of effectiveness, or the willingness of different groups on the ground, but institutional and bureaucratic barriers which may prevent partnerships and cooperation; i.e., separate funding regimes, different governmental departments, and different working discourses. The Sustainable Development Goals (SDGs) both encourage and necessitate further cross-sector work and collaboration between different development institutions, and the BabyWASH coalition, a multi-stakeholder platform which was founded to address the issue of sectoral integration, will need to ensure it is practiced and maintained. Indeed, it will be necessary to define exactly what is required by sectoral integration in the field and across institutions, and to strengthen and uphold that definition.

Lastly is the challenge of context. As is described, the relative contribution of risk factors attributed to stunting vary in estimate and prevalence – not only at global and national level[122] but potentially down to individual household level. Whilst eliminating a few key risk factors may largely reduce the burden of stunting worldwide, changes in the diet, environment and health are both quantitative and qualitative, so that whilst broad themes appear to be standard, there may be substantial variation worldwide.

Recent research into longitudinal determinants of stunting suggested that causative factors vary widely by the child's age and the community's main livelihood practice.[123] Indeed, early commentary on healthcare delivery in developing settings has noted how large variations in landscape, culture and communities necessitates 'a patchwork' of different health facilities.[124] Further public health research suggests interventions would be more effectual if they were decentralised and adapted to specific population groups[124,125]; as such, at the local level interventions may merit a more focused, tailored design. Similarly, as with any research question, there exist differences between the 'evidence' (research, clinical experiences) and the contextual understanding (cultural and local) of both the issue and the solutions. As such, differences in the principal contributing factors to EED, the cultural value of hygiene, faecal matter and animal husbandry and the possible interpretations of messaging will need to be considered at each stage of formation, intervention, and analysis: including at the hypothetical, measurement, and design stages, when building effective behavioural change campaigns and later during information dissemination if interventions are to be both effective and sustainable.

### 2.8 Conclusion

Accumulating evidence continues to support the hypothesis that the subclinical changes and inflammation as seen in EED may underlie linear growth failure. Whilst it is important not to ignore the critical role of adequate nutrition in optimal growth, the anabolic contribution of nutrition to linear growth appears severely compromised in the presence of EED-related inflammation, a common experience in developing settings. Although difficult to explain quantitatively and highly open to issues of confounding, it is likely WASH conditions certainly play an important role in optimal child growth, and so WASH interventions which effectively disrupt the pathogen burden and levels of exposure, and which particularly address the contribution of animals to domestic contamination, may be necessary for the reduction of stunting in developing countries. Success in some countries supports this,[126] and recent WASH intervention trials finishing analysis are expected to add to the evidence, and further clarify both the effects of WASH independently and together with complementary feeding on linear growth.

Whilst it seems unlikely that WASH interventions alone will eradicate the current prevalence of stunting, what does seem possible is that a design which is more holistically focused, baby-centric, and which aligns WASH, ECD, improved nutrition and animal husbandry (veterinary science) into programming may contribute greatly to reducing the burden. Specifically, with regards to WASH, there is a need for more considerate, more integrated WASH intervention design that include not just toilet provision and handwashing promotion, but which also focuses on contamination of the entire household environment, and how that might be reduced. Through its existing structures and framework, WASH can plausibly contribute to the control of zoonoses and help reduce the related pathogen burden within and across the domestic environment. Integrating WASH and animal husbandry management interventions into the nutrition framework is then necessarily a key aspect; SDG 6 however, which although broad in its framework, is not sufficiently comprehensive that it considers the contribution of zoonoses to environmental hygiene (and the issue that certain domestic animal husbandry practices may mitigate the benefits of improved WASH). These include the surrounding sanitary and pathogenic environment in which the infant plays and lives (including animal husbandry and animal faecal pathogen contamination), caregiver hygiene and feeding practices, improved drinking water, other WASH facilities and use, wastewater use and irrigation. That WASH must act in consideration of other factors which bear equal importance for optimal child growth and development during the first thousand days (nutrition security, improved nutrition quality and quantity and sustainable agriculture – that is, SDG 2) means WASH interventions must be more mindful of the surrounding environment and prevailing conditions. This, by nature, will require strong coordination, collaboration, and communication across the WASH and nutrition sectors, a task of some considerable (but not impossible) effort if the SDGs are to be achieved. Given the number, breadth, and ambition of the proposed SDGs to which child growth and development, and thus both nutrition, WASH and animal husbandry interventions relate, it seems a decisive time for a multi-sector approach – and indeed a baby-focused approach – for more inspired, creative action to prevent growth failure worldwide. This sort of multi-sector approach might benefit from a 'nexus' approach which serves to highlight 'strong linkages among sectors, scales and regions and the potential need to be aware of trade-offs and to seek synergies when solving major problems'[137] and is fitting for integrated SDG implementation. Critical to this is the willingness and cooperation of policymakers, governments, and stakeholders to ensure interventions are timely, supported and sustained.

## 2.9 Author contributions

AP, PH and CG had substantial roles in the development of the review question. SB principally wrote the manuscript. AP, PH and CG assisted in assessing the paper quality and contributed to the writing and review of the manuscript.

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## 2.11 Declaration of interest

CG is employed by People In Need, who work within the water, sanitation, and nutrition sectors across the developing world. All other authors have no conflict of interests related to this manuscript.

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# 3 Fieldwork phase 1: Do domestic animals contribute to bacterial contamination of infant transmission pathways? Formative evidence from Ethiopia

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## 3.1 Abstract

*Child stunting is commonly observed in regions with poor WASH. WASH interventions, however, have shown little effect on growth, and recent research suggests that bacterial contamination of hands and floors from domestic animals and their faeces, and infant ingestion via normal hand-to-mouth behaviours, may explain this. This small formative study used microbial testing and survey and observational data to characterise principal infant bacterial transmission pathways in the home, considering WASH facilities, infant behaviours, and animal husbandry. Twenty infants were visited in their home in rural Ethiopia. Microbial swabbing showed common contamination of hands and floor surfaces with thermotolerant coliform (TTC) bacteria. Animal husbandry practices, such as keeping animals inside, was significantly correlated ($p<0.005$). There was no evidence that WASH 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 is an important source of domestic bacterial contamination. Interventions aiming to reduce pathogen transmission to infants must think beyond*

*improving WASH and consider contextual animal husbandry practices and the need to separate infants and animals in the home. Interventions can determine whether this reduces infant infection and improves linear growth.*

## 3.2 Introduction

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[1] and remains a key public health issue, both in terms of infant morbidity and mortality and in loss to national economic productivity.[2,3] Defining the precise causes of stunting remains elusive. Whilst an inadequately diverse and nutrient-dense diet likely affect growth outcomes[3] (see **Figure 5**), supplementary and complementary feeding interventions may only improve stunting by a height-for- age z-score (HAZ) of around 0.7[4] – far from the average discrepancy of -2.0 in parts of sub-Saharan Africa.[5] Diarrhoeal incidence, another factor correlated with undernutrition,[6] also does not explain a large proportion of the stunting burden: it is estimated that eliminating diarrhoea within the first two years of life would increase length by a HAZ score of only 0.13.[7] 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 WASH, supporting an underlying role of exposure to pathogenic bacteria and infection[8,9]. Certain pathogenic strains which are widespread across low- and middle-income countries and which appear linked to stunted growth, include faecally-associated *Campylobacter*,[10–12] *Cryptosporidium*,[13,14] *Giardia*[15] and pathogenic *E. coli*.[16,17] Although not well described, increased prevalence of these enteropathogens in healthy infants is associated with growth faltering,[18,19] even in the absence of other clinical insults like diarrhoea.[20-22] 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.[23] 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’– proposed some 60 years ago as an important map of causes of enteric infection.[24] Fundamental to WASH research and programming, the diagram underpins WASH interventions to prevent infectious disease via both primary barriers (sanitation facilities and handwashing with soap after defecation) and secondary barriers (water treatment and handwashing at key points; safe food preparation), which should block pathogen transmission. However, several recent, large trials which have assessed the effect of either an individual component or an individual plus combined components of water, sanitation and hygiene across different study arms have demonstrated little impact on infant health, or a significant reduction in environmental faecal or pathogenic contamination.[25–29] This remained the case even in combination with a nutrition program. Following largely insignificant results across the different study designs and settings, researchers have concluded that such interventions, whilst necessary, were perhaps not sufficient in coverage to show noteworthy improvements in growth.[30] Perhaps more importantly, these trials may have neglected to address in particular the main pathogen transmission pathways specific to infants, having not considered the age-related behaviours which alter infection risks – as well as sources of faecal contamination other than human.

### 3.2.1 WASH interventions and infant-specific behaviours and risks

Whilst WASH interventions aiming to improve infant nutritional status have traditionally focused on improving latrine facilities, communal and household water supply and adult hygiene practices,[31] for infants different needs and behaviours create additional exposure to pathogens.[17,32] 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.[33,34] This risk is higher across low- income countries where, whilst crawling and playing, infants may come into contact with contaminated soil, faeces and enteric pathogens which are brought inside the home.[17,35] Faecal indicator bacteria and associated pathogens have been detected in soil[36] and hand-to-mouth contact appears to result in significantly higher faecal intake in infants than consumption of stored water.[37] Whilst direct ingestion of faeces is more rare, infants frequently place soil in their mouth or put their hands in their mouths after touching soil,[34,38,39] meaning hand recontamination is likely. Both direct and indirect consumption are associated with diarrhoea, markers of infection and inflammation and growth failure in infants.[40,41] Whilst pathogenic bacteria of both human and animal origin can cause diarrhoea, even with improvements in sanitation these associations remain,[42] suggesting other external sources of faecal contamination not illustrated in the original F-diagram and considered in WASH interventions.

In lower-income countries domestic animals – usually livestock and poultry – are often not contained or separated from the household environment[43] and animal faecal contamination appears widespread across the home. Recently studies using molecular techniques have shown animal faecal markers in soil from the outside yard, household floor and infant hands,[35,44] and animal presence has been associated with higher levels of contamination from enteric pathogens across multiple pathways, including of soil[42] and contaminated food.[39] Both quantitative molecular techniques[37] and microbial source tracking[39,43] have shown a high burden of contamination from zoonotic and other enteric pathogens in living areas, particularly of hands and soil, which appears more prevalent than human contamination.[43] However, interventions underpinned by the F-diagram have largely focused on removing human faeces, with few objectives to remove animal faeces or reduce exposure. Such interventions that are limited in scope may miss the burden of animal faecal contamination as a critical risk factor, alongside not acknowledging the transmission pathways particular to infants, like contaminated hands and soil. This is of importance given the differing pathogens present in animal faeces that cause enteric infection and present different risks to health. Considering the high prevalence of animal faeces and contamination of related enteric pathogens and/or other pathogenic organisms around the home,[17,45–47] the behaviours which expose infants to faeces and the associations with lower HAZ scores,[46,48,49] animal faecal contamination of the domestic environment is an issue particularly significant to infants 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 infant health outcomes. **Figure 7** illustrates the contribution of animal faeces to contamination from enteric pathogens within the home and the integral relationship with infant behaviours and microbial ingestion.

### 3.3 Study aims

It follows that an improved understanding of the key sources of contamination and principal faecal-oral transmission pathways to infants 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.[33] In order to inform a larger trial intending to address pathogen transmission to infants, this small formative study sought to: i) quantify thermotolerant 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 iii) to understand if and how these environmental transmission pathways within the home influence and impact one another through cross-contamination.

## 3.4 Study methodology

### 3.4.1 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. Whilst 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.[50] 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 Sidama zone, Southern Nations, Nationalities, and Peoples' (SNNPR) region, Ethiopia as the geographical outreach area of the non-governmental organisation People In Need (PIN). 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, sixteen kebeles (neighbourhoods) were grouped into peri-urban (n=6) or rural (n=10). A simple random sampling method was used, whereby kebeles within the PIN intervention area were listed, given a number, and using a lottery method, eight kebeles were selected at random. From these eight kebeles, twenty households which included an infant aged twelve to twenty-four months old and not engaged in any other research with PIN 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.

### 3.4.2 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 frequency of loose or watery stools over the past seven days and subsequently applied World Health Organisation criteria).[51] This was administered alongside a one-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 mouthed or touched by the infant, where mouthing 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 under-emphasised key pathogen transmission pathways in infants. As illustrated in **Figure 7**, a 'modified F-diagram' describes additional key pathways specific to infants – namely geophagy and direct faecal ingestion. After entering 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 one-hour observation period of the infant. This included mouthing 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. These observations were captured using a similar semi-structured tool used by another team conducting similar research.[17] This helped avoid subjectivity bias in recording. Survey data were re-checked and cross-checked daily to maintain consistency in data collection. Any obvious errors or inconsistencies were discussed and households were revisited when necessary.

### 3.4.3 Microbiological analysis

Microbial samples were collected during the same visit as the survey in order to minimise social desirability bias and changes in behaviour. Following the survey and observation period, swabs were taken of infant and caregiver hands. If an infant was playing with a potentially contaminated item (described as a vector), this too was also sampled. Further, a weighed sample of floor material (soil, dirt) within crawling reach of the infant was also collected from eighteen households. Nineteen of twenty households did not have hands sampled due to one baby asleep in the caregivers' arms during the observation period. For each sample approximately 1.0 g (weighed to the nearest .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. Faeces were observed within the homes but were not sampled. Hand swabs and vector swabs used a similar methodology as described by Ngure et al[17] 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 six hours. All samples were analysed for TTC counts with a DelAgua single incubator using the water filtration method.[52] 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 sixteen to eighteen hours at 44°C. In total, 83 samples were collected from 20 households. 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 (1/83) was found to be contaminated during sample processing. At this point it should be re-emphasised that this methodology could not distinguish between TTC of human or animal origin.

### 3.4.4 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, US) 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, US). 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. It should be noted here that where the study was not powered to estimate significance, p-values should be interpreted with that in mind. Confidence intervals provide direction of effect of the data but do not necessarily include the 'true' value.

### 3.4.5 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 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 was 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).

## 3.5 Results

### 3.5.1 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). 70% 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 animals were mostly uncontained. 100% 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-hour period; across these infants, the reported mean duration of a diarrhoeal episode was 3.3 days. **Table 2** illustrates these findings along with general hygiene characteristics of the infant's environment.

Table 2. General characteristics of the home environment and specific hygiene characteristics.

| **Characteristic (survey)** | **n (N=20)** | **%** |
|---|---|---|
| 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 defecation | 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)** | **n (N=20)** | **%** |
| 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 |

*Calculated from the number of infants who were visibly dirty by at least one characteristic (see table S2).

### 3.5.2 General hygiene characteristics

Nineteen infant-caregiver pairs were observed for 20 hours during the infant observation period which also detailed general hygiene characteristics. These are detailed in **Table 2**. 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.

### 3.5.3 Infant observation period results

**Table 3** details the key vectors which were touched or mouthed by the infant during the observation period. Infants were frequently observed to mouth their own hands a mean of 31 times over one hour, or to mouth those of their caregiver (mean of 21 times over one hour), which in most 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 was directly ingested by two infants, and floor surface material was also picked up and directly entered the infants' mouths on seven occasions.

Table 3. Vectors identified during hand-to-mouth episodes throughout the infant observation period.

| **Key vector** | **Hand-to-mouth instances (N=20)** | **Visibly dirty** |
|---|---|---|
| | n | % |
| Hand-to-mouth contact (all objects) | 95 | - |
| Hands (own) | 31 | 90 |
| Hands (caregivers) | 21 | 86 |
| Domestic floor area | 7 | 100 |
| Faeces | 2 | 100 |
| Canvas mat | 3 | 100 |
| Jerry can | 5 | 100 |
| Food* | 2 | 100 |
| Plastic bottle | 10 | 80 |
| Plastic shoe | 2 | 100 |
| Table edge | 2 | 100 |
| Metal spoon | 2 | 100 |
| Wooden necklace | 3 | 100 |
| Cardboard carton | 3 | 0 |
| Soap packet | 2 | 0 |

### 3.5.4 Microbiological data

In total, 83 samples were collected from 20 households. 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 3**).

The relationship between key vectors and transmission pathways, as measured by microbial testing, are presented in **Figure 8.** 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, indicates that levels of TTC were much greater in households that 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 8**, graphs 6A [$p<0.005$] and B [$p<0.005$]), and floor surface TTC CFU count was also higher in these households (**Figure 8**, $p=0.006$). Similarly, graphs 6A, B and C show CFU animals living inside during the day was 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 (, graphs 6A [$p=0.57$] and B [$p=0.38$]); nor for floor surface (graphs 6C [$p=0.68$]). A similar observation can be made for whether the household owned a latrine (yes) or openly defecated (no) (graphs 6A, B and C), where owning a latrine was not related to a reduced hand CFU count for infant or caregiver ($p=0.76$ and 0.86 respectively) nor for floor surface samples ($p=0.36$).

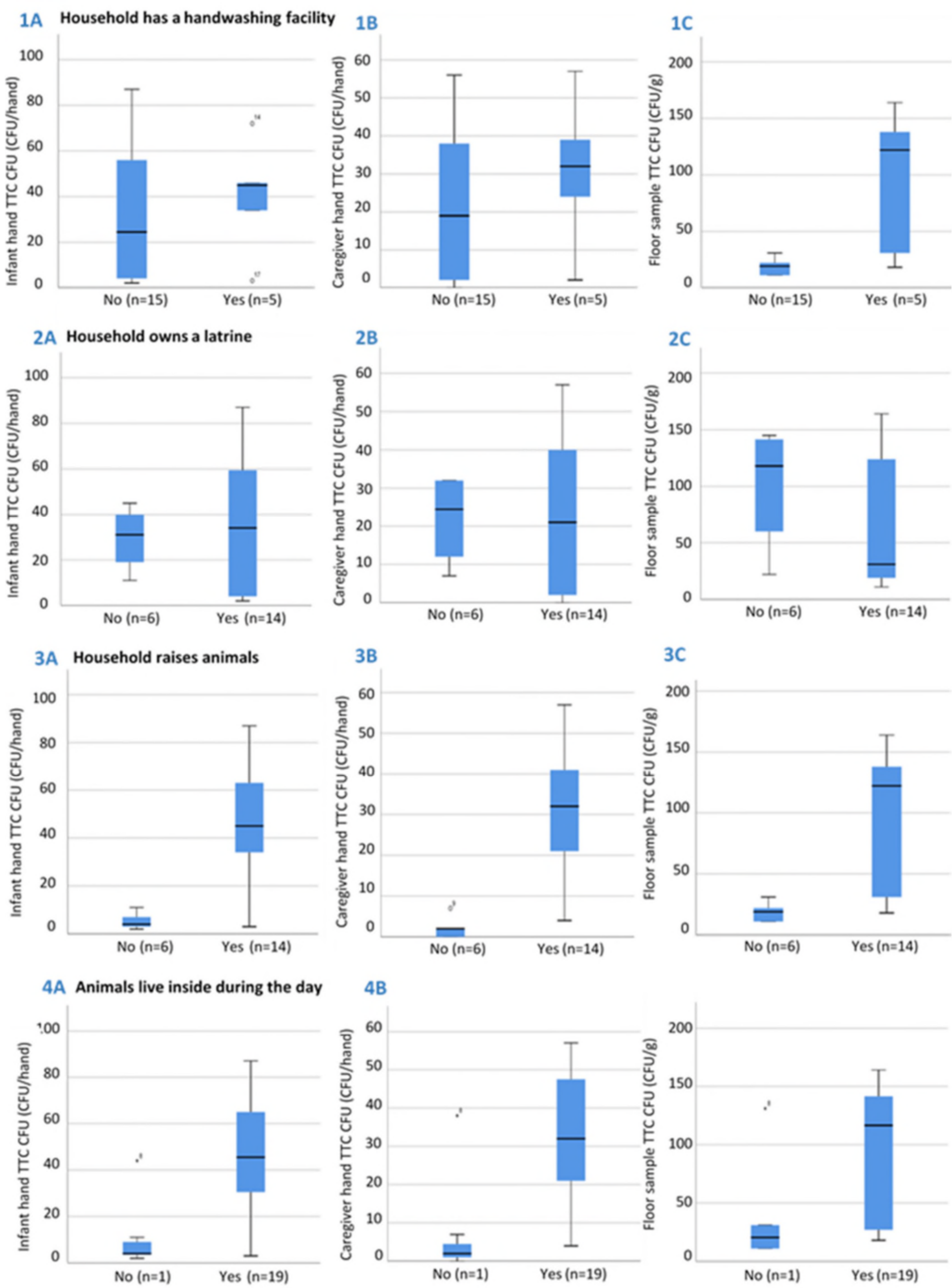


Figure 8. Association between infant and caregiver hand and floor surface sample TTC CFU count with specific household hygiene characteristics.

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 (Y) (n=16) or openly defecated (N) (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 2C) floor surface sample (p=0.006); 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).

**Table 4** shows the paired t-test results which was run to assess any statistically significant mean differences between CFU counts on hands and floor samples and key exposure pathways. Again, owning a latrine was not related to higher hand CFU count for infant or caregiver (p=0.76 and 0.86 respectively) nor for floor surface samples (p=0.36). This also held true for owning a handwashing facility. Interestingly owning a handwashing facility was correlated with slightly lower CFU count for caregivers but least so for the floor surface sample (p=0.38 and 0.68 respectively), suggesting floor contamination is less influenced by household sanitation. Again, whether the household raised animals and if animals lived inside during the day were significantly related to an increase in CFU count on both hands and floor surface samples, supporting the possibility that faecal contamination is increased due to the presence of animals within the household environment.

Table 4. Paired T-test assessing the relationship between infant and caregiver hand and floor surface sample CFU count and specific hygiene characteristics.

| | **Infant hand CFU** | **Caregiver hand CFU** | **Floor sample CFU** |
|---|---|---|---|
| | Sig.* (95% CI) | | |
| Household raises animals | <0.005 (-61.10−-21.02) | <0.005 (-45.59−-17.15) | 0.006 (-113.25−-26.34) |
| Household has a handwashing facility | 0.57 (-40.05−23.12) | 0.38 (-32.82−13.38) | 0.68 (-82.8−55.77) |
| Household openly defecates (Y) or owns a latrine (N) | 0.76 (-37.78−28.25) | 0.86 (-26.49−22.36) | 0.36 (-40.32−102.68) |
| Animals live inside during the day | <0.005* (-56.90−-14.51) | <0.005 (-41.74−-10.02) | 0.04 (-115.31−-1.69) |

*Significant at p<0.005.

### 3.6 Unpublished data

Further data presented in this chapter was not included in the published paper but offers meaningful contributions to the hypothesis. Firstly, **Table 5** presents the TTC counts for hands, vectors, and floor surface samples taken from households during the fieldwork using membrane filtration (N=83). As expected, soil taken from the kitchen floor was the most contaminated vector of all samples taken during microbial testing with a mean CFU/g of 76.5. The high counts in soil may reflect the common presence of animals inside the house as well as the common occurrence of faeces within the domestic environment (**Table 2**). This is of particular concern given the soil was collected within crawling reach of the infant and was observed to enter the infants' mouths as well as contaminate their hands. Infants hands were more commonly contaminated than those of their caretakers (mean TTC CFU count 33.3 versus 23.6), the latter of which had two negative samples. This is unsurprising in a context where hygiene conditions were generally poor and most households lacked a separate handwashing facility (**Table 2.**). The CFU counts captured in this study are relatively similar in comparison to other studies with similar methodologies[17,53] and the high count on hands is unsurprising given the general unsanitary level of the domestic environment.

Table 5. Overall mean and number of samples in each category of thermotolerant coliform count by vector.

| Key vector | Number of samples (N=83) | TTC | | | |
|---|---|---|---|---|---|
| | | CFU count per category | | | |
| | (n) | Mean* | Range | <100 | ≥100 |
| Hands (infant) | 19 | 33.3 | 2−87 | 19 | 0 |
| Hands (caretakers) | 19 | 23.6 | 0−57 | 19 | 0 |
| Soil | 18 | 76.5 | 11−164 | 10 | 8 |
| Canvas mat | 1 | 23.0 | - | 1 | 0 |
| Jerry can | 6 | 9.2 | 1−19 | 6 | 0 |
| Food* | 2 | 2.0 | - | 2 | 0 |
| Plastic bottle | 7 | 5.6 | 3−8 | 7 | 0 |
| Plastic shoe | 1 | 11.0 | - | 1 | 0 |
| Table edge | 6 | 3.2 | 2−5 | 6 | 0 |
| Metal spoon | 1 | 9.0 | - | 1 | 0 |
| Wooden necklace | 1 | 11.0 | - | 1 | 0 |
| Cardboard carton | 1 | 3.0 | - | 1 | 0 |
| Soap packet | 1 | 1.0 | - | 1 | 0 |

TTC, thermotolerant coliform; CFU, colony forming unit.
*Mean counts are geometric means CFU/mL or CFU/g.

Secondly, a Pearson product-moment correlation was run to assess the strength of a linear association between key vectors in the study (infant hands, caretaker hands and floor surface samples). The closer the correlation coefficient (*‘r’*) to +1 or -1, the closer the clustering around the line of best fit and a stronger association. Values are shown in **Table 6**. Two observations are notable. Firstly, that contamination of infant and caregiver hands correlate and secondly, that floor contamination correlates with both. The correlation does not consider whether a variable was classified as dependent or independent and thus correlation is observed without explaining the direction of association. It also does not mean a dose-dependent response between vectors. However, levels of faecal contamination do appear to correlate across these key transmission pathways (or vectors). The high intra-vector significance reinforces the significance of cross-contamination. Considering the results from the paired T-test (**Table 5**), this might support the theory that the presence of domestic animals may constitute a major source of transmission.

Table 6. Pearson product-moment correlation between infant and caregiver hand and soil thermotolerant coliform counts.

| **Vector TTC CFU count** | **Caregiver hand TTC CFU count** | | |
|---|---|---|---|
| | Pearson correlation *(r)* | Sig. | Number of infant-caregiver pairs (n) |
| Infant hands | .952* | .000 | 19 |
| | **Floor sample TTC CFU count** | | |
| | Pearson correlation *(r)* | Sig. | Number (n) |
| Caregiver hands | .875* | .000 | 18 |
| Infant hands | .801* | .000 | 18 |
| CFU, colony forming unit; TTC, thermotolerant coliform; Sig, significance.<br>*Correlation is significant at the 0.01 level (2-tailed). | | | |

### 3.7 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,[54] 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. 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 with enteric pathogens or other pathogenic organisms. This is also backed up by broader studies.[35,39,55,56] 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. Related to this is the issue of seasonality. The study was cross-sectional and not able to take seasonality into account but which can profoundly affect TTC count with water quality usually deteriorating in the rainy season. Other quality screening tool to assess moderate and high levels of faecal contamination might be more appropriate given this, such as tryptophan-like fluorescence.[57] This would also address limitations regarding transport, storage, laboratory preparation and incubation of samples.[57] Lastly, this study only provides part of the picture of total infection risks to infants. Whilst hands and floors are key transmission pathways, contaminated food[39] and water[56] also constitute important pathways, of which we did not measure contamination. A broader study that seeks to quantify each of these pathways and assesses additive effects would be a productive route for extending this research.

### 3.8 Discussion

This formative study found faecal contamination as measured by TTCs 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.[58] Contamination of caregiver and infant hands and domestic floor surface samples with TTCs suggest infants 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 infant hands themselves became vectors for transmission of faecal microbes, corroborating research found in similar settings.[17,38,39,59] In this study, 35% of infants directly ingested soil over the one-hour 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 five-hour observation.[60] In another study in rural Ghana, 28% of children aged 6−36 months reportedly ingested soil a median of 14 times in the past week.[38] Ingestion of floor surface materials by infants is of concern giving the growing number of studies linking ingestion with negative health outcomes such as diarrhoea[41,61] enteric dysfunction and linear growth failure.[40]

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 $\log_{10}$ CFU/g in soil (per dry gram) and a mean 1.52 $\log_{10}$ CFU/hand before handwashing.[54] An earlier study in a Tanzanian community with improved, non-networked water supplies found a mean E. coli count of 3.1 $\log_{10}$ CFU, but over two hands.[53] 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 and related pathogens[45,59] and animal presence is associated with high levels of contamination from related enteric pathogens across multiple pathways.[58,63,64] These results suggest faecal contamination of different transmission pathways is related, with presence of animal faeces as the common contamination factor – supported by this study by the strong difference in CFU count in households with animals (**Figure 6**). 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,[38] 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.[54] In this study poultry were likely a key factor in contamination levels due to their common presence in the home – of concern given demonstrated associations between poultry faeces, diarrhoea[10,61] and poor growth.[65]

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, whilst households with fewer contaminated toys and objects were those with high latrine coverage and WASH infrastructure,[66] the absence of animals was highlighted as a possible noteworthy factor to low levels of contamination from faecal bacteria and pathogenic organisms. In this study it is possible latrines were not being used and open defecation was practiced, although 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 of contamination, transmission and infection will not decrease.[67,68] Studies have shown that even after handwashing, E. coli count on hands, possibly from human and animal contamination of dirt and sand,[36,69] can increase 2-3 $\log_{10}$ CFU within minutes of resuming normal activity.[70,71] Furthermore, Barnes et al 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.[56] 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 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.[39] Ercumen et al found significantly higher levels of E. coli in food in compounds where animals lived – primarily increased by the presence of poultry.[42] It therefore stands to reason that if other external sources of contamination from animals are not considered, all pathways will remain contaminated and transmission of enteric pathogenic or other pathogenic organisms 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 socioeconomic 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.[71] An analysis of cross-sectional datasets from Ethiopia, Kenya and Uganda found a negligible beneficial effect of household livestock ownership on child stunting prevalence.[72] In another study in Kenya, greater household livestock ownership at baseline was not related to baseline infant HAZ score.[73] What seems apparent is that whilst 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 proximity of livestock may be of detriment to the health of infants. This research advocates that further research within the WASH field should consider animal husbandry practices and work more closely with i) 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,[42] Zimbabwe,[17] Peru[45] and Zambia[59] poultry were 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.[17,59,61] Due to their mobility and the difficulty with which their faeces are noticed, small animals like poultry may pose a greater risk to infants.

### 3.9 Conclusion

Although the evidence presented here is of a small sample, results support the growing body of evidence of which suggests WASH interventions must address animal faecal contamination across the domestic environment: a 'total environmental hygiene' approach which fully addresses multiple sources of contamination and increased prevalence of pathogenic bacteria and other pathogenic organisms. 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. Like another recent study,[34] this study did not observe human faeces within the home and suggests faecal contamination from animals and related zoonotic pathogens 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 from zoonotic enteric pathogens and others 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 infants 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 infants. Similarly, if interventions targeted towards infants are predicated on health grounds, effects may be limited when animals share household space. Whilst 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 policy makers to better understand the contribution of specific risk factors and transmission pathways within the home and in the allocation of resources to infant-focused WASH interventions that aim to improve growth.

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## 3.11 Author contributions

AP, PH and CG held a role in the development of the research question. SB principally wrote the manuscript, designed, and ran the fieldwork and study analysis. AP, PH, CG and ST assisted in assessing the paper quality and contributed to the writing and review of the manuscript. TT and MG managed field teams, logistics and data collection in Ethiopia.

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## 3.13 Declaration of interests

All authors have no competing interests to declare.

## 3.14 Data access

Data is available from the lead author upon request.

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## 3.16 Supplementary information

**S1. Questionnaire 1. Latrine facilities, handwashing practices, animal husbandry, diarrhoea incidence**

The following questionnaire addresses mothers or caretakers of children under two in the household.
- Fill in the details at the top of the form
- Go through each question with the caretaker
- Circle according to the response. Make sure all information is filled in correctly.

Date of interview (dd/mm/yyyy): _ _/_ _/_ _ _ _

Time of interview (24-hour): _ _/_ _

Fieldworker initials: _ _ _

Researcher (signature): ___________________

| | | | |
|---|---|---|---|
| **Infant ID** | Number: | | |
| | Letter: | | |
| **Infant sex** | Sex: | Male | |
| **Date of birth** | Month: | | Don’t know |
| | Year: | | Don’t know |
| | Age: | _ _ year(s) _ _month(s) | Don’t know |

A. Latrine facilities

| | |
|---|---|
| ***Where do you and your family members defecate?*** | Defecate in the open |
| | Pit latrine without slab |
| | Pit latrine with slab |
| | Use ventilated improved pit latrine |
| | Use flush or pour toilet (connected to a sewer system or septic tank) |
| | Use composting toilet |
| | Other (specify): |
| | No response |
| Can you please show me the latrine? | Latrine was shown |
| | Latrine was not shown *(skip next question)* |
| For data collector: *Does the latrine show visible signs of being used?* | Latrine is likely used |
| | Latrine is likely not used |

B. Handwashing practices

| | |
|---|---|
| **Can you please show me where you wash your hands?** | Area was shown |
| | Area was not shown *(skip next question)* |
| **For data collector:** *Does the area show visible signs of being used?* | Handwashing is likely |
| | Handwashing is not likely |

C. Animal husbandry and keeping practices

| | |
|---|---|
| ***Do you raise any animals?*** | Yes |
| | No |
| ***If yes, which?*** | Cattle |
| | Goats |
| | Donkey |
| | Sheep |
| | Chickens |
| ***Where do the animals live during the day?*** | Outside, enclosed in an area |
| | Outside, roaming free |
| | Inside in the same room as the family |
| | Inside in a separate room to the family |
| | Other: |
| ***Where do the animals sleep during the night?*** | Outside, enclosed in an area |
| | Outside, roaming free |
| | Inside in the same room as the family |
| | Inside in a separate room to the family |
| | Other: |

D. Diarrhoea incidence

*'Now I would like to find out about if your child has recently had diarrhoea.'*

| | | |
|---|---|---|
| ***In the last 7 days, has your child had diarrhoea? (3 or more watery/loose stools in one day)*** | Yes<br>No | Don't know |
| ***How many days has this happened?*** | _ _ days | Don't know |
| ***Was your child sick (vomiting) at the same time as the diarrhoea?*** | Yes<br>No | Don't know |

**S2. Infant observation period; semi-structured tool**

| | | |
|---|---|---|
| **Infant ID** | *Number:* | |
| | *Letter:* | |

| Time of observation period (24-hour): | *00:00 – 00:00* | _ _:_ _ – _ _:_ _ | | | |
|---|---|---|---|---|---|
| **Object/surface** | **Touched** | **Mouthed** | **Visibly dirty? (Y/N)** | **Total count** | **Sample collected (Y/N)** |
| **Soil** | | | | | |
| **Food** | | | | | |
| **Faeces (Human)** | | | | | *n/a* |
| **Faeces (Animal)** | | | | | *n/a* |
| **Toy** | | | | | |
| **Spoon or utensil** | | | | | |
| **Other (specify)** | | | | | |
| **Infant hygiene** | | | | | |
| **Feature / item** | **Visibily dirty (y/n)*** (Note stains) | **Type of dirt (soil, food, faeces)** | | | |
| **Hands**** | | | | | |
| **Fingernails** | | | | | |
| **Face** | | | | | |
| **Arms** | | | | | |
| **Legs** | | | | | |
| **Clothes (note if naked)** | | | | | |
| **Bottom or diapers** | | | | | |

*Data collectors and the researcher discussed assessing whether the infant was visibly dirty. This included looking for visible dirt and soil and/or other marks from faeces or food. Stains were also noted.
**Visibly dirty hands included checking for visible dirt on palms and under nails.

# 4 Fieldwork phase 2: Risk factors and transmission pathways associated with infant *Campylobacter* spp. prevalence and malnutrition: A formative study in rural Ethiopia

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## 4.1 Abstract

*Early infection from enteropathogens is recognised as both a cause and effect of infant malnutrition. Specifically, evidence demonstrates associations between growth shortfalls and* Campylobacter *infection, endemic across low-income settings, with poultry a major source. Whilst improvements in WASH should reduce pathogen transmission, interventions show inconsistent effects on infant health. This cross- sectional, formative study aimed to understand relationships between infant* Campylobacter *prevalence, malnutrition, and associated risk factors, including domestic animal husbandry practices, in rural Ethiopia. Thirty-five households were visited in Sidama zone, Southern Nations, Nationalities and*

Peoples’ region. Infant and poultry faeces and domestic floor surfaces (total = 102) were analysed for presumptive Campylobacter spp. using selective culture. Infant anthropometry and diarrhoeal prevalence, WASH facilities and animal husbandry data were collected. Of the infants, 14.3% were wasted, 31.4% stunted and 31.4% had recent diarrhoea. Presumptive Campylobacter spp. was isolated from 48.6% of infant, 68.6% of poultry and 65.6% of floor surface samples. Compared to non-wasted infants, wasted infants had an increased odds ratio (OR) of 1.41 for a Campylobacter-positive stool and 1.81 for diarrhoea. Positive infant stools showed a significant relationship with wasting ($p = 0.026$) but not stunting. Significant risk factors for a positive stool included keeping animals inside ($p = 0.027$, OR 3.5), owning cattle ($p = 0.018$, OR 6.5) and positive poultry faeces ($p<0.001$, OR 1.34). Positive floor samples showed a significant correlation with positive infant ($p = 0.023$), and positive poultry ($p = 0.013$, OR 2.68) stools. Ownership of improved WASH facilities was not correlated with lower odds of positive stools. This formative study shows a high prevalence of infants positive for Campylobacter in households with free-range animals. Findings reaffirm contaminated floors as an important pathway to infant pathogen ingestion and suggest that simply upgrading household WASH facilities will not reduce infection without addressing the burden of contamination of zoonotic pathogens from animals, alongside adequate separation in the home.

## 4.2 Introduction

### 4.2.1 Infant growth, infection, and animal exposure

Enteropathogen infection and associated diarrhoea in infancy and the relationship with linear growth failure (stunting) is a dynamic area of research in infant malnutrition. Whilst child deaths from diarrhoea dropped by over half in just 15 years between 2000−2015,[1] diarrhoeal episodes have not similarly decreased[2] suggesting a need for better measures to detect and prevent infection. Early diarrhoea and diarrhoea-related sequelae hold both acute and chronic consequences. Whilst good evidence indicates that a heavy early diarrhoeal burden does affect growth and worsen nutritional status,[3−5] there is debate about its relative contribution to long-term growth faltering.[6,7] Other direct, biological causes under study include environmental enteric dysfunction (EED): a condition characterised by the disturbance of gut immunity, structure, and function, which ultimately impairs nutrient absorption and linear growth – even without diarrhoea.[8−10] Nonetheless, the common underlying factor to these different contributors is early exposure to pathogenic bacteria and repeated infection.[11,12] As such it is increasingly evident that stunting will not be resolved by improved nutritional intake or acute rehabilitation alone[13] but with parallel improvements in water quality, WASH which act as barriers to infection.

Recent cluster RCTs have sought to investigate the effect of improved WASH, alone and in combination with nutrition supplementation, on child health. However different study designs and settings have for the most part failed to show consistent evidence for a reduction in diarrhoea or improvements in malnutrition indicators.[14–19] One possibility is that despite thorough design, interventions mainly focused on containing human excreta and did not consider (and conventionally have not considered) the role of animal faeces in domestic contamination from zoonotic pathogens and illness[20]: surprising given over 60% of infectious diseases in humans are caused by zoonotic pathogens.[21] Transmission pathways are not mutually exclusive, and inadequate separation of animals from the home environment may inevitably result in faecal-oral transmission through direct contact with animal faeces or contaminated soil, or the contamination of hands by faecal pathogens, food, objects or water sources.[22–24] Infants are also vulnerable to transmission routes specific to age-related behaviours, including contaminated floors, where they crawl and directly or indirectly ingest faecal material.[25–27] As such, animal faecal contamination of the home with related enteric pathogens and other pathogenic organisms is a neglected factor potentially contributing to infection, diarrhoea and linear growth failure.

### 4.2.2 Infant *Campylobacter* infection and transmission

Previous studies have sought to understand the disease burden attributed to animal faeces which acts as a transmission vector via the faecal-oral pathway.[20–22] Key zoonotic pathogens related to infant infection, growth failure and EED include G*iardia,*[28,29] *enteroaggregative* and *enteropathogenic E.coli,*[28–30] *Shigella*[31,32] and *Cryptosporidium*[33,34] which are transmitted across multiple pathways within the home and ingested through normal infant hand-to-mouth behaviour.[25,35] Among those pathogens of highest concern, *Campylobacter* consistently emerges as one of the key contributors to diarrhoea and malnutrition[31–33] and EED.[29] One of the most widespread infectious diseases, Campylobacteriosis is endemic across lower-income countries, especially in children[36] – responsible for 30,931 diarrhoeal-related deaths in 2015.[37] The infectious dose for Campylobacteriosis is low compared to other bacterial infections, with reported minimum values of around 500 CFU leading to infection in adults[38,39]: this value may also be lower for infants where immune systems are immature. Infection is acute and generally self-limiting: however, while mean excretion is reported at around seven days,36 the bacteria has been isolated from faeces up to two weeks following infection.[40,41] Prolonged excretion may enhance transmission and incidence[42] and where it also affects the epithelial barrier[43] may contribute to gut mucosal damage and other EED-like abnormalities.[44]

Large studies across many different low-income settings have attributed both asymptomatic and symptomatic *Campylobacter* infection with shorter length attainment of up to one centimetre[31,44] and with changes in EED clinical markers.[43,45] Thermophilic *C. jejuni* (~90%) and *C. coli* are the most commonly isolated *Campylobacter* species in diarrhoeal disease,[46] and as part of the normal intestinal flora of birds, poultry represents one of the major sources of transmission, contamination and infection.[47] An essential component of livelihoods and nutrition security, poultry ownership – particularly chickens – is ubiquitous across many low-income nations.[48] Largely free-ranging and dependent on scavenging, chickens frequently openly defecate inside the home and so infants are frequently exposed to, and often consume, chicken faeces and/or contaminated floor surface material during crawling or play.[26,49,50] As domestic floors are usually made of compacted soil, detection and removal of small poultry faeces is difficult and so Campylobacteriosis risk in crawling infants is high. Beyond six months of age critical developmental stages of weaning and crawling mean infection risk increases,[51] with obvious implications for short- and long-term growth and development. However, the evidence base describing the links between domestic animal ownership (particularly chickens), WASH facilities and use and infant nutritional status is limited to a few observational studies,[26,52–55] which have not consistently measured *Campylobacter* carriage and/or infection. There is insufficient evidence to fully describe the extent to which infection is caused by exposure to domestic animals in low- and middle-income countries, and furthermore, if infant nutritional status affects whether infection is clinical or subclinical.

### 4.3 Study aims

In Ethiopia, despite substantial recent reductions, linear growth failure affected more than a third of infants in 2016.[56] Ethiopia has one of the highest domestic animal densities per $km^2$ worldwide[57] and poultry are ubiquitous in rural households. Some research in Ethiopia has documented the proximity and exposure of infants to chickens and their faeces in regions[58] and the relationship with infant growth,[53] and a few regional studies have associated *Campylobacter* infection with infant diarrhoea and malnutrition.[59–61] However further research is required in Ethiopia on the epidemiology of infant *Campylobacter* prevalence and infant health outcomes and the relationship to poultry ownership and WASH facilities. Thus, there is a need for further research which describes *Campylobacter* prevalence in young infants and the relationship to animal ownership and health outcomes, whilst also considering household WASH facilities and use. Further data is also needed on infection and age-related transmission pathways, including domestic floors which are of high risk to this age group.[62–64] This small study aimed to provide formative evidence toward the prevailing hypothesis that infant health is negatively associated with stools positive for *Campylobacter* and exposure to domestic animals, whilst not mitigated by WASH facilities. It aimed to determine: i) Infant *Campylobacter* prevalence in a sample of rural, subsistence households in Sidama zone, Ethiopia with domestic animals ii) The relationship between both asymptomatic and symptomatic *Campylobacter* positive infants and anthropometric indices across households and iii) Risk factors and possible transmission pathways associated with infants positive for *Campylobacter*.

As this study was designed to provide formative evidence, a sample size calculation was not performed. Where this study is described as ‘formative research’ merits justification. Formative research is often conducted as part of the process of a larger study design and provides data for research teams to plan interventions or further data collection. Formative research is early phase data and is not powered to detect differences between groups. As such, this study results must be interpreted in this context, where it provided indicative data towards the hypothesis but was not sufficiently powered for conclusive evidence.[65]

## 4.4 Study methodologies

### 4.4.1 Country context and study sample

This small, formative study was conducted in SNNPR, Sidama zone (regional subdivision), Ethiopia, as the geographical outreach area of the non-governmental organisation People In Need. The study took part in the month of June 2019 – the start of the region’s rainy season. Two rural kebeles (neighbourhoods) were chosen from a woreda (zonal subdivision) which were accessible for data collection purposes, which were not included in the previous fieldwork and which remained representative of typical rural livelihoods across Sidama zone. A simple random sampling method was used to identify households fulfilling the eligibility criteria. Where in the previous study infants beyond 18 months were starting to walk and it was recognised their risk factors and exposure profile changes, infants in this study were included aged 10−18 months. Households were included which also owned free-range poultry. The random sample is described as follows. After communication with a government HEW local to each kebele, the team produced a sampling frame for both kebeles of all infants aged 10−18 months from households known by the HEW to own poultry. For both sampling frames, households were sequentially numbered on paper and using a simple lottery method 17 and 18 infants were randomly drawn from the two kebele frames respectively for a total sample of 35 infants. Households were visited on a single occasion.

### 4.4.2 Survey and anthropometry

Field team members who assisted during data collection were trained during a 2-day training programme on accurate survey data collection and anthropometry (one member was already trained in the latter). A survey previously validated in the region[50] (see S1 in Chapter 2) assessed latrine type and use, handwashing practices and soap availability, domestic animal ownership and husbandry practices and infant diarrhoeal prevalence and duration. To assess diarrhoea, caregivers were asked the frequency of loose or watery stools during the last day and over the past seven days. World Health Organisation (WHO) criteria was applied retrospectively, where diarrhoea is defined as at least three loose or watery stools within a 24-hour period.[66] Reported diarrhoea was later compared with the quality of stool samples, where all cases of reported diarrhoea matched visible diarrhoeal stool consistency. Presence and evidence of use of a working latrine and handwashing station were also validated by direct observation. After primary introductions with the caregivers and informed consent, a fieldworker completed the survey with translation from the HEW. Anthropometry measures were infant recumbent length (measured to the nearest 0.1 cm) and weight (measured to the nearest 100 g), taken by trained personnel following standard procedures[67] using a hanging Salter scale and a portable, fixed base length board. Survey and anthropometry data were re-checked and cross-checked each evening to maintain consistency in data collection. Any obvious errors or inconsistencies were discussed and households were revisited when necessary.

### 4.4.3 Sample collection and transport

A day prior to household visits, HEWs distributed sterile sample collection bags with a sterile scoop to households for faecal sample collection (Whirl-Pak® WPB01478WA, Sigma-Aldrich, UK). Caregivers were shown how to use the sterile scoop and seal the bags to minimise contamination and were requested to collect a fresh faecal sample from their poultry (inside the home) and infant as close as possible to sample collection within 24 hours. During the study visit a third sample was collected from the floor surface inside the home (households were not notified of this prior to the visit to avoid floors being cleaned prior to arrival). The infant's mother was asked to indicate the location the infant usually plays, and a researcher collected a sample of compacted floor surface (approximately 20 g) into another collection bag. All samples were transported in an insulated cool bag on ice to the laboratory at Hawassa University College of Medicine and Health Sciences within five hours. Upon arrival to the laboratory, samples were stored refrigerated (2−8°C) prior to analysis and plates were inoculated and incubated within two hours of arrival to the laboratory. Sample collection and transport methods echo similar methods in studies conducted in Ethiopia.[61] Thus each household sampling event (total=35) comprised three samples (poultry and infant faeces and floor surface). Due to damaged collection bags, three floor surface samples were discarded to give a total of 102 samples analysed for presumptive *Campylobacter* spp. Samples were numbered anonymously which linked the relevant household but removed all identifiers.

### 4.4.4 Isolation of *Campylobacter* spp.

Presumptive thermotolerant *Campylobacter* spp. was isolated from fresh faecal samples from poultry, infants, and floor surface samples. Methods were briefly as follows. Aseptic techniques were followed, and samples weighed using sterile disposable weighing boats to 1 ± 0.05 g wet weight. Samples were then aliquoted into sterile plastic centrifuge tubes containing 9 mL of prepared sterile peptone water and vortexed well. For poultry faecal samples only, 100 µL of sample was pipetted into sterile tubes containing 900 µL of peptone water to prepare a 10-fold serial dilution up to $10^5$ dilution. 100 µL of floor surface and infant faecal samples and poultry faecal sample dilutions of orders $10^1$, $10^3$ and $10^5$ were drop plated on pre-labelled plates and spread using disposable L-shaped spreaders. Blood-free chromogenic CHROMagar™ Campylobacter media (CHROMagar™, France) was used for the selective detection and differentiation of presumptive thermotolerant *Campylobacter*, prepared and used according to manufacturer instructions.[68] Inoculated plates dried under a laminar flow for approximately five minutes as per manufacturer instructions, inverted and stacked into anaerobic jars and incubated at 42°C for 48 hours under microaerophilic conditions. CampyGen™ 2.5 L sachets (Thermo Scientific™, UK) were used to obtain a hydrogen-free microaerophilic atmosphere of approximately 5% $O_2$, 10% $CO_2$ and 85% $N_2$, suitable for the growth of *Campylobacter* spp.

### 4.4.5 Identification of *Campylobacter* spp.

After 48 hours, presumptive *C. jejuni*, *C. coli* and *C. lari* appear on the chromogenic agar as intense red coloured colonies on a translucent base. Other non-target microorganisms are inhibited (i.e., small, blue colour or absent colonies[68]) and high specificity and sensitivity versus other media is well demonstrated.[69–71] Quality control and preparation of the medium was tested by isolating the ATCC® strain *C. jejuni* (33291) under representative conditions at Cranfield University prior to fieldwork. Blank samples with no growth confirmed no external contamination in all batches.

### 4.4.6 Ethics

At the start of each household visit, the study was introduced by the field team and HEW and informed consent was described to the caregiver in their first language of Amharic or Sidamo. Fieldworkers tested the caregivers' understanding of consent by asking them questions regarding the study and the consent process, and explained all data was anonymised. As most adult caregivers were illiterate, oral consent and assent for their infant was recorded. The survey was written in English, translated to Amharic by the field team and verbally translated into Sidamo by a HEW. The study protocol was approved by two institutional review boards: Cranfield University Research Ethics Committee (CURES/7774/2019) and Hawassa University College of Medicine and Health Sciences (IRB/222/11).

### 4.4.7 Statistical analysis

Analyses were performed at the household level. Plates were visually inspected for presumptive *Campylobacter* spp. and recorded as growth or non-growth and the prevalence (as percentage) of positive poultry, infants and floor surfaces was calculated. Whilst the presence of *Campylobacter* does not necessarily indicate active infection, for the purpose of analysis, samples with presumptive *Campylobacter* growth were classified as 'positive' or with no growth as 'negative'. Positive infant faecal samples were then described as symptomatic (the positive stool sample was diarrhoeal), or asymptomatic (the stool sample was not diarrhoeal). Z scores were calculated for length-for-age and weight-for-length (LAZ and WLZ respectively) using the WHO 2006 Child Growth Standards.[72] Z-scores were categorised into stunting and wasting using the standard cut-off value less than −2 standard deviations of the reference.[72] Anonymised household survey data were entered into Microsoft Excel, coded for descriptive analysis, and further analysed using SPSS (version 22.0, IBM, New York). Simple frequency distribution tests described survey response data, anthropometric data, and *Campylobacter* prevalence. Fisher's exact test for independence tested associations between variables for the small sample size (5% significance). Results with significant p-values from the Fisher's exact test reported odds ratio (OR) risk estimates with corresponding 95% confidence intervals (CI). As per the first phase of fieldwork, it should be noted here that where the study was not powered to estimate significance and p-values should be interpreted with that in mind. Confidence intervals provide direction of effect of the data but do not necessarily include the 'true' value.

## 4.5 Results

### 4.5.1 Survey and anthropometric data

Data were collected from all 35 households identified in the sampling frame. Results from the survey and anthropometric data are shown in **Table 7**. Average infant age was 15 months. Almost a third (31.4%) of infants had experienced diarrhoea within the past 7 days with an average duration of 3.1 days. Eighty-eight-point six percent of households owned a latrine, most of which were improved pit latrines with a slab (82.9%). Less than half (40.0%) of households had some form of handwashing facility available (including a simple basin and jug) and half (51.4%) owned soap. Aside from poultry ownership, cattle were the second most common form of animal husbandry (total=19, 54.3%). Regarding animal husbandry practices 97.1% of households reported that during the day their animals shared the same living space as the family, and 91.4% during the night. Mean WLZ score was -0.61 (range -2.14−0.64, SE 0.15) and mean LAZ score was -0.81 (range -2.53−0.94, SE 0.19). Overall, five infants (14.3%) were classified as wasted (WLZ <-2 SD), eleven (31.4%) as stunted (LAZ <-2 SD) and four infants both wasted and stunted (11.4%, WLZ and LAZ <-2 SD). Of those infants classified as wasted (total=5), all had experienced diarrhoea within the past seven days ($p<0.001$; OR 1.83, 95% CI 1.07−3.14). Diarrhoeal prevalence was not significantly related to stunting ($p=0.709$).

Table 7. Infant and household characteristics, animal husbandry practices and anthropometric indicators.

| Household characteristic | Count (N=35) | Average or percent of total |
|---|---|---|
| Infant sex | | |
| Male | 19 | 54.3% |
| Female | 16 | 45.7% |
| Average age (months) | | 15 |
| Diarrhoea during the last 7 days | 11 | 31.4% |
| Average duration of diarrhoea (days) | | 3.7 |
| Household owns a latrine | 31 | 88.6% |
| Household latrine type | | |
| Open defecation (no latrine) | 1 | 2.9% |
| Use neighbour's toilet (no latrine) | 3 | 8.6% |
| Pit latrine without slab | 2 | 5.7% |
| Pit latrine with slab | 29 | 82.9% |
| Household has a handwashing facility | 14 | 40.0% |
| Household has soap available | 18 | 51.4% |
| Household domestic livestock ownership | | |
| Chickens | 35 | 100% |
| Cattle | 19 | 54.3% |
| Goats | 11 | 31.4% |
| Donkey(s) | 2 | 5.7% |
| Livestock practices during the day: | | |
| Live outside | 35 | 100.0% |
| Live inside in the same room as the family | 34 | 97.1% |
| Live inside in a separate room to the family | 1 | 2.9% |
| Livestock practices during the night: | | |
| Live inside in the same room as the family | 32 | 91.4% |
| Live inside in a separate room to the family | 3 | 8.6% |
| **Nutrition indicator** | **Count (N=35)** | **Percent of total** |
| WLZ | | |
| -2 to -3 SD (wasted) | 5 | 14.3% |
| LAZ | | |
| -2 to -3 SD (stunted) | 11 | 31.4% |
| WLZ and LAZ | | |
| -2 to -3 SD (stunted and wasted) | 4 | 11.4% |
| WLZ, weight-for-length; SD, standard deviation; LAZ, length-for-age. | | |

### 4.5.2 *Campylobacter* prevalence and correlation with infant health measures

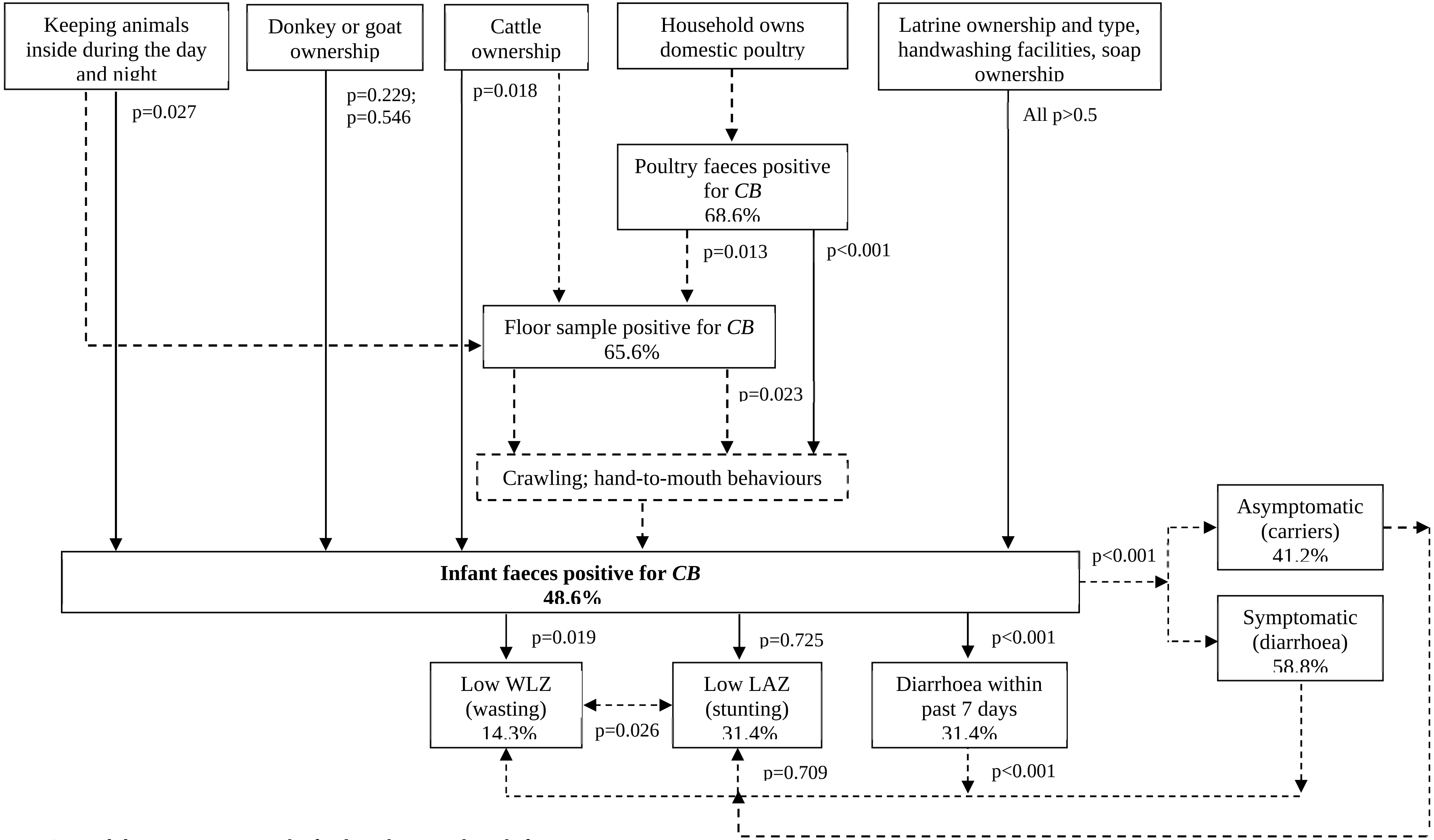
The following sections describe the relationships between survey variables, prevalence of presumptive *Campylobacter* and infant health outcomes. A total of 102 samples from poultry, infants and floor surface were cultured for *Campylobacter* spp. Overall, *Campylobacter* was recovered from 48.6% (total=17) of 35 infant faecal samples, 68.6% (total=24) of 35 poultry faecal samples and 65.6% (total=21) of 32 floor surface samples. The associations between risk factors and transmission pathways in relation to infant health outcomes are detailed in **Table 8.** Differences in the prevalence of positive samples which were symptomatic (a diarrhoeal stool sample) and asymptomatic (non-diarrhoeal stool, 'carriers') was seen among positive infants presenting with diarrhoeal stools (total=10, 58.8%) versus without diarrhoea (total=7, 41.2%) (p<0.001). Furthermore, infant who were wasted (low weight-for-length) versus not wasted were compared for *Campylobacter* prevalence. Those wasted were more likely to test positive for *Campylobacter* (p=0.019; OR 1.41, 95% CI 1.04−1.92). Wasted infants thus appeared to have 1.83 times the odds of diarrhoea and 1.41 times of a sample positive for *Campylobacter* versus those not wasted. However, diarrhoea was not associated with infant stunting (p=0.709), nor was *Campylobacter* prevalence (p=0.725).

Table 8. Odds ratios for exposure measures predicting an infant stool positive for *Campylobacter*.

| Variable | OR | 95% CI | P value |
|---|---|---|---|
| Infant wasting (WLZ <−2 SD) | 1.41 | 1.04−1.92 | 0.02 |
| Positive poultry faeces | 1.34 | 1.21−1.69 | <0.01 |
| Keeping animals inside (day and night) | 3.50 | 1.31–8.77 | 0.03 |
| Owning cattle | 6.50 | 1.47−28.90 | 0.02 |
| Positive floor sample | 7.00 | 1.50−23.40 | 0.02 |
| OR, odds ratio; CI, confidence interval; WLZ, weight-for-length z-score. | | | |

### 4.5.3 Risk factors and transmission pathways related to infant *Campylobacter* prevalence

Further analysis using correlation explored the relationship between potential risk factors and transmission pathways to infant stools positive for *Campylobacter*. Considering associated risk factors, animal husbandry practices of keeping animals inside during the day and night (as a composite variable) was strongly correlated with increased odds of infants positive for *Campylobacter* (p=0.027, OR 3.5, 95% CI 1.31–8.77). Owning donkeys or goats showed no association (p=0.229 and p=0.546 respectively), but owning cattle was significantly associated with increased odds, although with high uncertainty of effect (p=0.018, OR 6.5, 95% CI 1.47−28.90). Poultry faeces positive for *Campylobacter* showed significant correlation with infant *Campylobacter* (p<0.001, OR 1.34, 95%CI 1.21−1.69). However, owning a latrine, different types of latrine, owning a handwashing facility and ownership of soap were all not correlated (all p>0.5). Considering potential transmission pathways, positive floor samples showed a significant association, although again with high uncertainty of effect (p=0.023, OR 7.0, 95% CI 1.5−23.4). Positive poultry faeces and positive floor samples were also highly correlated (p=0.013; OR 2.68. 95% CI 1.64−12.62). **Figure 9** illustrates these associations whereby the dotted lines describe the main transmission pathways to an infant stool positive for *Campylobacter*.




CB, *Campylobacter*; WLZ, weight-for-length; LAZ, length-for-age.

Figure 9. Pathways between variables that predict infant stools positive for *Campylobacter* and relationships with health outcomes.

Dotted lines demonstrate the hypothesised pathway linking poultry ownership, *Campylobacter* prevalence and health outcomes via (sub-)clinical disease. ‘Symptomatic’ infection refers to infants positive for *Campylobacter* with a diarrhoeal stool. P values <0.05 were significant. This diagram is expanded in **Figure**

## 4.6 Discussion

Results from this small cross-sectional study suggest that in these rural Sidamo households raising free-range domestic poultry, the prevalence of infants testing positive for *Campylobacter* spp. is high. With presumptive *Campylobacter* isolated in almost half of infant stools, results mirror high prevalence found in similar age infants in Zimbabwe (32.3%),[73] Mexico (66.0%),[42] Madagascar (43.3%)[74] and across eight low-resource settings where 84.9% of infants had at least one positive faecal sample by one year of age.[45] The high prevalence in this study may be due to sample collection during the rainy season where pooled water inside the home facilitates the spread of faecal bacteria: however other studies have found constant high prevalence not affected by seasonality.[44,75] In this study, 58.8% of the 17 infants positive for *Campylobacter* were symptomatic with diarrhoeal stools. With an average *Campylobacter* excretion of seven days[36] (and reported protracted excretion of more than 14 days[41]) this may lend support that current diarrhoea in these infants was from Campylobacteriosis. Studies in northern Ethiopia[59,60] and in the same zone as this study61 suggest *Campylobacte*r is a major regional cause of diarrhoea Comparing infants who were wasted (total=5) versus those non-wasted, wasting was correlated with positive *Campylobacter* prevalence and diarrhoeal stools. Campylobacteriosis may have contributed to these outcomes, but it is likely other coexisting infections also contributed.[31,76]

Whilst in early infancy infection may produce clinical symptoms and affect short-term weight, repeated enteropathogens colonisation may contribute to the development of EED. Although this study was not able to collect biological measures of EED, 41.2% (total=7) of positive infant stools were asymptomatic (non-diarrhoeal stools). This supports findings from the MAL-ED study where subclinical infection was more strongly related to growth failure than overt diarrhoea.[12] Although positive stools showed no significant correlation with stunting, this may be partly due to the small sample size. Furthermore, research suggests that growth shortfalls resulting from early exposure to *Campylobacter* manifests later in infancy.[31] Studies have associated cohabiting with poultry with reduced length-for-age[54,77] and others have shown that infants who frequently test positive for *Campylobacter* have lower LAZ scores at 24 months of age, which had a stronger correlation with subclinical infection, or *Campylobacter* carriage.[32,44] Other studies have also demonstrated a relationship between poultry ownership and lower WAZ but not lower LAZ,[54] suggesting both acute and chronic effects on health. Other significance lies in the overlap between wasting and stunting among infants in this group (p=0.026), supporting evidence that the two forms of malnutrition can, and often do, coexist in the same infant,[78] that they may share common causal factors of repeated carriage and/or infection.[79]

This study aimed to further describe the relationship between domestic animal ownership and infant pathogen prevalence and growth, where free-roaming domestic animals may contribute to contamination of the home environment with related pathogenic bacteria and other pathogenic organisms. Indeed, in this study, households were instructed to collect poultry samples from indoors and only two collected samples from outdoors, highlighting the ubiquity of poultry faeces inside the home. Infection is possibly transmitted to infants via age-specific behaviours and pathways. In this study, the significant risk factors that correlated with positive infant stools were specific animal husbandry practices of keeping animals inside during the day and night (ubiquitously in the same room as the family), owning cattle, positive domestic floor samples and positive poultry faeces. The analysis showed some uncertainty of effect and the small sample size may reduce the validity of findings. The study was not powered and thus may not have ‘truly’ detected ‘real’ differences where the sensitivity was low. However, the data quality was high, and the confidence intervals indicate a direction of effect of the data.  and Thus there is some confidence that the data highlight specific risk factors to infants, including contaminated domestic floors as a potentially important transmission pathway. This and the previous fieldwork should serve as a basis to guide powered studies with more sensitivity to detect a ‘real’ difference. Longitudinal data from the MAL-ED team showed the effect of *Campylobacter* infection on growth is related to age – highlighting an increased level of risk as infants start to crawl.[32] Whilst this study did not capture hand-to-mouth contact events, previous research by this  team in the same geographical area recorded infants mouthed their own hands or those of their caregiver a mean 31 and 21 times respectively over one hour, which were often visibly dirty (90.0% and 86.0% respectively).50 In the same study 35.0% of infants directly ingested floor surface material and poultry faeces was directly ingested by two infants (10.0%).[50] Other studies have also recorded infants frequently ingesting poultry faeces from the floor during normal exploratory play.[26,80,81]

Other factors not measured in this study, such as contaminated hands, food (particularly milk) and drinking water may account for the remaining sources of and transmission pathways to infant infection. Although a fastidious organism, *Campylobacter* is widespread in the environment, transmitted particularly through contaminated groundwater and stored drinking water,[46] surviving for several days in an ambient temperature.[49] Consequently research has suggested that in households where poultry are free-roaming, even with good water supply it is unlikely handwashing will effectively interrupt transmission.[49] *Campylobacter* transmission is also increased when WASH facilities are poor[36]: similar cross-sectional studies in Ethiopia also found higher *Campylobacter* prevalence in households without clean water and which had direct contact with chickens.[82,83] In this study latrine ownership and type (improved or not), ownership of handwashing facilities and soap were not correlated with stool samples negative for *Campylobacter*, perhaps suggesting that simply providing WASH facilities will not prevent transmission and infection. However, it is possible facilities are also not used, particularly by children, which remains a limitation. In rural communities it can be difficult to assess and accurately report the use of latrines and soap for handwashing. Whilst in this study the visual inspection of latrines suggested they were all used, soap ownership would often be reported but not seen. Regardless, it seems logical that when sharing living spaces so closely, domestic animals contribute to infection from zoonoses and widespread contamination of multiple pathways. There are intrinsic and inseparable connections between these various transmission pathways. This is illustrated in **Figure 10** which illustrates causal pathways to poor infant health outcomes when animal faecal contamination and age-specific infant behaviours are not considered as important risk factors.

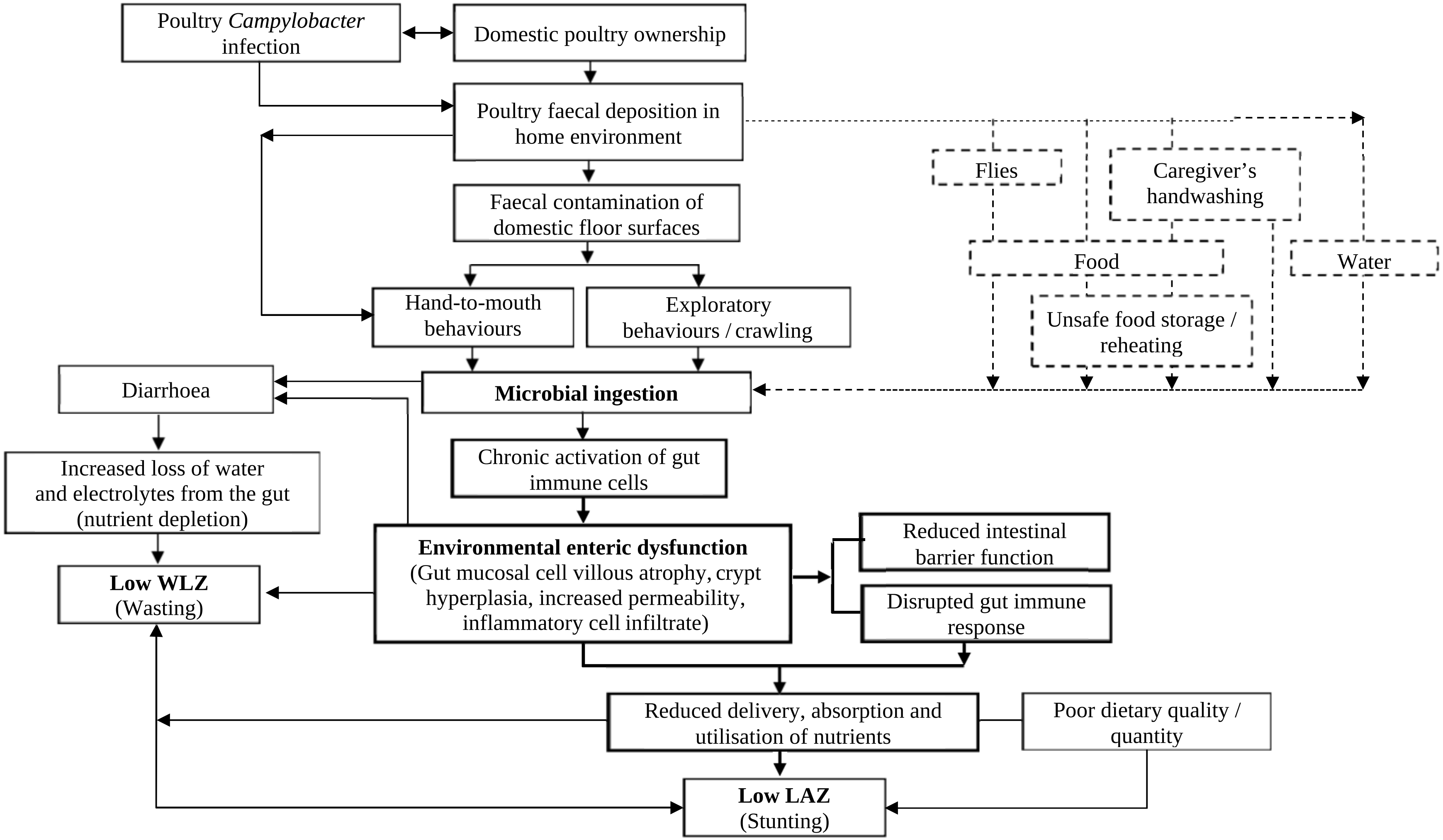



Figure 10. The hypothesised pathways by which domestic poultry ownership contributes to infant malnutrition via infection from, and transmission of, *Campylobacter*.

The thicker part of the diagram illustrates the hypothesised relationship with environmental enteric dysfunction (EED). The dotted part of the diagram to the upper right constitutes the original 'F-diagram', representing other transmission pathways by which infants are exposed to *Campylobacter.* Adapted alongside a previously published diagram[10] and the 'F published by Wagner and Lanoix.[84]

## 4.7 Study limitations

The validity and broader applicability of findings from this study are mostly limited by the small sample size which may affect data validity and generalisability of the results. As discussed, the data suggest a direction of effect but which may not hold up in a powered study with adequate sensitivity. The single time point of testing in this formative research and the cross-sectional study design prevent determining causality. However, the results are emphasised as formative evidence which contribute to theory-building and support emerging hypotheses which associate free-range poultry ownership, household contamination from zoonotic pathogens and infant infection with undernutrition. Although this study intentionally sampled households who owned poultry, the risk of transmission may be greater than estimated as free-range chickens from neighbouring households may also increase contamination. Also, faecal samples from other domestic animals which also harbour *Campylobacter*, such as cattle,[46] were not sampled. On the other hand, there was no evaluation of the prevalence of other pathogenic or parasitic organisms, so it is not certain that the presumptive *Campylobacter* isolated in samples was the definite cause of wasting and/or diarrhoeal prevalence seen here. A few studies have reported mixed infections of *Campylobacter* and viral pathogens and their associations with infant morbidities.[31,85] This presence of *Campylobacter* alongside the carriage of multiple pathogens may correlate as a proxy for infants with greater overall levels of exposure to enteric pathogens in their environment; this in turn may associate with those with poor growth and/or wasting.

Lastly, the use of culture-based method alone holds limitations: firstly, due to changes in *Campylobacter* cell physiology and loss of viability between sample deposition, collection, transport, and plating (whereby cells enter the viable but non-cultivable [VBNC] state). This may have underestimated the true prevalence of *Campylobacter* in stool samples and rates of infant infection (given relative infectivity of VBNC cells which still demonstrate pathogenic potential). On the other hand, culture holds limited sensitivity and high rates of false detection[86]; whilst there is evidence for good specificity of the agar in comparison and evaluation studies, there is no certainty of the rate of false positives in this study. Lastly, whilst the culture media shows high specificity, it was not possible to differentiate between or quantify different *Campylobacter* species. The parallel use of qPCR alone or PCR with ELISA methods would enhance culture-based findings.[32,87]

### 4.8 Conclusion

This formative study adds further preliminary evidence to the body of research documenting infant *Campylobacter* carriage and infection in households rearing free-range poultry. In these households, increased wasting and diarrhoea was seen in infants positive for presumptive *Campylobacter*. Repeated symptomatic infection and low weight may mean infants risk entering a spiral of weight loss and subsequent growth deficits. Alternatively, frequent carriage, or asymptomatic infection, and a high prevalence of stunting (although not correlated) suggest a longer-term impact of exposure to *Campylobacter* that may operate through EED. The time frame for when, and thresholds at which repeated *Campylobacter* infection becomes subclinical, contributes to the development of EED and affects growth are important remaining questions which a larger prospective cohort might address.

More broadly, this study also contributes to discussions around general WASH facilities and use, living conditions and the impact on reducing pathogen transmission. Where contaminated domestic floors are a risk factor for pathogen transmission to infants[63,88] and WASH facilities also appear have little effect in mitigating transmission, this emphasises the high thresholds of hygiene and living conditions necessary to improve infant health. While improvements to basic WASH usually included in interventions may address some secondary pathogen transmission routes (that is, unsafe drinking water, dirty unwashed hands, and contaminated food), a remaining burden of infection may be expected when animals share the living spaces and where animals contaminate water sources. Similarly, sanitation intervention may reduce human faecal contamination but animal faecal contamination may mask or mitigate effects where it is not addressed. A multifaceted approach to improve infant health will require not only improved WASH facilities within the home, but working more broadly with households and communities to adapt animal husbandry practices, encourage the safe handling and disposal of both animal and adult/infant faeces, safe preparation and storage of food, handwashing with soap after animal/faecal contact and education on the risks of infant exposure. These multiple, concurrent needs form the rationale for the recent push toward ‘transformative WASH’[89] Future research must develop and test transformative WASH interventions to achieve the high hygiene thresholds that support infant growth.

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## 4.10 Author contributions

SB wrote the manuscript. MB, PH and AP had input on the design of the study. MB, PH, AP, ST, FH, CG and MM assisted in assessing both the paper quality and contributed to the writing and review of the manuscript. FW and MJ managed and coordinated the field team, logistics and data collection in Ethiopia.

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## 4.12 Declaration of interest

All authors have no conflict of interest to declare.

## 4.13 Data access

All data created during this research is openly available from the Cranfield Online Research Data at 10.17862/cranfield.rd.9907385.

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# 5 Ongoing fieldwork: Multisectoral participation in the development of a household playspace for rural Ethiopian households

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## 5.1 Abstract

*Growing evidence suggests current water, sanitation and hygiene interventions do not improve domestic hygiene sufficiently to improve infant health: nor consider the age-specific behaviours which increase infection risk. An household playspace (HPS) is described as one critical intervention to reduce direct faecal-oral transmission within formative growth periods. This paper details both the design and development (materials and methods) and piloting (results) of an HPS for rural Ethiopian households. Design and piloting followed a multisectoral, multistep participatory process. This included a focus group discussion (FGD), two user-centred and participatory design workshops in the UK and Ethiopia, discussions with local manufacturers and a Trials by Improved Practices (TIPs) leading to a final prototype design. Piloting included the FGD and TIPs study and a subsequent randomised*

*controlled feasibility trial in Ethiopian households. This multisectoral, multi-stage development process demonstrated an HPS is an acceptable and feasible intervention in these low-income, rural subsistence Ethiopian households. An HPS may help reduce faecal-oral transmission and infection – particularly in settings where free-range domestic livestock present an increased risk. With the need to better tailor interventions to improve infant health, this paper also provides a framework for future groups developing similar material inputs and highlights the value of participatory design in this field.*

## 5.2 Introduction

In certain lower middle-income countries, poor infant (age less than two) health outcomes remain a key public health issue. Poor nutrition can leave infant and young children underweight, weak, and thus vulnerable to infections[1] – primarily from a weakened immune system. Where growth is interrupted, the cycle continues.[2] Diarrhoeal disease remains highly prevalent,[3] despite recent reductions in mortality[4] and infants may experience up to eight diarrheal episodes a year before age two,[3] suggesting very early, chronic pathogen exposure. Repeated diarrhoea and infection create a vicious cycle that can negatively impact linear growth[5] and both cognitive and psychosocial development.[6] As such, stunting remains high in certain areas.[7] Trends over time show improved water, hygiene, sanitation (WASH) and the hygiene environment contribute significantly to accelerations in average height in infants and children.[8,9] With an aim to interrupt faecal-oral transmission and thus improve undernutrition (in terms of linear growth failure), UNICEF linked improved household WASH to their undernutrition framework almost three decades ago.10 Substantial evidence suggests WASH availability, quality and consistent use contribute to good infant health.[11,12] However large, randomised controlled trials testing improved household WASH (with or without a nutrition component) have shown variable, mostly insignificant, effects.[13–15] Thus it is likely that to improve infant health outcomes, intervention design requires an overhaul to improve environmental hygiene. Although it is presently unclear what it will consist of, a call for ‘Transformative WASH’ necessitates a delivery of each element of WASH in tandem, and at substantial scale and quality.[16] This would include, but is not limited to, safe and consistent water quality and quantity and improved sanitation at the community level and handwashing facilities with soap and separation of animals and their faeces from living environments within the home. Such a package must address the local exposure context and risk factors which are significantly contributing to the overall pathogen burden as well as socioeconomic conditions. Improving conditions for the most resource-poor households will require these interventions (whether technical, structural, or behavioural) to be at once effective, feasible, and affordable. This may achieve the conditions necessary to improve infant health.[17]

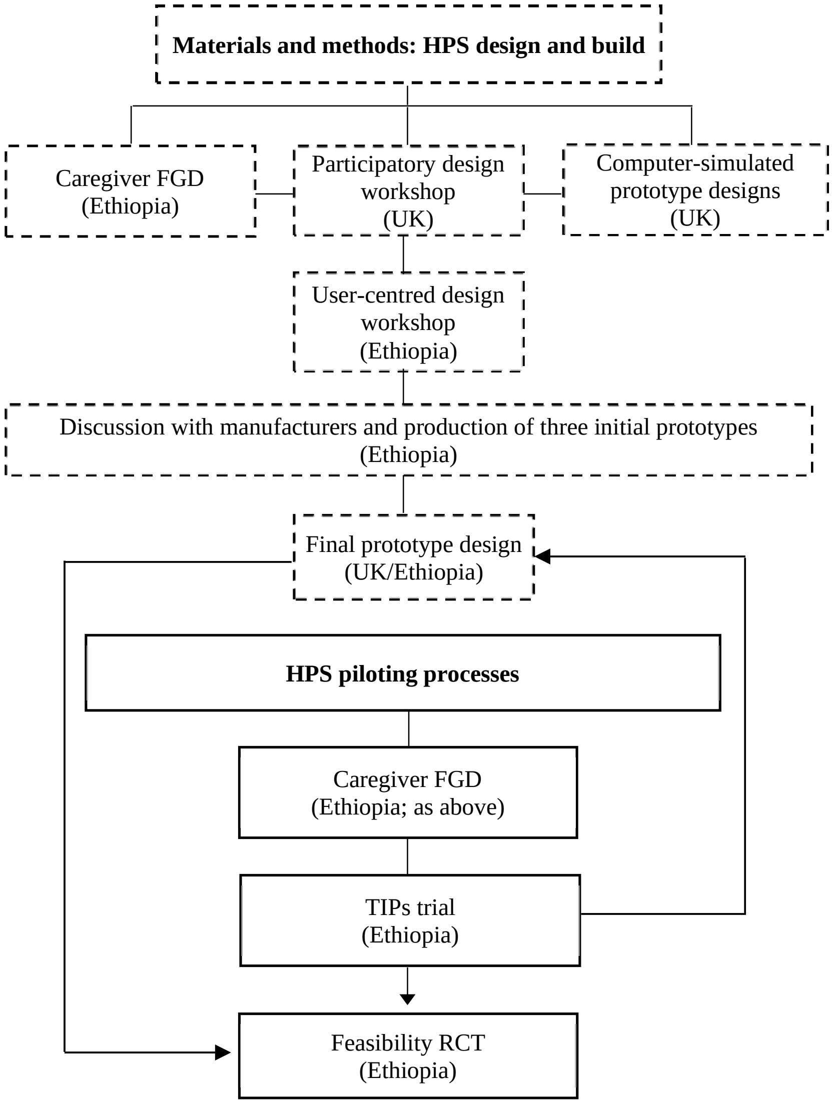
If WASH interventions aim to improve infant health, they must also be more effectively tailored towards this age group. The concept of 'BabyWASH' was recently established to promote intervention components which address the age- and behaviour-related pathways of infant faecal-oral transmission.[18] The BabyWASH concept noes that mouthing of contaminated objects is a particular risk pathway linked to unrestricted play and exploration, particularly in areas where domestic animals share living spaces.[19–22] Research describes how animal pathogen reservoirs contribute to the contamination of multiple faecal-oral pathways[22–24] and transmission between animals and infants.[25,26] Further, associations exist between animal proximity and infection, malnutrition and environmental enteric dysfunction (EED) – a subclinical condition affecting the gut which limits nutrient absorption and thus growth.[27,28] A household playspace (HPS), that is a protective, walled enclosure, is one intervention component which may help prevent direct ingestion of soil and faeces[29,30] and protection from contaminated surfaces.[31,32] Whilst an HPS sits 'within' the BabyWASH approach, it might be argued that what is needed is a comprehensive WASH package that tackles pathogen contamination across the broader home environment. This is important particularly as it affects infants where trials are predicated on infant health grounds. As such, the World Health Organisation deem an HPS a 'critical intervention' component of WASH[33] that may help prevent infection and improve infant health.[34,35] However, there is a lack of data around the potential of an HPS to reduce pathogen exposure and no reported development process which might serve as a template. This remains a barrier to both the donor community and for research groups developing and testing intervention components which address infant needs and behaviours.

### 5.3 Paper aim and structure

This paper aims to detail the design and piloting of an HPS for a low-income context. The design and pilot processes follows formative research between Cranfield University, the non-governmental organization People In Need (PIN) and Hawassa University, Ethiopia, demonstrating the importance of direct faecal-oral transmission to infant infection.[22,36,37] The final HPS prototype resulting from this design process was tested in a randomised, controlled feasibility trial, the CAMPI trial (Campylobacter-Associated Malnutrition Playspace

Intervention trial) which assessed the feasibility of an HPS in rural Ethiopian households.[38] Certain outcomes from the feasibility trial are presented here in this paper in order to demonstrate feasibility of the HPS as an intervention modality. Full findings from the trial are reported separately.[38]

It was speculated that the development of best practice guidelines on developing material interventions within WASH scope would facilitate knowledge sharing across research groups. By detailing these processes, the team aims to provide a framework for future interventions developing similar BabyWASH material inputs. Therefore, this paper is divided into three sections. Firstly, the paper reviews current evidence and ongoing research as part of a WASH intervention. Secondly, the materials and methods section describes the development of an HPS through a needs- and evidence-based multisectoral, multi-step participatory process. Third, the team recognised the need for further data on feasibility outcomes which would help to assess the potential for an HPS to reduce faecal-oral transmission. Thus, the feasibility and piloting section describes outcomes from formative testing which piloted prototypes and the final design to demonstrate acceptance and adherence. **Figure 11** illustrates the components of the design and piloting processes as they pertain to the layout of this paper.




HPS, household playspace; FGD, focus group discussion; TIPs, Trials by Improved Practice.

Figure 11. Components of the materials and methods and piloting processes and the layout of this chapter.

## 5.4 Current evidence on playspaces or playmats

The potential for an HPS to improve infant health outcomes has been, or is currently being studied by research teams and non-governmental organisations across different contexts. However, as a new intervention modality many of the results are pending. Details on the design, fidelity measures such as uptake, maintenance, time use, microbiological data, or infant-related outcomes such as reduction in faecal-oral contact or diarrhoea are limited. Some implementers have incorporated playmats without a supporting evidence base, but through evaluation are contributing. Through a brief review of current studies, this initial section highlights the need for more comprehensive and standardised design and testing research. Thus, this section firstly looks at efforts that include a playmat: that is a flat fabric and/or plastic sheet with no barrier/sides. It then reviews current HPS research.

A randomised controlled trial of BabyWASH interventions in South Kivu in the Democratic Republic of Congo is investigating the effect of either a household playmat, playspace or BabyWASH package to determine which format is the most effective strategy in preventing geophagy and decreasing EED.[39] Results are awaited. In Ghana, a playmat was a key enabling WASH technology in the SPRING 'WASH 1,000 Program' to provide a hygienic space for infants and prevent faecal-oral transmission.40 However, data on design, acceptability, uptake and use was not collected, nor data on bacterial/faecal contamination or infant health outcomes. As part of the USAID ENGINE Project, a small study investigated the market potential of subsidizing PVC playmats, marketed through micro-enterprises and local women's saving groups.41 Almost 4,000 mats were sold and most households (77%) reported always using the mat for the intended purpose. However, informal follow-up indicated many mats had tears after a short time and when infants became slightly mobile, they were ineffective (Save the Children, personal communication).

Thus, most studies to date examining the efficacy of a hygienic space have used flat mats with no walls. Whilst a playmat may be beneficial during travel and may help prevent some faecal-oral transmission, it may not fully prevent faecal ingestion from dirty floors, nor restrict animal or infant movement onto and off the mat. Nor are they often durable. Instead, of a playmat, few studies have tested a walled playspace. This design would better this prevent free movement and generally better demarcate a space that can provide better caregiver control. The two options of an imported plastic HPS and a locally-sourced plastic playmat were part of the SHINE trial in Zimbabwe. Extensive formative research informed the rationale and assessed demand29,35 and delivery of the intervention was high[15]: however, results suggested neither option reduced infection.[42] Upon spot check, HPS across intervention arms were 92−93% clean, but further data is pending on use behaviours and duration of use, and whether and by what magnitude either option reduced faecal-oral transmission. A team recently described a thorough, evidence-based design process to create an acceptable and community-built BabyWASH HPS in Zambia.[34] Though locally designed by the community and a solid, durable structure, the HPS was a fixed space situated outdoors. The study aimed to reduce faecal-oral transmission within the household, so an outdoor space may not have interrupted main domestic transmission pathways. It may also have encouraged other infants or children to enter, perhaps introducing other sources of contamination. It may also be more difficult for mothers to consistently watch their infants and lead to insufficient supervision when occupied; it was noted that the HPS introduced additional work that meant the mother spent less time working in the fields.[34] The HPS was tested alongside an imported, commercial plastic model. Reported use was similar between the two types, but caregivers expressed concerns over perceived durability and the potential for infants to climb out of the plastic model. This model was lightweight, collapsible, and visually appealing but the cost was prohibitive to these subsistence livelihood households. In Ethiopia, the USAID WASHPaLS Project engaged rural parents, NGOs, health extension workers and design specialists to design infant HPS from locally sourced materials. These were tested alongside one low-end commercial HPS for feasibility of use and cleaning, appeal, perceived value and E. coli contamination.[43] The designed HPS were immensely appealing to caregivers, who reported a number of hygiene, caregiving and developmental benefits; however, reported and observed use cast doubts on their effectiveness at substantially reducing pathogen exposure.

Therefore, a lack of evidence around the effectiveness of a walled HPS in reducing pathogen exposure remains a barrier to the donor community to invest as part of a more comprehensive WASH package. Another issue is affordability: currently there is no HPS product which is within financial reach of the rural poor. Without a low-cost, bulk-produced option, implementation of an HPS intervention would require intensive donor support which is not scalable. Attention is thus shifting to explore options for a locally-sourced and produced HPS which, if found effective and feasible, might offer a scalable program option. This assumes that a locally-sourced and produced HPS would be both financially accessible and would reflect local needs and preferences – also increasing uptake and continued use. Best practice suggests that involving end-users in a multi-sectoral, iterative design process is essential for designing and launching consumer products: especially so with vulnerable groups within developing countries.[44] With this process, design and development considers local contextual needs which are critical to intervention success for both users and stakeholders.

## 5.5 Materials and methods

This second section details the design and development of the household playspace. This process was a collaboration between Cranfield Water Science Institute, the Centre for Competitive Creative Design (C4D) at Cranfield University and PIN in SNNPR, Ethiopia, and enhanced by a supporting USAID-sponsored design workshop in Ethiopia. The full process spanned 18 months and encompassed several iterative steps within the UK and Ethiopia (**Figures 11** and **Figure 12**) to produce the final prototype (**Figure 13**). These are as follows:

1. Focus group discussion (FGD), Ethiopia
2. Participatory design workshop and initial computer-simulated designs, UK
3. User-centred design workshop, Ethiopia
4. Incorporating lessons from workshops and interactions with Ethiopian manufacturers
5. Trials by Improved Practices (TIPs), Ethiopia
6. Final prototype design

The methodologies of these stages are detailed below. Further information is included in supplementary information.

## 5.6 Ethics

The research followed standard ethical procedures and study aspects involving participants were approved by the Cranfield University Research Ethics Committee (CURES 4955/2018). Consent forms were translated into both Amharic and Sidamo and all participants provided written informed consent.

## 5.7 Methods for design

### 5.7.1 Focus group discussion, Ethiopia

The FGD was held by PIN and Cranfield University in Sidama zone, SNNPR, in June 2018. The FGD primarily aimed to understand the need and demand for a hygienic playspace among mothers in this rural, subsistence agriculture setting. Secondly, the FGD aimed to gain primary insights into design requirements which were appropriate for the context. So mothers could conceptualise and discuss a hygienic playspace for infants, seven days prior team members distributed a canvas mat (1.5 $m^2$) to households. Mothers were asked to use it as an infant play area for a week. Directions were given on keeping the mat clean (wash when visibly dirty and after the infant or an animal defecated or urinated, with water and soap). Mothers were also asked to consider how they would improve the design to better meet their infant’s needs and improve their health. Further methodological details are in S1.

The FGD highlighted that mothers were concerned about faeces from animal (particularly cattle and poultry) and human sources within the home as a risk factor for infant illness.

Mothers recognised that during crawling and play, infants were likely to mouth dirty objects and faeces which contributed to illness:

*Yes we are worried because if they took this to their mouth they will get disease as it contains bacteria.*

Although other research has suggested infant faeces may be perceived as benign,[35] mothers perceived the same severity of risk:

*Both adult faeces and child faeces are the same, they cause disease. So to prevent all of these things we clean the compound before we leave the children to play.*

Having had the canvas mat for a week, mothers were positive about the benefits of a hygienic space for their infant. Mothers could continue their work and watch the infant whilst providing a more hygienic surrounding:

*If our child plays on the mat he doesn't get the dirty material in his mouth, it's a way to keep him clean.*

*I can continue with my activities if the baby is on a mat.*

*It has additional value for us to protect from dirty things but still we are with him.*

Mothers reported cleaning the mat was easy and they were willing to keep it clean:

*Even if they urinate on the mat or defecate on the mat, we can clean it easily. We wash it and put it in the sun and then bring it back into the house.*

Commenting on the design, mothers all agreed the mat had benefits but would not prevent animals from contaminating it nor remove the risk of faeces:

*If the mat has its own protection this would protect them* [infants] *from going outside of the mat and stop animals from going in.*

*It must have sides. The animals can easily access the mat if we leave the baby at the moment.*

Findings from the FGD provided valuable feedback on perceived value, demand and potential uptake of an HPS, as well as initial insights into user needs for the design.

### 5.7.2 Participatory design workshop and computer-aided prototype design, UK

The initial design stage for the HPS involved a four-hour participatory design workshop held at Cranfield University. This was facilitated by researchers from the Cranfield Water Science

Institute and facilitated by C4D, whilst including some parents. The aim of the first workshop was to generate initial prototype designs which could be computer simulated and taken to the second workshop for further development. In the workshop the team reflected on feedback from the FGD and other developmental, emotional and safety needs and requirements of the infant, caregivers, and stakeholders. Following a presentation of the research background and workshop aims, a facilitated group discussion helped attendees to list design requirements, the following nine of which were identified:

1. Keeps out domesticated animals
2. Cheap and possible to mass manufacture within the local context
3. Provides cognitive and physical stimulation to infants
4. Lightweight and easy to distribute
5. Baby is visible – parent receives reassurance
6. Requires little water to clean
7. Not made of materials that harbour bacteria
8. Can cope in local weather conditions
9. Appropriate for the cultural context of the study (e.g., livelihood patterns, maternal work burden and needs, caregiving practices)

Considering these criteria, small groups used craft materials to develop small-scale models of an HPS (see **Figure 12**). These were recorded and used to develop a requirement rating scale. This was created by firstly assigning a value between 0−1.0 for each of the nine requirements above. Following, each prototype from the workshop was individually scored by assigning values 0–1.0 to attributes listed above as to whether the prototype achieved that attribute. The sum was then totalled. Thus, each design had a list of scores. Ranking these scores in order gave a set of specific design features that were deemed most necessary for the final prototype designs – described later in the results section. Considering this list, a design engineer at C4D created three computer-aided visualisations of different prototypes (see **Figure 12**). These three designs were taken by a WASH project manager at PIN to a second workshop in Ethiopia to share and further refine the designs.

### 5.7.3 User-centred design workshop, Ethiopia

A second workshop focused on user-centred design was hosted by the USAID WASHPaLS and Transform WASH Projects (implemented by Population Services International [PSI] and partners). The workshop was held in Bahir Dar, Amhara, after the initial UK workshop. Bahir

Dar Institute for Technical and Vocational Education and Training provided classroom and workshop spaces and staff members with various technical expertise. In conducting similar research as this team, WASHPaLS designed the workshop with aims to develop locally sourced, economical HPS models for use in their household trial.[45] The iterative design process engaged 15 'users' including parents, government Health Extension Workers (HEWs), local artisans, and the vocational college instructors and yielded three models that would be further refined for bulk production and household testing. The process was in three stages: gathering information, generating ideas and prototyping/piloting. PIN's WASH project manager attended the workshop to gain insight into prototype design ideas. This second design workshop also allowed further design inputs from rural households. Users grasped the concept of a protective space, feeling it would create a 'safe zone' and facilitate household chores; however, some stated this was something for 'city folk' and not accessible to them. Participants particularly appreciated the visibility provided by net siding used in two of the models, allowing visibility of the infant and so the infant did not feel isolated from the caretaker, and the removable padded mattress which facilitated cleaning. Some interviewees indicated they would be willing to pay around 250 birr (US $8) for the product, while others expressed that they would rather reproduce the model at home using nails and wood rather than bamboo; this implied users themselves might produce an HPS more cheaply than a locally-produced model. Thus, these participants were willing to sacrifice portability for ease of construction, and design for price. Based on feedback, one of the three prototypes was chosen to trial within homes – specifically due to the use of local materials, ease of production, portability, ventilation, and size. An additional in-depth interview with a local carpenter gave insight into issues with 'small scale' production, possible modifications to economise production, demand, and willingness to pay.

### 5.7.4 Incorporating lessons from workshops and interactions with Ethiopian manufacturers

Reflecting on the findings from the UK participatory design workshop, the FGD and the user-centred design workshop with WASHPaLS, three prototypes were developed. From the computer-aided designs, design complexity was scaled back, the size was reduced, and complicated roof designs eliminated. The three prototypes varied slightly in design and incorporated key attributes deemed important, including a soft foam mat with a washable cover, a portable wooden structure and infant visibility. PIN WASH team members sought to identify local artisans with experience in woodwork and production. Subsequent discussions identified materials that could be easily sourced in local markets: including bamboo, foam and cotton or canvas covers. Further discussions negotiated price and timescale. Specifications for the three prototypes, including side height and slat space, followed design and safety requirements taken from a relevant International Standard (ISO 7175-1:2019).[46] These included, but were not limited to, specifications ensuring the design did not promote lacerations, puncture wounds, choking, strangulation and entrapment. These were shared with manufacturers to support production. **Table 9** describes the three designs.

### 5.7.5 Trials by Improved Practices (TIPs)

The three prototypes were tested in a TIPs – described in the supplementary material (S2). Briefly, the TIPs trial was used to pilot each of the three HPS prototypes, one each within three households (N=9) in Sidama zone to provide some insights into practical design elements. It also allowed the team to pre-test the practices that the trial would engage, providing initial feasibility data on acceptability, time use and maintenance (correct use and cleaning). The trial enrolled households with an infant aged 10−18 months living within the pre-specified villages and raising domestic animals (cattle, poultry). The trial took place over one month, and stages were: 1. Household identification alongside a local HEW and household visit to recruit and consent households 2. Visit one: HPS allocation and behaviour negotiation; 3. Visit two: five days after the HPS allocation; 4. Visit three: one month after visit one. During the first visit, a PIN WASH team member and caregiver agreed a set amount of time for daily use and a cleaning schedule – negotiated as at least six hours. It was negotiated that the infant would be in the HPS when the mother was preparing coffee, meals during household activities, when the infant was not sleeping, after breastfeeding or having eaten. Mothers would not leave the infant in the HPS during activities outside the home, such as fetching water. Cleaning behaviours negotiated with all households were to clean the mat using water and soap and to dry the mat in the sun. Mothers agreed to clean the mat when the infant had defecated, when an animal had entered and defecated and at least once a week. During subsequent visits, the team member used observational and survey data to assess if, how and why these behaviours were maintained, allowing insight into the barriers and motivators that prevented or enabled HPS use. Time-use and other outcomes are described in section 3. Findings regarding HPS design were incorporated into the final prototype design. The evolution of the playspace design towards the final prototype is shown in **Figure 12.**

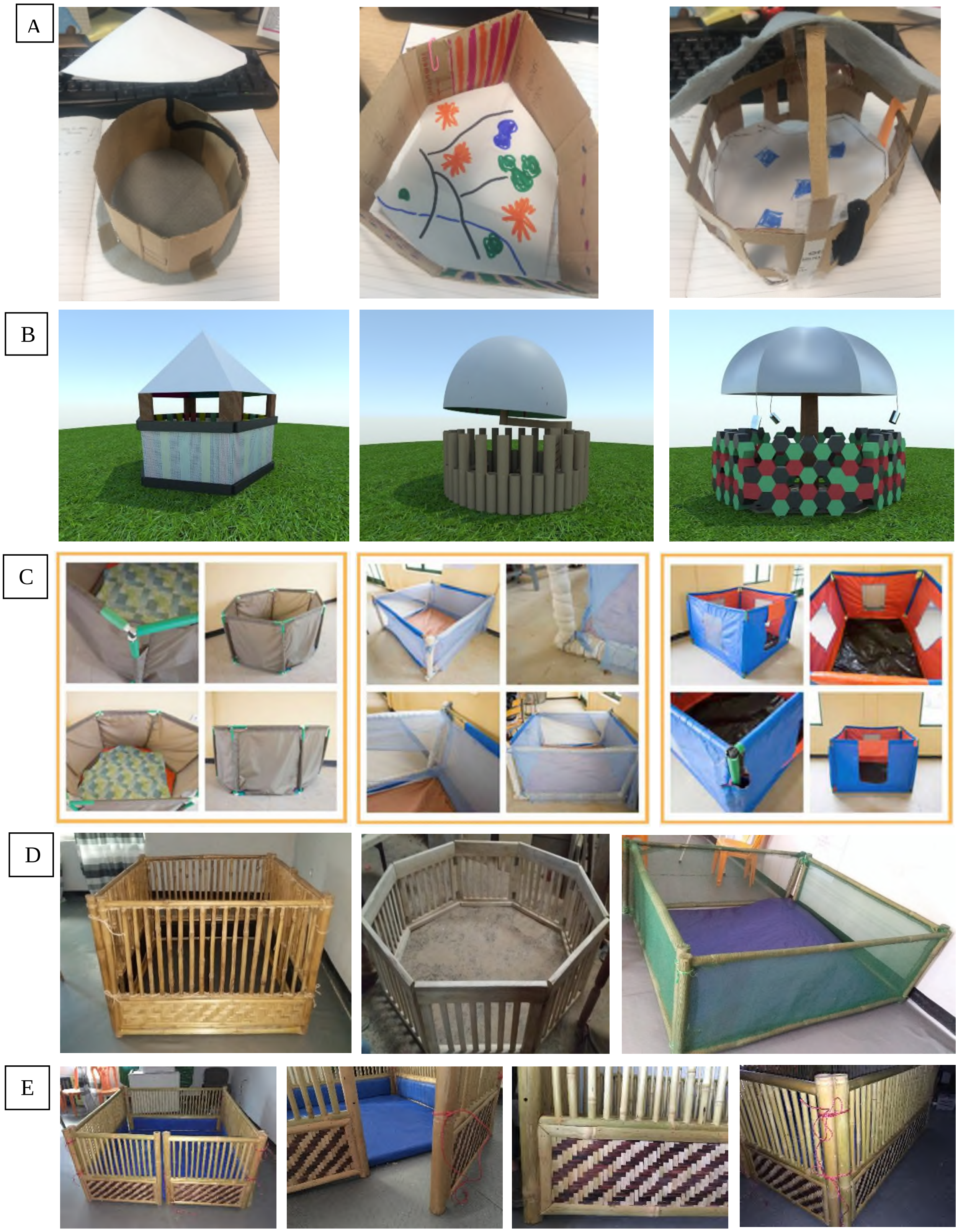



Figure 12. Design evolution of the playspace to the final prototype design.

*From top left to right in rows: A. Cranfield participatory workshop; B. Cranfield computer-simulated designs; C. Ethiopia user-centred design workshop; D. The three prototypes trialled in the Trials by Improved Practices; E. The final prototype design as trialled in the randomised feasibility trial (detailed in Figure 13).*

Table 9. Design specifications for three initial playspace prototypes.

| Prototype | Floor dimensions | Frame | Wall design | Side height | Slat space | Floor type | Mat design | Other features |
|---|---|---|---|---|---|---|---|---|
| **1** | 1.4 $m^2$ | Bamboo | • Bamboo poles<br>• 25 cm panel from floor | 70 cm | 4 cm | Flat bamboo | • 4cm foam<br>• Plastic canvas cover | • Foldable sides<br>• Sides connected by rope through drilled holes |
| **2** | | | • Bamboo poles<br>• 25 cm panel from floor | | 4 cm | No panel | | |
| **3** | | | Netted walls | | - | | | |

### 5.7.6 Design modifications and suggested changes

During the TIPs, households with a wooden floored HPS stated they found it harder to clean and were concerned over the risk of rotting in the rainy season. Households with prototypes made with wooden rungs were pleased the design allowed visibility and the infant to stand by holding. Households with prototypes made of netted sides did not like that infants were not clearly visible. Five households suggested the HPS was slightly too large for their small homes. All households appreciated that the HPS could be folded and taken outdoors (though outdoor use was not assessed). Some households suggested the HPS was quite heavy due to the bamboo structure – however more caregivers reported it was easy to move and appreciated its sturdiness and durability. Household feedback was mixed regarding the use of rope to tie the sides, but this was deemed the most safe, easy, and affordable solution. Metal hinges were expensive and a potential safety hazard from sharp edges and potential entrapment. There was no reported or observed damage to any HPS and the rope connecting sides remained correctly fastened in all households. Interestingly, two households hung plastic canvas above the HPS to protect the infant from dust accumulated on the roof from burning firewood.

### 5.7.7 Final playspace prototype design

Following results of the two workshops and TIPs, the research teams further developed the design of the final HPS prototype. Key changes to the final prototype design from the TIPs trial included: a reduction of the floor plan from 1.4$m^2$ to 1.2 $m^2$; foldable walls which were also detachable to allow movement of the HPS; no floor panel to avoid wood rot; a sufficiently thick mattress covered with canvas to allow for easy cleaning. Although caregivers expressed the need for toys in the TIPs, it was decided not to include toys in the feasibility trial. This was to avoid potential safety hazards and also where toys may act as vectors for faecal-oral transmission.

Again, specifications followed design and safety requirements from the ISO standard.[46] The processes leading to the final design, and final design specifications, are detailed in **Table 10**. These were sent to a local manufacturer who produced one prototype. The HPS was marginally scaled down to fit smaller households (1.20 $m^2$). All materials, including bamboo, foam and canvas were sourced locally with the final cost of 1500 ETB, including labour (approximately $45). Following build, the final prototype was then tested for safety using a second ISO standard developed for piloting purposes (ISO 7175-2:2019).[47] Relevant safety tests included but were not limited to: applying force to test stability and structural integrity; measuring squeeze (pinch) points; ensuring edges were rounded and free of burrs/sharp edges; measuring gap width to mitigate trapping of body parts and testing flammability of the canvas by flame spread rate and for any flash-effects. Finally, prototype safety was checked with a second British Standard assessment checklist which provides a structured approach to risk reduction and reducing harm from unintentional injury (Guide 50:2014; see Annex A, assessment checklist in [46]).[48] The final design successfully passed safety inspections from both the second ISO standard and the British Standard assessment checklist. **Figure 12** shows the evolution of the design process of the playspace, with the final prototype design in the final row. The final playspace design is shown in **Figure 13**.

Figure 13. Final playspace prototype design for the CAMPI feasibility trial.

Table 10. Development of design specifications for the final playspace prototype design, including safety considerations.

<table>
<tr><th rowspan="2">Feature</th><th colspan="2">Design process stage</th><th rowspan="2">Safety considerations<br>ISO 7175-1:2019</th><th rowspan="2">Final prototype design</th></tr>
<tr><th>Participatory workshop in UK; FGD; WASHPaLS UCD workshop; manufacturer consultation</th><th>TIPs trial feedback</th></tr>
<tr><td>Structure</td><td>• A wooden structure using locally sourced material<br>• Easy to wipe down and durable in heat; does not overheat<br>• Sides high enough to prevent animals entering and infants climbing out<br>• Floor plan approximately 1.6 $m^2$</td><td>• Bamboo structure appreciated<br>• Appreciation of local craftsmanship<br>• 1.4 $m^2$ floor plan too large for small households</td><td>• No element of the cot base shall break, nor the cot base become dislodged<br>• No accessible holes between 7−12 mm diameter<br>• Edges and protruding parts shall be rounded or chamfered and free of burrs and sharp edges</td><td>• Bamboo structure<br>• 1.2 $m^2$ floor plan<br>• Unvarnished and sanded</td></tr>
<tr><td>Walls / sides</td><td>• Sides and flooring connected as one piece<br>• A solid panel at the bottom preventing small animals from entering<br>• Sides which allow visibility of the infant, e.g. slatted walls or netted material<br>• A handrail along the inner wall which allows the infant to stand<br>• Joints made with simple holes drilled to size on the bamboo, connected with rope or a hinge</td><td>• Foldable design to take outdoors<br>• Slatted walls which allow visibility and the infant to pull themselves up to stand<br>• Walls sufficiently high so the infant cannot climb out</td><td>• Minimum distance between the upper side of the mattress base and the upper edge of the cot: at least 500 mm<br>• A mark should indicate the maximum thickness of the mattress from the top of the mattress and the upper side of the cot<br>• Less than 60 mm between two adjacent slats<br>• No accessible shear and squeeze points which close to less than 18 mm<br>• Folding cots shall be equipped with a locking system to prevent unintentional folding</td><td>• Foldable / detachable walls connected by rope<br>• Wall height: 70 cm<br>• Bamboo panel: 25 cm<br>• Space between slats: 4 cm<br>• A locking mechanism which locks doors shut during use<br>• A clear, bold mark on the inside of the playspace indicating appropriate mattress height</td></tr>
<tr><td>Floor and mattress</td><td>• A mattress, sufficiently padded with foam<br>• Lightweight and easy to remove to clean<br>• Mattress covering of plastic burlap tarp material (‘shara’) or cotton covering</td><td>• No wooden / bamboo floor to avoid rot<br>• Mattress covered with plastic / canvas which can easily be wiped down<br>• Mattress thickness of 4 cm deemed sufficient for play</td><td>• Maximum rate spread of flame of textiles, coated textiles or plastic covering: 30 mm/s; no flash-effect<br>• If a mattress is supplied with the cot, there shall be no gap more than 30 mm between the mattress and the side ends</td><td>• No floor panel / waterproof mattress to sit on ground<br>• Mattress size: 1.17 $m^2$<br>• Sponge filling with cover (plastic canvas)<br>• Thickness: 4 cm</td></tr>
<tr><td>Stimulation</td><td>• Toys, playing materials<br>• Paintings, patterns, floor designs</td><td>• Toys for stimulation</td><td>• No removable parts or items that the infant can fit in their mouth</td><td>• No toys to avoid choking hazards / vectors for pathogen transmission</td></tr>
<tr><td colspan="5">FGD, focus group discussion; UCD, user-centered design; TIPs, Trials of Improved Practices; $m^2$, meters squared; cm, centimeter; mm, millimeter; mm/s, millimeters per second.</td></tr>
</table>

## 5.8 Piloting processes

The HPS was piloted the TIPs and the randomised feasibility trial. A TIPs approach (described in section 2) was used to pilot the three HPS prototypes and alongside providing feedback on the prototype designs, gave initial insights into reasons for acceptability and use and barriers to use among study households. Further details of the methodology are in the supplementary material (S2). The final prototype design was then tested in the CAMPI feasibility trial – a two-armed, parallel-group, randomised, controlled feasibility trial in one hundred households randomised (blinded) to intervention or control (both n=50). It primarily aimed to describe feasibility of progressing to a full RCT and outcomes included recruitment, attrition, adherence, and acceptability. Secondary outcomes included effects on infant health, injury prevention and women's time. The trial methodology and full results are published separately.[38] The feasibility outcomes from the TIPs and the feasibility trial are described below in terms of Acceptability (acceptability of use, acceptability of design and time use)and Adherence (appropriate use, cleaning and infant hygiene).

### 5.8.1 Acceptability

The TIPs and the feasibility trial showed good overall acceptability among study households who received an HPS. Results for acceptability are separated into acceptability of use, acceptability of design and playspace time use.

**Acceptability of use**

There appeared no negative consequences of use, either observed or reported. One household expressed concern over whether the infant was happy inside and reiterated the need for toys. No households expressed any safety concerns. A modified Barrier Analysis conducted at the end of the CAMPI trial provided further insight into HPS acceptability through key attitudes and behavioural determinants of use. Methods are described in detail elsewhere[49,50] as followed by the feasibility trial.[38] Briefly, the Barrier Analysis assessed 12 categories of behavioural determinants, exploring all factors which would act as barriers or enablers to HPS use and maintenance. Through certain determinants, the Barrier Analysis also demonstrates acceptability. Partial results relating to acceptability are shown in **Table 11**. Caregivers reported high approval from neighbours (96.0%, n=48) and immediate family (66.0%, n=33) and low disapproval (friends of parents 12.0%, n=6; neighbours 8.0%, n=4). The determinants *Perceived divine will*, *Policy* and *Culture* suggest social acceptability within this context.

Many cited advantages, related and unrelated to infant health, further demonstrated good acceptability. Caregivers (mothers) mentioned how the HPS prevented geophagy (80.0%, n=40), 76.0% (n=38) and injury from many causes and eased their workload (56.0%, n=28) and time pressures (46.0%, n=23). Reported disadvantages of using the HPS related to lack of help to supervise the infant (32.0%, n=16) and toys (32.0%, n=16).

**Acceptability of design**

Although the three households with prototype three (**Table 9**) did not like the mesh walls, overall feedback on each prototype was positive. Six mothers commented they felt happy to see their child standing, facilitated by the walls. All mothers commented they were happy the HPS kept their child clean and 'for being healthy, to prevent disease'. Researchers noted households commented on neighbours' positive feedback (*'They really like it and are jealous of it'; 'Anyone who saw the playspace become happy and they have positive feedback.')* The Barrier Analysis indicated mixed acceptability of design among households. The use of the rope to tie the sides was the safest, easiest solution during playspace design. Fifty-four percent (n=27) found this easy to manage but 38.0% (n=19) found the rope difficult. The size, door fixture and structure were largely appreciated.

**Playspace time use**

Acceptability among households was also assessed in terms of time use of the HPS. The TIPs trial provided initial indications of how often the HPS would likely be used during the day during the feasibility trial. During unannounced visits at five days and one month, the infant was inside the HPS upon arrival in all households. Using the daily activities template (Appendix A), daily time use of the HPS was assessed by caregiver interview. Here, caregivers were asked their daily activities and if the HPS was used and from that, time use was estimated. Results are detailed below in **Table 12**. Only two households used the HPS for the agreed six hours by the five-day visit. By one month, all households had reduced the amount of time by at least one hour, except one household. As shown, households who initially used the HPS the most reported the greatest decrease in time use. Among reasons for discontinuing use, four households noted an absence of playing materials as a main reason and caregivers removed the infant if they started crying. Two households reported that after one month the infant was walking and was too old to stay inside. Most (six) households suggested the HPS was too big to keep assembled and was a reason for non-use.

At two and four weeks in the feasibility trial, primary caregivers were asked open-ended questions to record their activities during the past 24 hours, and if they did or did not use the HPS. Full results are shown in the supplementary material (S3) and aggregated by category in the feasibility trial paper.[38] Broadly, use decreased during food preparation and eating and also during visits outside of the home (to church, the market, neighbours). In contrast use increased during other activities inside the home (washing clothes, breastfeeding) and outside of the home (preparing enset [false banana], farming). Second, analysing HPS use according to daily activities and time period (time of day) suggested use was highest in the mornings (**Table 13**). Use in the evenings did increase later in the trial.

*Table 11. Partial Barrier Analysis results from the intervention group in the CAMPI trial.*[38]

| **BA determinant and question** | | Yes | | No | | Don't know | |
|---|---|---|---|---|---|---|---|
| | | n (50) | % | n (50) | % | n (50) | % |
| *Perceived divine will* | Do you think God approves of you using the HPS? | 48 | 96.0 | 1 | 2.0 | 0 | 0.0 |
| *Policy* | Are there any community rules which prevent you from using the HPS? | 0 | 0.0 | 50 | 100.0 | 0 | 0.0 |
| *Culture* | Are there any cultural rules that you know of against using the HPS? | 0 | 0.0 | 50 | 100.0 | 0 | 0.0 |

HPS, household playspace.

| **BA determinant** | **BA question** | **Inductive theme** | n (50) | % |
|---|---|---|---|---|
| *Perceived positive consequences* | What are the advantages of using the HPS? | Prevents ingestion of dirt/soil/dirty objects | 40 | 80.0 |
| | | Prevents injury (falling, fire, drowning, dust/ash, road) | 38 | 76.0 |
| | | Prevents injury from animals | 29 | 58.0 |
| | | Decreases/Eases mother's workload | 28 | 56.0 |
| | | Mother worries less for infant's health/safety | 26 | 52.0 |
| | | Eases time pressure for mother/stress | 23 | 46.0 |
| | | Improves infant's physical development | 21 | 42.0 |
| | | Infant/Clothes stay clean | 20 | 40.0 |
| | | Prevents ingestion of faeces | 20 | 40.0 |
| | | Infant feels happy playing inside/comfortable | 18 | 36.0 |
| | | Prevents diarrhoea/Other disease | 14 | 28.0 |
| | | Protects from sunlight | 4 | 8.0 |
| | | Promotes infant's independence | 2 | 4.0 |
| *Perceived negative consequences* | What are the disadvantages of using the HPS? | No disadvantage | 26 | 52.0 |
| | | Cost of extra cleaning materials | 11 | 22.0 |
| | | Takes up space inside the home | 7 | 14.0 |
| | | Infant cries (from boredom) | 7 | 14.0 |
| | | Extra item to clean | 6 | 12.0 |
| *Perceived self-efficacy* | What makes it easy for you to use the HPS? | Easy to assemble/rope easy to tie | 27 | 54.0 |
| | | Weighs little/Easy to move (including mattress) | 25 | 50.0 |
| | | Good size/Takes little space inside | 22 | 44.0 |
| | | Door facilitates easy use | 14 | 28.0 |
| | | Safe design/Infant easily visible | 14 | 28.0 |
| | | Design encourages infant play (size/comfort) | 13 | 26.0 |
| | | Bamboo structure strong/Stable/Durable | 12 | 24.0 |
| | | Can be taken outside | 8 | 16.0 |
| | | Older children who can watch infant | 8 | 16.0 |
| | | Good width to slats to encourage standing | 4 | 8.0 |

| | | | | |
|---|---|---|---|---|
| | What makes it difficult for you to use the HPS? | Difficult to rethread rope when dismantled | 19 | 38.0 |
| | | No older children to watch infant | 16 | 32.0 |
| | | Lack of toys | 16 | 32.0 |
| | | Difficult to move outside/Heavy without help | 8 | 16.0 |
| | | Rope may become loose/Structure falls | 4 | 8.0 |
| | | Nothing | 3 | 6.0 |
| | | Takes up space/House is small | 2 | 4.0 |
| | | No older children to watch infant | 2 | 4.0 |
| | | Plastic can get hot in sun | 1 | 2.0 |
| | | Height insufficient | 1 | 2.0 |
| *Access* | What makes it easy for you to keep the HPS clean? | Plastic covering easily cleaned | 39 | 78.0 |
| | | Mattress lightweight/Small to carry/Removable | 38 | 76.0 |
| | | Requires little water | 34 | 68.0 |
| | | Dries quickly (in/out of sun) | 16 | 32.0 |
| | | Bamboo stays clean/easy to wipe | 14 | 28.0 |
| | | Requires little soap | 13 | 26.0 |
| | | Plastic does not absorb smell/urine/dirt | 5 | 10.0 |
| | | Soap easy to buy/Inexpensive | 2 | 4.0 |
| | | Water easily available | 2 | 4.0 |
| | What makes it difficult for you to keep the HPS clean? | Lack of/Expense of buying soap | 28 | 56.0 |
| | | Water unavailable at times | 13 | 26.0 |
| | | Requires extra cleaning materials/Associated cost | 12 | 24.0 |
| | | Nothing | 6 | 12.0 |
| | | Material (rough bamboo/rope/open seams) | 5 | 10.0 |
| *Perceived social norms* | Who are the people who approve of you using the HPS? | Neighbours | 48 | 96.0 |
| | | Immediate family (parents, grandparents, siblings) | 33 | 66.0 |
| | | HEW/HDA/Other government worker | 24 | 48.0 |
| | | Husband | 20 | 40.0 |
| | | Friends of parents | 18 | 36.0 |
| | | Aunts/Uncles/Family-in-law | 18 | 36.0 |
| | | Community members/Guests/Passers-by | 11 | 22.0 |
| | | Laborer/Customers | 3 | 6.0 |
| | Who are the people who disapprove of you using the HPS? | Nobody | 37 | 74.0 |
| | | Friends of parents | 6 | 12.0 |
| | | Neighbours | 4 | 8.0 |
| | | Community members/Colleagues/Customers | 3 | 6.0 |
| BA, Barrier Analysis; HPS, household playspace. | | | | |

Table 12. Daily time use of the playspace during the TIPs trial at five days and one month.

| **Household Number (N=9)** | **Agreed HPS time use at baseline** | **Reported HPS time use at five days** | **Reported HPS time use at one month** | **Difference in HPS time use** |
|---|---|---|---|---|
| 1 | 6 or more hours | 6 hours | 4 hours | - 2 hours |
| 2 | | 6 hours | 4 hours | - 2 hours |
| 3 | | 4 hours | 3 hours | - 1 hour |
| 4 | | 6 hours | 5 hours | - 1 hour |
| 5 | | 4 hours | 4 hours | No change |
| 6 | | 4 hours | 3 hours | - 1 hour |
| 7 | | 5 hours | 4 hours | - 1 hour |
| 8 | | 3 hours | 2.5 hours | - .5 hour |
| 9 | | 3 hours | 2.5 hours | - .5 hour |
| HPS; household playspace. | | | | |

Table 13. Reported playspace use and non-use during daily activities in the past 24 hours across daily time periods: at two and four weeks in the intervention group in the CAMPI feasibility trial.

| | Morning | | Afternoon | | Evening | |
|---|---|---|---|---|---|---|
| | Two weeks | Four weeks | Two weeks | Four weeks | Two weeks | Four weeks |
| Reported use of HPS | 154 | 153 | 119 | 153 | 93 | 105 |
| Reported non-use of HPS | 24 | 32 | 28 | 32 | 42 | 60 |

HPS, household playspace.
Figures are summed from reported daily activities table in S3.

### 5.8.2 Adherence (appropriate use and cleaning, infant hygiene)

During the TIPs, all households reported they had cleaned the HPS at least once during the week (data on exact times not collected). Although all households reported using soap, this could not be confirmed. However, the field team reported that all HPS were clean upon observation at both visits with no sign of faecal contamination or dirt. One household had a small plastic dish and one household a plastic bottle inside the HPS which were visibly dirty. Households with an HPS with no mattress reported it was difficult to clean and two had put down a plastic sheet.

**Table 14** details some HPS use behaviours, infant hygiene and HPS cleaning practices across study time points in the feasibility trial. Infants in the HPS were mostly watched by an older child (85.0%, n=85 throughout the trial) and were often left inside when the caregiver went out, although this decreased between study time points (82.0%, n=41 at two weeks to 52.0%, n=26 at four weeks). In the absence of toys, caregivers found items for infants to play with, most frequently plastic cups or water bottles (65%, n=65; 54.0%, n=54 respectively, throughout the trial). Observational data on infant and HPS hygiene suggest cleanliness improved slightly by four weeks, including mattress cleanliness (visible dirt: 12.0%, n=6 to 6.0%, n=3, respectively). This contrasts with data on HPS cleaning routines where daily cleaning dropped between two to four weeks (60.0%, n=30 to 32.0%, n=16) but twice weekly increased (18.0%, n=9 to 34.0%, n=17, respectively). Using soap alongside water also marginally increased by three respondents (90.0%, n=45 to 96.0%, n=48). Further detailed results on appropriate use and cleaning behaviours are reported in the feasibility trial paper.[38]

*Table 14. Playspace use behaviours and infant hygiene and playspace cleaning practices in the intervention group in the CAMPI feasibility trial.*[38]

| **HPS use behaviours** | | | | | | |
|---|---|---|---|---|---|---|
| | Two weeks | | Four weeks | | Both time points | |
| | n (50) | % | n (50) | % | N (100)* | %** |
| Who watches the infant: Another child | 42 | 84.0 | 43 | 86.0 | 85 | 85.0 |
| Mother | 27 | 54.0 | 28 | 46.0 | 55 | 55.0 |
| Husband | 18 | 36.0 | 24 | 48.0 | 42 | 42.0 |
| A grandparent | 0 | 0.0 | 1 | 2.0 | 1 | 1.0 |
| Infant in HPS when leave house | 41 | 82.0 | 26 | 52.0 | 67 | 67.0 |
| Other child shares the HPS | 14 | 28.0 | 18 | 36.0 | 32 | 32.0 |
| Who shares the HPS: Mother to feed | 6 | 12.0 | 10 | 20.0 | 16 | 16.0 |
| Sister or brother | 4 | 8.0 | 4 | 8.0 | 8 | 8.0 |
| Another child | 2 | 4.0 | 6 | 12.0 | 8 | 8.0 |
| Twin | 1 | 2.0 | 1 | 2.0 | 2 | 2.0 |
| Infant given toys or items to play | 43 | 86.0 | 46 | 92.0 | 89 | 89.0 |
| Items given: Plastic cup | 32 | 64.0 | 33 | 66.0 | 65 | 65.0 |
| Plastic water bottle | 27 | 54.0 | 27 | 54.0 | 54 | 54.0 |
| Jerry can cover | 8 | 14.0 | 6 | 12.0 | 14 | 14.0 |
| Empty plastic container | 7 | 13.0 | 5 | 10.0 | 12 | 12.0 |
| Mobile phone | 6 | 12.0 | 6 | 12.0 | 12 | 12.0 |
| Small ball | 5 | 10.0 | 5 | 10.0 | 10 | 10.0 |
| Store-bought plastic toys | 2 | 4.0 | 6 | 12.0 | 8 | 8.0 |
| Book/paper | 2 | 4.0 | 2 | 4.0 | 4 | 4.0 |
| Reasons to remove infant: Infant hungry | 49 | 98.0 | 49 | 98.0 | 98 | 98.0 |
| Infant is crying | 44 | 88.0 | 46 | 92.0 | 90 | 90.0 |
| Infant has defecated/urinated | 39 | 78.0 | 37 | 74.0 | 76 | 76.0 |
| To clean the playspace | 30 | 60.0 | 26 | 52.0 | 56 | 56.0 |
| To wash/change infant | 25 | 50.0 | 30 | 60.0 | 55 | 55.0 |
| To breastfeed/feed | 11 | 22.0 | 15 | 30.0 | 26 | 26.0 |
| Infant is sleeping | 4 | 8.0 | 1 | 2.0 | 5 | 5.0 |
| To go out | 1 | 2.0 | 2 | 4.0 | 3 | 3.0 |
| **Infant hygiene and HPS cleaning** | | | | | | |
| **Observational data** | | | | | | |
| Infant visibly dirty upon arrival | 20 | 40.0 | 19 | 38.0 | 39 | 39.0 |
| Infant has dirty hands and nails | 28 | 56.0 | 24 | 48.0 | 52 | 52.0 |
| Visible dirt on mattress | 6 | 12.0 | 3 | 6.0 | 9 | 9.0 |
| Urine or faeces on mattress | 1 | 2.0 | 1 | 2.0 | 2 | 2.0 |
| Animals inside HPS (observed) | 1 | 2.0 | 0 | 0.0 | 1 | 1.0 |
| **Caregiver-reported data** | | | | | | |
| How often clean HPS: Every day | 30 | 60.0 | 16 | 32.0 | 46 | 46.0 |
| Twice a week | 9 | 18.0 | 17 | 34.0 | 26 | 26.0 |
| Every other day | 6 | 12.0 | 6 | 12.0 | 12 | 12.0 |
| Only when infant defecates/urinates | 3 | 6.0 | 11 | 22.0 | 14 | 14.0 |
| Only when it is dirty | 2 | 4.0 | 0 | 0.0 | 2 | 2.0 |
| Cleaning materials used: Water only | 5 | 10.0 | 2 | 4.0 | 7 | 7.0 |
| Water and soap | 45 | 90.0 | 48 | 96.0 | 93 | 93.0 |
| Animals seen inside HPS: Yes | 4 | 8.0 | 0 | 100.0 | 4 | 4.0 |
| Which animals? Cat | 2 | 50.0* | 0 | 0.0 | 2 | 2.0 |
| Poultry | 2 | 50.0* | 0 | 0.0 | 2 | 2.0 |

HPS, household playspace.
*Calculated as a cumulative total of both time points.
**Percent is of the cumulative total.

## 5.9 Discussion

### 5.9.1 Design and build (materials and methods)

The team designed and built an HPS that was locally produced and acceptable among households in the local context by way of a user-centred design process. The multi-stage, participatory process, including an FGD, two participatory and user-centred workshops and a TIPs, supported the development of the final prototype. This was then finally tested in a feasibility trial.

The TIPs and the modified Barrier Analysis in the feasibility trial suggested the design was acceptable and appropriate among study households. It addressed user needs where it was easy to assemble, a good size, the infant was easily visible and it was easily moved outside. Issues with the design included the rope which attached side: future designs might consider metal hinges but which were decided as a potential safety concern here. Other alternatives might include a latch such as a hook and eye form. Some caregivers reported the HPS was prohibitively heavy; the bamboo structure did add weight, however more caregivers said it was easily moved and appreciated its sturdiness and durability. The plastic covering and foam mattress were lightweight and easily cleaned, requiring little water and soap, both of which were at times unavailable. During the TIPs and the feasibility trial, caregivers expressed the need for toys, and almost all gave infants other objects to play with which were frequently dirty. Some stimulation for play is clearly required and is a necessary consideration for child psychosocial development.[51,52] Providing toys with the HPS may have improved time-use and adherence. However, in the TIPs and feasibility trial, toys were not included. This was to avoid potential safety hazards and as potential vectors for faecal-oral transmission. Research shows toys can introduce external bacteria to infants[53] and where often visibly dirty, were a common hazard in Zambia.[34] The HPS might offer visual and tactile stimulation within the design: alternatively, caregivers may be counselled on providing non-hazardous toys that can be cleaned regularly. Another potential exposure risk is other children sharing the HPS. Although not recorded in this study, the WASHPaLS team noted this occurred frequently (reported more than observed).[43] Older children are often required to watch and/or entertain the infant which may introduce other contamination (including giving items/toys to the infant) and must be considered as sources of infection risk.

### 5.9.2 Piloting and feasibility

Research groups and organisations have recorded a strong demand from caregivers for a hygienic space.[30,34,54,55] Initial findings from discussions with mothers during the FGD supported this demand. Acceptability outcomes from the TIPs and the feasibility trial suggested that an HPS was highly valued and largely feasible among the study households in terms of acceptability and adherence. The TIPs results suggested households mostly kept the HPS clean and the feasibility trial demonstrated infant and HPS hygiene improved marginally over the trial duration: however daily cleaning became less frequent. Soap use reportedly increased, however the modified Barrier Analysis suggests accessing soap was difficult, and previous data from this team suggest soap ownership was not common.[22,37] As reported in the feasibility trial paper, appropriate use and cleaning remained largely consistent across the four weeks, but for a small decline.[38] Providing soap alongside an HPS would be a key consideration in future interventions.

Time-use was inconsistent across and within households within the TIPs and feasibility trials. In the former it decreased by up to two hours and in the latter during certain daily activities, though increasing when the caregiver left the home. Further data on time-use in relation to daily routines is discussed in the feasibility trial results paper.[38] Together, results suggest that whilst compliance during initial use may be high, it will likely fall away over time. When this falls away and why, and what can be done to help avoid this, are key questions moving forward with this research. A behavioural module is therefore a likely necessary component to a future definitive trial or intervention which might improve time-use.

### 5.9.3 A household playspace as part of a Transformative WASH package

As intended by the BabyWASH approach, small but fundamental behavioural changes enabled by tailored, feasible and acceptable technologies may help improve infant growth. The TIPs and the feasibility trial demonstrated that an HPS, where it is able to separate infants from animals and both animal and human faeces, may provide some benefit to preventing faecal-oral transmission and thus infection.[38] However, it is not certain that once given specific enabling technologies, behaviour change will automatically follow. The ENGINE study reported inconsistent household use of their locally-produced mats where many households remained unaware of the benefits.[41] A participatory design process, as followed here, seeks to avoid that: however, there is also a need to empower the target audience (caregivers) and develop self-efficacy by improving knowledge of risks.[56] This highlights the importance of appropriate messaging to communities, particularly through existing structures like HEWs and savings groups to improve HPS use.[34] Moreover from this, it would be important to incorporate culturally-relevant behaviour change theory into the design of the intervention from the start. The integration of key behavioural, social, or psychological theories into a Theory of Change framework can help specify techniques and activities that might strengthen behaviour change during the intervention.[57] This is likely an important consideration during a Transformative WASH strategy. Further, where an HPS may serve as one material intervention component to help prevent faecal-oral transmission, it will not block all routes. Other necessary components to help block transmission infection will include safe water, proper food hygiene and the separation of domestic animals within the home.[16,36–38]

Although true participatory design process in developing settings is difficult to achieve,[44] the process did help facilitate the development of two outcomes: a product that met user needs and the psychological empowerment of caregivers where they hope to improve their infant's health.[44] The final HPS prototype embodied the needs and requirements of the main users (infants and their caregivers) as well as multiple stakeholders (research teams, donor and implementer communities, government health workers). This came from a consideration and discussion of local contextual needs, including livelihood patterns, maternal work burden and caregiving practices and maternal/caregiver needs for their infant's health. These are important factors to consider during WASH intervention design which will dictate if an intervention component is acceptable and adhered to in terms of use and maintenance. Further, the design resulted from a caregiver understanding of infection risk and pathways to infection (primarily through direct faecal-oral transmission) and thus specifically aided in preventing this risk. Notably, as may be of particular importance in a Transformative WASH approach, participatory design provides the opportunity to engage and further develop the abilities and skills of the main users (caregivers).[44] This might encourage a new way of thinking about design processes and facilitate the development of new WASH intervention modalities and technologies to improve infant health.

### 5.9.4 Limitations and further considerations

Limitations of this preliminary work mostly concern the TIPs, including the sample size and data quality. The trial aimed to assess initial behaviours, attitudes and use within a small number of households. However, this was within a small timeframe where the HPS remained novel and high adherence may have been an artefact of this. Whilst the TIPs provided rich data from individual households, it was not designed to explore behaviours or attitudes at the population-level. Rather it serves as a template for how others might design and test similar sorts of interventions intended to form part of a transformative WASH package. Other limitations surrounding data quality and the methodologies assessing use include the use of self-reported data which can hold inherent inaccuracies. The daily activities form to assess playspace use (Appendix A) aimed to overcome difficulties of measuring time in a context where hourly intervals are not widely comprehended. However, time use was assessed *after* the caregiver negotiated an agreed daily period of use: this leaves the strong possibility that reported time use was exaggerated. This cannot be confirmed without observational data.

A further consideration for this type of material intervention is economic, including cost, the ability to scale up production and household willingness to pay. The final prototype cost $45 or 1500 ETB. This would be prohibitively expensive to rural households. Similarly, the team in Zambia reported that the plastic HPS was prohibitively expensive which supported the development of a community-built model.[31] Although this model, constructed using locally-sourced material and labour, was deemed affordable there was no information on cost. This an important route forward would be to understand how an HPS might be subsidised as part of a WASH intervention.  Whilst this research did not assess economic demand this is also an important route for further research linking to evaluations of cost effectiveness and market potential. Whilst the HPS was valued and a demand may exist, this is based on stated preferences with known biases. During their formative follow-up study, the USAID ENGINE Project subsidised the market price of locally produced playmats at almost 50% and could not see a sustainable business model without the subsidy.[28] Although by year four, savings groups sold out of mats and a supplier was identified, no group purchased a resupply. Seasonality (dictating household income) was also a strong predictor of willingness to pay.[28] The artisanal manufacture also means there are no real economies of scale. Thus, donors or governmental bodies, implementers or research groups aiming to produce this design in bulk or similar material inputs would also benefit from researching the potential for large-scale manufacture. Alternatively, in the user-centred design workshop in Ethiopia, households indicated they would be willing to pay around $8 for a playspace. Although a design as advanced as the final prototype could not be produced at that price, a different forward might be understanding how households can create their own solutions on a budget with available materials, when there is no subsidy available.

#### 5.9.5 Playspace safety

The design and build of the HPS followed both international safety standards for cots and child's furniture[46,47] and a British standard safety checklist.[48] During the TIPs and the feasibility trial there were no reported concerns from caregivers regarding HPS safety. When discussing safety protocols with households (Appendix B), caregivers were instructed to not leave their infant in the HPS for more than an hour. This was to avoid lack of supervision and neglect, where 'low-severity lack of supervision' is defined in the Modified Maltreatment Classification System (MMCS) guidelines (further discussed in the supplementary material, S1).[58] While caregivers reported consistent supervision of the infant, this may not have been the case. The feasibility trial noted an increase in caregivers leaving the infant alone towards week four which may have implications for safety and development.[38] Further observational data is required to understand actual use of the HPS, interactions between the caregiver and infant and whether any safety concerns arise from poor supervision or extended periods left alone.

### 5.10 Conclusion

Evidence suggests that current WASH intervention design does not adequately improve environmental hygiene, nor sufficiently consider infant behaviours, for better infant health. Where there are multiple sources of faecal contamination, it is unlikely there is one solution. Instead, the WASH sector must identify individual components that are necessary parts of a comprehensive 'transformative' intervention, which are at once feasible, practical and acceptable within the local context and aim to reduce bacterial transmission through a BabyWASH lens. Whilst caregivers appear aware of the health risks associated with infant faecal ingestion[30,59] education alone is unlikely to prevent this without a material component which blocks exposure.[60] An appropriate technology may thus help drive behavioural change and prevent faecal-oral transmission and infection. This paper details the evidence-based design and piloting of a household playspace – one potential intervention component of a Transformative WASH approach. Results from this iterative process suggest an HPS was an acceptable and feasible option among these low-income, rural subsistence households in Ethiopia. In these settings where free-range livestock and domestic animals present an increased risk, an HPS may help reduce faecal-oral transmission during critical, early growth periods.

The design and piloting process as detailed in this paper responds to a clear need for suitable material inputs in the BabyWASH sector. The paper aims to serve as a framework for future, similar HPS interventions in other similar contexts, or for teams developing similar material inputs, and to share and develop best practice within the field. Further research on HPS feasibility must assess use (ideally via observation) over a longer time period, understand reasons for diminishing use and explore methods to address drops in compliance. A tailored behavioural module would be a necessary consideration going forward. Further, data is also needed on any time-use ‘threshold effect’ of an HPS which might limit exposure and reduce infection.

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## 5.12 Author contributions

SB wrote the manuscript. AP, PH and CG had input on design and piloting processes and contributed to the paper quality, writing and review. JR contributed to the paper quality, writing and review. TT, FW and MJ managed and coordinated the field team, logistics and data collection in Ethiopia and contributed towards the design, piloting and manufacture processes. BE and LW contributed towards the design processes.

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## 5.14 Declaration of interest

All authors have no conflict of interests to declare.

## 5.15 Data access

All data created during this research will be openly available from the Cranfield Online Research Data (uploaded following thesis completion).

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## 5.17 Appendix

**A1. Template for recording playspace time use during the Trials by Improved Practice (Ethiopian time)**

| Time (hours) | What the mother is usually doing (O) Out of house / (I) In House | What is the father usually doing (O) Out of house / (I) In House | If there is another caregiver, what are they usually doing? (O) Out of house / (I) In House | Who is responsible for the child at these times? | When do the parents / caregivers think the child could be in the playspace? | What was the negotiated agreement for time use? |
|---|---|---|---|---|---|---|
| 0:00 | | | | | | |
| 1:00 | | | | | | |
| 2:00 | | | | | | |
| 3:00 | | | | | | |
| 4:00 | | | | | | |
| 5:00 | | | | | | |
| 6:00 | | | | | | |
| … | | | | | | |

**A2. Safety protocols discussed with caregivers during the Trials by Improved Practices**

Safety protocols adapted from ISO 7175-1:2019.[38]

Warning:

- Be aware of the risk of open fire and sources of strong heat near the playspace
- Do not use the playspace if any part is broken, torn or missing
- Do not leave anything in the playspace that could harm the child
- Do not leave anything in the playspace that your child can fit into their mouth and swallow
- Do not place the playspace close to another product which could allow the child to climb out of the playspace
- Do not place the playspace close to another product which could cause suffocation or strangulation (for example, ropes or cables)
- Do not use more than one mattress in the playspace
- Do not replace the mattress with a different mattress

Instructions for use:

- The child should not be in the playspace for periods longer than one hour
- The child should not be left unattended in the playspace
- The mattress should be cleaned regularly using soap and water
- When your child is able to climb out of the playspace, the playspace should no longer be used for that child

## 5.18 Supplementary information

**S1. Focus group discussion methodology**

Alongside a local Health Extension Worker (HEW), eight mothers were purposefully selected and recruited from kebeles (villages) within PIN outreach and which represented typical subsistence livelihoods across the zone. Criteria were households which owned livestock or poultry and with an infant aged 10−18 months. The FGD explored how an HPS might be incorporated into daily life by discussing usual routine – particularly in relation to infant care and play. Other questions explored if mothers already set a particular space for the infant to play, whether that was protected by a physical barrier and current methods to control infant behaviours, such as crawling and the mouthing of objects. Structured questions explored perceived severity of animal and human faeces near the infant, perceived positive and negative consequences of the mat and cleaning practices. Secondly, the FGD aimed to understand HPS design requirements from the mothers' perspectives given their daily routines and caregiving practices. Mothers were asked how they would change the design to better look after the infant, to make it more enjoyable for the infant, to ensure animals stayed off and how to easily clean it.

**S2. Trials by Improved Practice methodology**

TIPs is a participatory, formative research technique which allows 'audiences' or practitioners to identify, test and/or refine actual practices and enabling products that a program or intervention will eventually promote. Simply, the trial consists of a series of visits where the interviewer and participants analyses current practices, discuss potential changes and together agree behaviours and/or products to try over the trial period. These are then assessed throughout the trial period, and results feed directly into product or program design.[50] Thus the TIPs process provided user feedback on the three household playspace (HPS) designs. It also allowed the team to pre-test the actual practices that the randomised feasibility trial would engage, providing initial feasibility data on acceptability, time use and maintenance (correct use and cleaning). During the first visit, a PIN WASH team member and caregiver agreed a set amount of time for daily use and a cleaning schedule. During subsequent visits, the team member used observational and survey data to assess if, how and why these behaviours were maintained, allowing insight into the barriers and motivators that prevented or enabled HPS use. Follow-up visits were unannounced to avoid changes in caregiver behaviour. The TIPs stages were: 1. Household identification alongside a local HEW and household visit to recruit and consent households 2. Visit one: HPS allocation and behaviour negotiation; 3. Visit two: five days after the HPS allocation; 4. Visit three: one month after visit one.

**TIPs stage 1: Household selection**

The rural Woredas (administrative district) of Lokabaya and Aletawondo were chosen for their close proximity to the PIN office, Hawassa and which represent typical rural subsistence livelihoods across the zone. PIN WASH team members used pre-specified eligibility criteria and engaged a local HEW to identify households from respective Kebeles. Criteria included: households with an infant aged 10−18 months; within the pre-specified villages; raising domestic animals (cattle, poultry) and not involved in any other PIN intervention. In the nine households, the study team met the caregivers, verified the age of the infant and if the household raised domestic animals. A PIN team member described the study using a participant information sheet and discussed consent using pre-translated forms in either Amharic or Sidamo. The mother provided both signed consent and assent on behalf of her infant. Any questions or expectations were addressed.

**TIPs stage 2: Household visit one: Playspace allocation and behaviour negotiation**

Prior to the first visit, prototypes were randomly assigned to households using a simple random sample (lottery) method. Upon arrival, PIN team members brought the HPS to the home and ensured all caregivers were present who would supervise the infant. Team members discussed with caregivers the importance of using the HPS and the significance to their infant's health. Team members and caregivers negotiated behaviours by discussing:

- A description of household activities in hourly periods throughout the day and during which of these the caregiver would use the HPS (agreeing 'use' behaviour; Appendix A)
- How often the caregiver would clean the HPS and with what materials (agreeing 'maintenance' behaviour)
- Safety protocols, correct use of the HPS and any immediate concerns the caregivers had about safety (also agreeing 'maintenance' behaviour)

The first point provided initial feedback on how many hours a day the HPS could be used. The field team and all households agreed to use the HPS for six hours or more. It was negotiated that the infant would be in the HPS when the mother was preparing coffee, meals during household activities, when the infant was not sleeping, after breastfeeding or having eaten. Mothers would not leave the infant in the HPS during activities outside the home, such as fetching water. Actual time use as recorded during follow-up visits would then suggest what was realistic to promote during the trial.

Cleaning behaviours negotiated with all households were to clean the mat using water and soap and to dry the mat in the sun. Mothers should clean the mat when the infant had defecated, when an animal had entered and defecated and at least once a week. Again, recorded behaviours during follow-up would suggest a cleaning schedule realistic to promote in the trial.

Safety protocols discussed with households can be viewed in Appendix B. Mothers were counselled on these and shown how to dismantle and assemble the HPS. Importantly, caregivers were instructed to not leave their infant in the HPS for more than an hour. This was to avoid lack of supervision and neglect: 'low-severity lack of supervision' is defined in the Modified Maltreatment Classification System (MMCS) guidelines,[51] as noted in similar HPS testing.[31] Infants require supervision and also regular, consistent interaction and leaving them for long periods can hold negative implications for development.[52] Thus periods exceeding 90 minutes were classified as a safety hazard, again following similar research.[31]

**TIPs stage 3: Household visits two and three**

The second household visit took place five days after HPS distribution. A WASH team member observed upon arrival whether the HPS was in use, HPS cleanliness (visible dirt, faeces or liquid), location of the HPS, damage or any modifications made and animals or other objects inside. A modified template based on daily household activities captured previously (Appendix A) was used to ask the mother about HPS use during the previous day, enabling an estimation of time use. For the agreed upon use and maintenance behaviours, mothers were also asked questions which followed a barrier analysis format:

- What made it difficult or easier to use and clean the HPS?
- How would they change the design to make it easier to use and clean the HPS?
- Perceived positive and negative consequences of the HPS
- Social norms: were there any positive or negative comments and from whom?

During this first visit, the mother had the opportunity to negotiate the initial agreement on use, cleaning and maintenance. Any agreed changes were recorded.

The third visit at one month followed the same structure using both observational data and structured questions to capture the same data.

**S3. Reported daily activities and reported use or non-use of the playspace during the past 24 hours, across daily periods and study time points in the intervention group in the CAMPI feasibility trial[36]**

| | Morning | | | | | | | | Afternoon | | | | | | | | Evening | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Two weeks | | | | Four weeks | | | | Two weeks | | | | Four weeks | | | | Two weeks | | | | Four weeks | | | |
| | Used HPS | | Did not use HPS | | Used HPS | | Did not use HPS | | Used HPS | | Did not use HPS | | Used HPS | | Did not use HPS | | Used HPS | | Did not use HPS | | Used HPS | | Did not use HPS | |
| | n* | %** | n | % | n | % | n | % | n | % | n | % | n | % | n | % | n | % | n | % | n | % | n | % |
| Prepared breakfast | 40 | 89.0 | 5 | 11.0 | 42 | 89.0 | 5 | 11.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Prepared coffee | 32 | 94.0 | 2 | 6.0 | 37 | 95.0 | 2 | 5.0 | 5 | 83.0 | 1 | 17.0 | 14 | 88.0 | 2 | 12.0 | 32 | 91.0 | 3 | 9.0 | 34 | 85.0 | 6 | 15.0 |
| Cleaned the house | 37 | 86.0 | 6 | 14.0 | 35 | 83.0 | 7 | 17.0 | 3 | 75.0 | 1 | 25.0 | 9 | 100.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 3 | 75.0 | 1 | 25.0 |
| Fetched water | 22 | 96.0 | 1 | 4.0 | 17 | 85.0 | 3 | 15.0 | 18 | 100.0 | 0 | 0.0 | 26 | 96.0 | 1 | 4.0 | 0 | 0.0 | 0 | 0.0 | 1 | 100.0 | 0 | 0.0 |
| Prepared lunch/snacks | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 48 | 96.0 | 2 | 4.0 | 44 | 98.0 | 1 | 2.0 | 6 | 100.0 | 0 | 0.0 | 4 | 67.0 | 2 | 33.0 |
| Prepared enset | 9 | 82.0 | 2 | 18.0 | 7 | 100.0 | 0 | 0.0 | 16 | 84.0 | 3 | 16.0 | 12 | 92.0 | 1 | 7.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Washed clothes | 2 | 50.0 | 2 | 50.0 | 1 | 33.0 | 2 | 67.0 | 4 | 67.0 | 2 | 33.0 | 12 | 82.0 | 1 | 7.0 | 0 | 0.0 | 0 | 0.0 | 2 | 100.0 | 0 | 0.0 |
| Farmed / maintained shop | 2 | 67.0 | 1 | 33.0 | 6 | 86.0 | 1 | 14.0 | 0 | 0.0 | 1 | 100.0 | 9 | 90.0 | 1 | 10.0 | 2 | 100.0 | 0 | 0.0 | 3 | 75.0 | 1 | 25.0 |
| Prepared dinner | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 45 | 92.0 | 4 | 8.0 | 43 | 88.0 | 6 | 12.0 |
| Went to church / meeting | 1 | 100.0 | 0 | 0.0 | 0 | 0.0 | 4 | 100.0 | 0 | 0.0 | 3 | 100.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Went to market | 1 | 100.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 13 | 93.0 | 1 | 7.0 | 12 | 75.0 | 4 | 25.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Breastfed / fed baby | 7 | 88.0 | 1 | 12.0 | 7 | 70.0 | 3 | 30.0 | 5 | 63.0 | 3 | 37.0 | 4 | 57.0 | 3 | 43.0 | 3 | 30.0 | 7 | 70.0 | 9 | 69.0 | 4 | 31.0 |
| Cleaned playspace | 0 | 0.0 | 1 | 100.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 3 | 100.0 | 0 | 0.0 | 4 | 100.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Washed infant | 0 | 0 | 2 | 100.0 | 0 | 0.0 | 3 | 100.0 | 0 | 0.0 | 4 | 100.0 | 0 | 0.0 | 5 | 100.0 | 0 | 0.0 | 12 | 100.0 | 0 | 0.0 | 6 | 100.0 |
| Chopped wood | 0 | 0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 6 | 86.0 | 1 | 14.0 | 6 | 75.0 | 2 | 25.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Visited neighbours/ other | 1 | 50 | 1 | 50.0 | 1 | 33.0 | 2 | 67.0 | 1 | 50.0 | 1 | 50.0 | 2 | 40.0 | 3 | 60.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 4 | 100.0 |
| Ate a meal | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 2 | 100.0 | 0 | 0.0 | 0 | 0.0 | 6 | 26.0 | 17 | 74.0 |
| Slept / rested | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 2 | 100.0 | 3 | 60.0 | 2 | 40.0 | 5 | 24.0 | 16 | 76.0 | 0 | 0.0 | 13 | 100.0 |

HPS, household playspace.
*Number represents reported incidence of that activity within the past 24 hours. Households (n=50) were asked an open-ended question on their daily activities during the past 24 hours. Not every activity was reported by every respondent.
**Percentages are calculated from the total number of households who reported that activity.

# 6 Fieldwork phase 3. A randomised controlled feasibility trial of a household playspace: The CAMPI study


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## 6.1 Abstract


*WASH interventions should support infant growth but trial results are inconsistent. Frequently, interventions do not consider behaviours or transmission pathways specific to age. An HPS is one intervention component which may block faecal-oral transmission. This study was a two-armed, parallel-group, randomised, controlled feasibility trial of an HPS in rural Ethiopia. It aimed to recommend proceeding to a definitive trial. Secondary outcomes included effects on infant health, injury prevention and women's time. From November 2019−January 2020 106 households were identified and assessed for eligibility. Recruited households (N=100) were randomised (blinded) to intervention or control (both n=50). Outcomes included recruitment, attrition, adherence, and acceptability. Data were collected at baseline, two and four weeks. Feasibility outcomes were as follows. Recruitment met a priori criteria (≥80%). There was no loss to follow-up, and no non-use, meeting adherence criteria (both ≤10%). Further, 48.0% (95% CI 33.7−62.6; n=24) of households appropriately used and 56.0% (41.3−70.0; n=28) cleaned the HPS over four weeks, partly meeting adherence criteria (≥50%). For acceptability, 41.0% (31.3−51.3; n=41) of infants were* *in the HPS during random visits, failing criteria (≥50%). Further, the proportion of HPS use decreased during some activities, failing criteria (no decrease in use). A modified Barrier Analysis described good acceptability and multiple secondary benefits, including on women's time burden and infant injury prevention. Despite failing some a priori criteria, the trial demonstrated good feasibility among intervention households. A definitive trial to determine efficacy is warranted.*

***Trial registration:*** *RIDIE-ID-5de0b6938afb8.*

## 6.2 Introduction

Final height in adults results from many environmental factors which support growth in childhood.[1] Conversely, adverse influences which begin *in utero* and continue through puberty can lead to growth failure.[1] This includes the cyclical relationship between infection and nutrition. Symptomatic infection is common during early years in low-income countries, and repeated diarrhoea impairs growth, weight gain and long-term cognitive development.[2] Moreover, enteric infections which are asymptomatic, but which result in subclinical enteropathy[3] are also associated with growth shortfalls[4,5] – suggesting infection affects development without overt outcomes like diarrhoea. Population-level nutrition and hygiene status are thus critical for proper growth, but are not sufficient alone: where there are widespread infection and inflammation, the effect of nutrition on growth is seriously compromised.[1] Indeed, the modest effects on growth in nutrition interventions suggests that a combination of recurrent infections, chronic inflammation, and gut enteropathy limit the effects of nutrition.[6] Thus RCTs are testing WASH interventions alongside supplementary nutrition to improve infant health.

Despite substantial evidence suggesting safe WASH contributes to good child health,[7] RCTs testing improved household WASH (with or without supplementary nutrition) have shown variable, mostly insignificant, effects.[8-11] Whilst it is improbable that interventions at the coverage in these trials will alleviate growth failure, results have prompted discourse on what is necessary. The concept 'Transformative WASH'[12] highlights the necessity of substantially improving environmental hygiene amongst the poorest, whom disproportionately experience poor child health. It also recognises the significant burden of pathogenic contamination from domestic animals – largely unaddressed in WASH trials or programs.[13] In rural, subsistence agriculture settings it is common for domestic animals to share living and sleeping spaces. Acting as natural reservoirs for several zoonotic pathogens, they likely contribute substantial contamination to multiple transmission routes,[14,15] associated with growth failure and gut abnormalities.[16,17] Further, a transformative approach will require that interventions (whether technical, structural, or behavioural) consider age-related behaviours and transmission pathways to prevent infant infection.[18] One such 'critical' WASH intervention component[19] is an HPS which, as part of a broader WASH intervention which substantially addresses pathogenic contamination across the home, might help reduce faecal-oral transmission from ingested soil and faeces,[20,21] and contaminated floors.[22] In rural areas, an HPS may offer some protection from infection during early growth periods.

The evidence on the health and non-health benefits of an HPS or playmat has been previously reviewed.[23] Further formative data during the participatory design and build of the HPS prototype suggested caregivers liked it and were glad to use it during daily routines. However, there remains a need to assess how long an HPS would be used throughout the day and appropriately maintained and cleaned. Data on infant health outcomes would provide insight into the potential for an HPS to reduce infection from within the home. Moreover, WASH interventions deliver both health and non-health outcomes, all of which contribute to household wellbeing. Thus, broader benefits of an HPS, including on women's' time and child socioemotional development, also require exploration through a definitive RCT.

### 6.3 Aims

The Campylobacter-Associated Malnutrition Playspace Intervention (CAMPI) trial was a randomised, controlled feasibility trial to establish the feasibility of a definitive RCT of an HPS in rural Ethiopia. The HPS design is described elsewhere[23] (see **Chapter 5**, **Figure 13**) underpinned by previous formative research.[24-26] Primary aims of the trial were to:

1. Establish the feasibility of future definitive RCT to evaluate efficacy of an HPS
2. Evaluate the HPS as a public health intervention through measures of recruitment, attrition, adherence, and acceptability, and as efficacy methods within an RCT
3. Evaluate the appropriateness of the study design and make recommendations to adjust the intervention and design for future trials.

As formal hypothesis testing for effectiveness is not recommended in feasibility studies, the trial did not aim to determine the effect of the HPS on health outcomes and was not powered for this. However, further evidence was required towards the infection-exposure hypothesis as well as effects on broader outcomes. Thus, secondary outcomes aimed to:

1. Confirm the prevalence of *Campylobacter* infection in the study population
2. Describe effects of the HPS on *Campylobacter* infection and diarrhoea
3. Describe secondary effects, including on women's use of time, childcare, or injury prevention.

## 6.4 Methods

### 6.4.1 Design

This feasibility trial was designed by Cranfield University alongside People In Need (PIN) and Hawassa University and conducted in the Southern Nations, Nationalities and Peoples' region, Ethiopia. It was a two-armed, parallel-group, randomised controlled feasibility trial with equal group allocation. The Consolidated Standards of Reporting Trials (CONSORT) 2010 statement with extension to pilot trials was followed during study design and reporting.

### 6.4.2 Randomisation and masking

As a feasibility trial, a sample size calculation was not performed. A target of 100 households was deemed sufficient to inform researchers about practicalities of running the trial and for sufficient precision to estimate rates of recruitment, retention, and trial outcomes. Eligible households were identified, contacted, and enrolled into the trial November 2019 and January 2020. Four kebeles (two intervention, two control) were chosen from a woreda (zonal subdivision) representative of rural livelihoods across the region, without geographical overlap. Alongside government HEWs, PIN team members produced a blinded sampling frame from kebeles of all households fulfilling eligibility criteria. Households were sequentially numbered and using statistical software, 25 households were randomly drawn from each frame for a total sample of 100 (50 intervention, 50 control). Inclusion criteria were: 1. Subsistence agriculture households raising domestic animals, within PIN intervention scope; 2. With an infant aged 8−16 months (10−18 months at trial commencement); 3. Not participating in other PIN projects. Exclusion criteria: 1. Outside 10-18-month range at trial start; 2. Participating in other PIN projects; 3. Infant was pre-term, low birth weight, or had other birth complications. PIN staff and HEWs approached households with the study information and participants were given time to make an informed decision. Households were then revisited, eligibility was re-verified, and if households were willing, consent was gained. Households were blinded to their status in the trial until after baseline data collection. **Figure 14** describes trial enrolment and numbers.

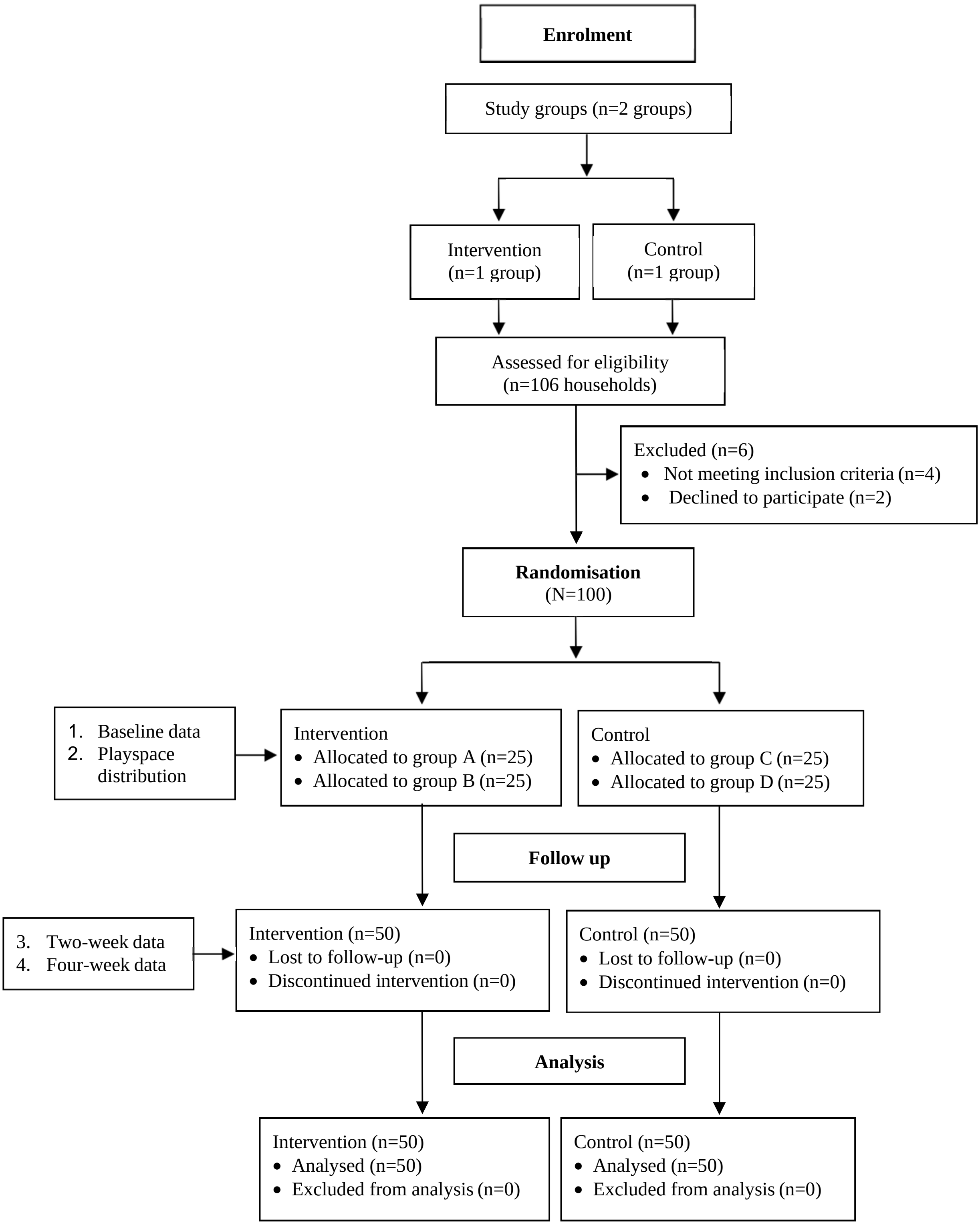


Figure 14. Modified version of CONSORT 2010 flow diagram of participants in the CAMPI feasibility trial.

## 6.5 Study intervention

The trial was conducted in Sidama zone, January−March 2020. Two field teams managed intervention and control kebeles. After baseline data collection, caregivers from intervention households were called to the kebele health post for a 'sensitisation' day. The PIN field team, HEWs and data collectors formally discussed the study rationale, caregiver beliefs around infant faecal-oral transmission and health outcomes, transmission routes and how an HPS might interrupt these to improve infant health. Correct HPS use, maintenance and cleaning was detailed. Caregivers watched and practiced HPS assembly and discussed potential safety issues. Use was discussed in relation to daily routines and activities and caregivers agreed to use it when possible. Households agreed to clean the HPS at least every other day (and always after defecation or urination) with both soap and water. Playspaces were distributed with safety instructions printed in both Sidamo and Amharic with illustrations. HEWs visited intervention households in the following days to ensure correct HPS assembly. The control group received an HPS upon study completion.

## 6.6 Participant data

### 6.6.1 Survey and anthropometry

Households were visited at baseline and at two and four weeks. The primary caregiver present was interviewed, usually the mother. Baseline data included a previously validated survey[25,26] on WASH facilities and use and animal husbandry. Food hygiene, breastfeeding, and diarrhoea incidence were also assessed and again at two and four weeks. Trained data collectors took weight, height, and mid-upper arm circumference (MUAC) following standard procedure[27] with a digital mother-child smart scale (Ultratec®), a foldable infantometer to 5 mm accuracy (seca 210®) and standard MUAC tape to 1 mm accuracy, respectively. Seven-day diarrhoea prevalence was by caregiver report.

### 6.6.2 Laboratory confirmation

Collection and processing of infant faecal samples followed a validated methodology.[26] Briefly, a day prior to household visits data collectors distributed sterile sample collection bags (Whirl-Pak®, Sigma-Aldrich, UK) and demonstrated sterile sample collection. After collection, samples were transported on ice for the isolation of presumptive *Campylobacter* spp. using CHROMagar™ selective media and appropriate microaerophilic conditions by trained laboratory staff at Hawassa University College of Medicine and Life Sciences. Samples were processed for all 100 households at each study time point.

## 6.7 Implementation outcomes

### Evaluation of trial outcomes and proceeding with future definitive trial

Among the intervention group, surveys at two and four weeks assessed feasibility outcomes: Recruitment (number of households contacted who consented); Attrition (the proportion of participants lost to follow-up at the trial end); Adherence (proportion of HPS non-use, as well as Appropriate use/maintenance and cleaning), and Acceptability (random observation of HPS use and change in incidence [proportion] of use from two to four weeks). A modified Barrier Analysis at four weeks provided further insight into acceptability. As these outcomes were the main measures to determine whether to proceed to a definitive trial, *a priori* threshold criteria were established as follows: 1. Recruitment: the proportion of contacted households participating in the trial would be ≥80%; 2. Attrition: the level at the trial end would be ≤10%; 3. Adherence: the proportion of non-use of HPS would be ≤10% at both time points and over the trial; 4. Adherence: the proportion of correct HPS use and cleaning would be ≥50% at both time points and over the trial; 5. Acceptability: the proportion of infants in the HPS at random check would be ≥50% at both time points and over the trial, and 6. Acceptability: reported incidence of HPS use during daily activities (as a proportion) would not decrease from two to four weeks. Outcomes would also indicate appropriateness of an RCT and provide recommendations for adjusting the intervention design.

## 6.8 Statistical analysis

Data were managed in Excel and analysed in SPSS (v26, IBM). Descriptive statistics summarised survey data and health outcomes. Trial outcomes are displayed with 95% confidence intervals (CI). The adherence outcome included ‘Appropriate use’ and ‘Appropriate cleaning’, created as composite binary outcome variables (described in table footnotes) and described across study time points. Adherence as ‘HPS non-use’ was described as reported non-use after baseline. Acceptability as ‘Infant in playspace upon arrival’ was calculated for both visits. Acceptability as change in HPS use was calculated from reported HPS use during reported daily activities over two and four weeks and the difference in proportions. A Generalised Estimating Equation (GEE) was used as a semi-parametric model, using a robust variance estimator and an unstructured working correlation matrix. A binary logistic GEE estimated factors associated with ‘Appropriate use’ and ‘Appropriate cleaning’ at two and four weeks. Models were initially run separately: however, the merged composite variable of ‘Appropriate use and cleaning’ showed no difference in parameter estimates between models and is presented. Pre-specified variables included infant sex and age; maternal age; maternal education; number in household; number of children; household owns soap; safe water storage; animal husbandry practices; water availability, and mother collects water. Results are expressed as populated averaged odds ratios (ORs) with 95% CI.

Acceptability was further assessed through a modified Barrier Analysis which explored determinants of use among all participants. Methods and analysis are described in detail in supplementary information (S1). Derivation of themes was data-driven, where codes resulted from the analysed data as they related to each determinant (**Chapter 5** and **S1**). Coded themes are discussed as either barriers or enablers to the implantation of, and improving outcomes during, a definitive trial. For secondary health outcomes, anthropometric z-scores were calculated (WHO Anthro v3.2.2) and categorised into stunting and wasting using standard cut-off values.[28] Samples positive for presumptive *Campylobacter* spp., colonies were counted using OpenCFU. Change in diarrhoeal and *Campylobacter* prevalence between study groups was estimated using a GEE intercept-only model with OR and 95% CI.

### 6.9 Ethics

Upon recruitment, PIN staff and HEWs discussed the study with primary caregivers who understood data were anonymous. Informed consent and assent on behalf of infant participants was obtained, or participants offered a thumbprint in place of a signature. Surveys were translated to Amharic by PIN staff and administered verbally in Amharic or Sidamo. Various checks throughout the trial assessed HPS safety and monitored for adverse events. This included regular survey checkpoints (data concerns from households and HPS safety and visual inspection of HPS for unsafe use or assembly), and the distribution of feedback response mechanism cards to contact PIN staff. Infants with moderate or severe acute malnutrition measured by MUAC were advised to contact their local health post, which was followed up by a HEW. The study was approved by Cranfield University Research Ethics Committee (CURES/9357/2019) and Hawassa University College of Medicine and Health Sciences Institutional Review Board (IRB/010/12).

## 6.10 Results

### 6.10.1 Baseline characteristics

Household demographic characteristics are described in **Table 15** for both study groups and as a whole. Characteristics were largely balanced across groups. Average infant age was 10.8 months (median 10.0; range 7−18). Average length-for-age (LAZ) and weight-for-length (WLZ) at baseline did not vary substantially across intervention and control groups at -1.00 and -0.96 (LAZ) and -0.49 and -0.46 (WLZ) respectively. Stunting and wasting affected 33.0% (n=33) and 13.0% (n=13) of all infants respectively with some severe acute malnutrition (11.0%, n=11). Mothers were mostly aged 18−25 (50.0%, n=25; 62.0%, n=31, respectively) and educated to second grade (44.0%, n=22; 52.0%, n=26, respectively). Whilst most households had a pit latrine with a slab (51.0%, n=51), open defecation was still common (19.0%, n=19). Cattle and chickens were the most frequent domestic animal, and husbandry practices indicated animals frequently shared living spaces during the day and night, with infrequent use of pens.

Table 15. Household demographic characteristics, and water, sanitation and hygiene, animal husbandry and nutrition indicators across study groups and as a total at baseline (N=100).

| | **Intervention** (n=50) | | **Control** (n=50) | | **Total** (N=100) | |
|---|---|---|---|---|---|---|
| | n | % | n | % | n | % |
| **Demographics** | | | | | | |
| Infant sex: Male | 28 | 56.0 | 24 | 48.0 | 52 | 52.0 |
| Average infant age (months) | 10.1 | | 11.6 | | 10.8 | |
| Respondent: Mother | 45 | 90.0 | 48 | 96.0 | 93 | 93.0 |
| Maternal age: <18 | 1 | 2.0 | 0 | 0.0 | 1 | 1.0 |
| 18-25 | 25 | 50.0 | 31 | 62.0 | 56 | 56.0 |
| 26-35 | 21 | 42.0 | 18 | 36.0 | 39 | 39.0 |
| 36-45 | 3 | 6.0 | 0 | 0.0 | 3 | 3.0 |
| >45 | 0 | 0.0 | 1 | 2.0 | 1 | 1.0 |
| Maternal education: Cannot read/write | 12 | 24.0 | 6 | 12.0 | 18 | 18.0 |
| First grade | 13 | 26.0 | 15 | 30.0 | 28 | 28.0 |
| Second grade | 22 | 44.0 | 26 | 52.0 | 48 | 48.0 |
| Secondary and above | 3 | 6.0 | 3 | 6.0 | 6 | 6.0 |
| Number in household: 1-3 | 5 | 10.0 | 9 | 18.0 | 14 | 14.0 |
| 4-6 | 34 | 68.0 | 33 | 66.0 | 67 | 67.0 |
| 7+ | 11 | 22.0 | 8 | 16.0 | 19 | 19.0 |
| Number of children: 1-2 | 22 | 44.0 | 23 | 46.0 | 45 | 45.0 |
| 3-4 | 18 | 36.0 | 23 | 46.0 | 41 | 41.0 |
| 5-6 | 9 | 18.0 | 4 | 8.0 | 13 | 13.0 |
| 7+ | 1 | 2.0 | 0 | 0.0 | 1 | 1.0 |
| Number of children ≤5: 1 | 35 | 70.0 | 36 | 72.0 | 71 | 71.0 |
| 2 | 12 | 24.0 | 13 | 26.0 | 25 | 25.0 |
| 3 | 3 | 6.0 | 1 | 2.0 | 4 | 4.0 |
| Main income: Farming/livestock | 48 | 96.0 | 49 | 98.0 | 97 | 97.0 |
| Trade | 17 | 34.0 | 19 | 38.0 | 36 | 36.0 |
| Employee | 1 | 2.0 | 0 | 0.0 | 1 | 1.0 |
| Household has formal means of saving | 9 | 18.0 | 8 | 16.0 | 17 | 17.0 |
| House material: Wood and mud | 38 | 76.0 | 47 | 94.0 | 85 | 85.0 |
| Wood and grass | 10 | 20.0 | 1 | 2.0 | 11 | 11.0 |
| Concrete | 2 | 4.0 | 2 | 4.0 | 4 | 4.0 |
| Floor material: Concrete / cement | 16 | 32.0 | 9 | 18.0 | 25 | 25.0 |
| Mud / soil | 34 | 68.0 | 41 | 82.0 | 75 | 75.0 |
| | **Intervention** (n=50) | | **Control** (n=50) | | **Total** (N=100) | |
| | n | % | n | % | n | % |
| **WASH indicators** | | | | | | |
| Latrine type: Defecate in open | 8 | 16.0 | 11 | 5.0 | 19 | 19.0 |
| Share neighbour's | 6 | 12.0 | 8 | 16.0 | 14 | 14.0 |
| Pit latrine without slab | 11 | 22.0 | 5 | 10.0 | 16 | 16.0 |
| Pit latrine with slab | 25 | 50.0 | 26 | 52.0 | 51 | 51.0 |
| Water source: Piped water / public tap | 50 | 50.0 | 50 | 50.0 | 100 | 100.0 |
| Who collects water: Mother | 39 | 78.0 | 39 | 78.0 | 78 | 100.0 |
| Father | 8 | 16.0 | 3 | 6.0 | 11 | 11.0 |
| A grandparent | 0 | 0.0 | 1 | 2.0 | 1 | 1.0 |
| Female child (≤15) | 11 | 22.0 | 10 | 20.0 | 21 | 21.0 |

| | Intervention n | % | Control n | % | Total n | % |
|---|---|---|---|---|---|---|
| Male child (≤15) | 3 | 6.0 | 7 | 14.0 | 10 | 10.0 |
| Labourer | 1 | 2.0 | 11 | 22.0 | 12 | 12.0 |
| Water available inside the home | 43 | 86.0 | 46 | 92.0 | 89 | 89.0 |
| Household safely stores water* | 12 | 24.0 | 14 | 28.0 | 26 | 26.0 |
| Household owns soap | 34 | 68.0 | 39 | 78.0 | 73 | 100.0 |
| **Animal husbandry** | | | | | | |
| Number of cattle: 1-3 | 31 | 62.0 | 25 | 25.0 | 56 | 56.0 |
| 4-6 | 9 | 18.0 | 11 | 22.0 | 20 | 20.0 |
| 7+ | 0 | 0.0 | 1 | 2.0 | 1 | 1.0 |
| Number of goats: 1-3 | 8 | 16.0 | 8 | 16.0 | 16 | 16.0 |
| 4-6 | 2 | 4.0 | 1 | 2.0 | 3 | 3.0 |
| 7+ | 1 | 2.0 | 1 | 2.0 | 2 | 2.0 |
| Number of donkeys: 1-3 | 1 | 2.0 | 6 | 12.0 | 7 | 7.0 |
| Number of sheep: 1-3 | 0 | 0.0 | 10 | 20.0 | 10 | 10.0 |
| Number of chickens: 1-3 | 11 | 22.0 | 16 | 32.0 | 27 | 27.0 |
| 4-6 | 15 | 30.0 | 16 | 32.0 | 31 | 31.0 |
| 7+ | 18 | 36.0 | 7 | 14.0 | 25 | 25.0 |
| Animal dwelling during the day<br>Outside, enclosed in a pen | 1 | 2.0 | 0 | 0.0 | 1 | 1.0 |
| Outside, roaming free | 49 | 98.0 | 48 | 96.0 | 97 | 97.0 |
| Inside, same room as family | 33 | 66.0 | 40 | 80.0 | 73 | 73.0 |
| Inside, separate room | 1 | 2.0 | 2 | 4.0 | 3 | 3.0 |
| Animal dwelling during the night<br>Outside, enclosed in a pen | 7 | 14.0 | 10 | 20.0 | 17 | 17.0 |
| Outside, roaming free | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Inside, same room as family | 34 | 68.0 | 35 | 70.0 | 69 | 69.0 |
| Inside, separate room | 9 | 18.0 | 5 | 10.0 | 14 | 14.0 |
| | **Intervention** (n=50) | | **Control** (n=50) | | **Total** (N=100) | |
| | n | % | n | % | n | % |
| **Nutrition indicators** | | | | | | |
| LAZ z-score (average) | -1.00 | | -0.96 | | -0.98 | |
| LAZ (range) | -3.04−0.80 | | -2.76−0.66 | | -3.04−0.80 | |
| WLZ z-score (average) | -0.49 | | -0.46 | | -0.47 | |
| WLZ (range) | -2.30−0.87 | | -2.41−0.75 | | -2.41−0.87 | |
| MUAC[a] (mm; average) | 138.2 | | 138.1 | | 138.2 | |
| Stunting (LAZ ≤ −2 SD) | 17 | 34.0 | 16 | 32.0 | 33 | 33.0 |
| Wasting (WLZ ≤ −2 SD) | 6 | 12.0 | 7 | 14.0 | 13 | 13.0 |
| MUAC[a]: ≥135 | 36 | 72.0 | 39 | 78.0 | 75 | 75.0 |
| 125−135 | 8 | 16.0 | 6 | 12.0 | 14 | 13.0 |
| 115−124 | 6 | 12.0 | 5 | 10.0 | 11 | 11.0 |
| ≤115 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |

WASH, water, sanitation and hygiene; LAZ, length-for-age; WLZ, weight-for-length; MUAC, mid-upper arm circumference, where: ≥135, no risk of undernutrition; 12.5-13.5, at risk of moderate acute undernutrition; 11.5-12.4, moderate acute undernutrition; ≤11.5, severe acute undernutrition.
*Calculated as households who were marked ‘Yes’ to all three observation-based questions: Are water containers clean; Do the water containers have a protecting cover; Does the container have a tap or narrow mouth for drawing the water.

### 6.10.2 Trial outcomes

For ease of assessment, study outcomes are described together in **Table 16** and individually in sections below.

Table 16. Outcomes for the CAMPI trial to determine progression to a future definitive RCT, at two and four weeks and across the trial duration.

| **Quantitative trial outcomes** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Outcome** | Definition / Indicator | *A priori* criteria | Proportion (N=50) | | | | | | | |
| | | | Baseline | | Two weeks | | Four weeks | | Study duration | |
| | | | % | 95% CI | % | 95% CI | % | 95% CI | % | 95% CI |
| **Recruitment** | Proportion of contacted houses who consented | ≥80% | 94.3 | 88.1−97.9 | - | - | - | - | - | - |
| **Attrition** | Loss to follow-up | ≤10% | - | - | - | - | - | - | 0.0 | 0.0−3.6 |
| **Adherence** | Non-use of HPS | ≤10% | - | - | 0.0 | 0.0−0.07 | 0.0 | 0.0−0.07 | 0.0 | 0.0−0.07 |
| | Appropriate use | ≥50% | - | - | 70.0 | 55.5−82.1 | 64.0 | 49.2−77.1 | 48.0 | 33.7−62.6 |
| | Appropriate cleaning | ≥50% | - | - | 72.0 | 57.5−83.8 | 70.0 | 55.4−82.1 | 56.0 | 41.3−70.0 |
| | Appropriate use and cleaning | ≥50% | - | - | 52.0 | 37.4−66.3 | 48.0 | 33.7−62.6 | 26.0 | 14.6−40.3 |
| **Acceptability** | Infant in HPS upon arrival | ≥50% | - | - | 32.0 | 19.5−46.7 | 50.0 | 35.5−64.5 | 41.0 | 31.3−51.3 |
| | Proportion of HPS use during daily activities | No decrease | - | - | - | - | - | - | Decrease during certain activities | |

## Recruitment and attrition

Rates for recruitment and attrition are shown in **Table 16**. One hundred households were recruited from four kebeles. To achieve this, 106 households were assessed for eligibility; four households were then excluded for not meeting infant age criteria at the study start and a further two did not consent to participate (**Figure 14**). Thus, a recruitment rate of 94.3% (95% CI 88.1−97.9) met *a priori* criteria of ≥80%. All households completed the trial assessments at four weeks and there was no loss to follow-up (0.0%; 95% CI 0.0−3.6), meeting criteria for attrition (≤10% at trial end).

## Adherence

Adherence was first described as the proportion of HPS non-use at both time points and over the study period (**Table 17**). No households reported not using the HPS at either time point or over the study duration (0.0%, 95% CI 0.0−0.71), meeting *a priori* criteria ≤10%. Second, adherence was described through 'Appropriate use' and 'Appropriate cleaning' and combined, across the study time points and throughout the trial (**Table 17**). Appropriate use included maintenance, as described in the table footnotes alongside variable components (also in S2). When considering behaviours and time points separately, Appropriate use and cleaning were consistently above the *a priori* threshold of 50%. However, when assessing throughout, findings are mixed. Appropriate use did not meet the threshold (48.0%) whilst cleaning did (56.0%) and only 26.0% of households appropriately used and cleaned the HPS throughout the trial. Variables associated with adherence outcomes across the two time points were assessed using a binary logistic GEE model (**Table 18**). Results display the 95% CI for the effect size and odds ratio. The only variable to significantly predict Appropriate use or cleaning was 'Mother collects water alone', where an inverse relationship showed a reduced odds of 72.0% (0.28; 95% CI 0.12−0.66).

Table 17. Adherence: Appropriate playspace use and cleaning across study time points.

| **Adherence: Appropriate HPS use and cleaning (N=50)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Two weeks | | | Four weeks | | | Both time points[γ] | | |
| | n | % | 95% CI | n | % | 95% CI | n | % | 95% CI |
| Appropriate use[*] | 35 | 70.0 | 55.5−82.1 | 32 | 64.0 | 49.2−77.1 | 24 | 48.0 | 33.7−62.6 |
| Appropriate cleaning[**] | 36 | 72.0 | 57.5−83.8 | 35 | 70.0 | 55.4−82.1 | 28 | 56.0 | 41.3−70.0 |
| Appropriate use and cleaning[α] | 26 | 52.0 | 37.4−66.3 | 24 | 48.0 | 33.7−62.6 | 13 | 26.0 | 14.6−40.3 |

HPS, household playspace; CI, confidence interval.
[*]Created from the variables: Playspace is assembled correctly (observed), yes; Any changes/modifications to playspace (observed), no, or yes, modifications are safe; Others share playspace (reported), no; Animals in playspace (observed and reported), no; Caregiver leaves infant in playspace when leaving house (reported), no or yes IF; infant is watched by other adult (father, grandparent, or child ≥18).
[**]Created from the variables: Frequency of cleaning the playspace (reported), every day, every other day; Cleaning materials used (reported), water and soap; Mattress visibly dirty (observed), no; Urine or faeces on mattress (human or animal; reported), no.
[α]The sum of households who achieved ‘Yes’ for all criteria for both use and cleaning.
[β]The sum of households who achieved ‘No’ for all criteria for both use and cleaning.
[γ]The sum of households who achieved ‘Yes’ for all criteria across indicators at both two and four weeks.

Table 18. Adherence: A Generalised Estimation Equation estimating effects of parameters on the adherence outcome 'Appropriate use and cleaning' across study time points.

| **Adherence: Appropriate use and cleaning Generalised Estimating Equation (N=50)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Variable** | | | 95% Wald CI | | | 95% Wald CI for Exp(B) | |
| | B | Std. Error | Lower | Upper | Odds Ratio | Lower | Upper |
| (Intercept) | -0.07 | 1.06 | -2.14 | 2.01 | 0.94 | 0.12 | 7.49 |
| Infant sex = Male | 0.42 | 0.50 | -0.57 | 1.40 | 1.52 | 0.57 | 4.06 |
| Maternal age = ≤25 | -0.65 | 0.70 | -2.02 | 0.71 | 0.52 | 0.13 | 2.04 |
| Maternal education = Illiterate | -0.56 | 0.61 | -1.75 | 0.63 | 0.57 | 0.17 | 1.88 |
| Number in household = 1−3 | -0.0 | 0.78 | -2.52 | 0.52 | 0.37 | 0.08 | 1.68 |
| Number of children = 1-2 | 0.45 | 0.59 | -0.71 | 1.60 | 1.56 | 0.49 | 4.96 |
| Household owns soap = 1 | 0.63 | 0.53 | -0.41 | 1.67 | 1.87 | 0.66 | 5.31 |
| Water is safely stored = Yes | -0.11 | 0.54 | -1.17 | 0.95 | 0.90 | 0.31 | 2.59 |
| Animals inside day = Yes | -0.22 | 0.53 | -1.26 | 0.81 | 0.89 | 0.28 | 2.25 |
| Animals inside night = Yes | -0.38 | 0.69 | -1.73 | 0.97 | 0.68 | 0.18 | 2.63 |
| Water available = Yes | -0.55 | 0.75 | -2.03 | 0.93 | 0.58 | 0.13 | 2.54 |
| Mother collects water alone=Yes | -1.28 | 0.44 | -2.15 | -0.42 | 0.28 | 0.12 | 0.66 |
| Infant age (scale) | 0.12 | 0.10 | -0.07 | 0.31 | 1.13 | 0.93 | 1.37 |

## Acceptability

### Infant in playspace upon arrival, change in playspace use

The first measure noted if the infant was in the HPS during a random visit (**Table 16**). This increased from 32.0% (95% CI 19.5−46.7, n=16) at two weeks to 50% (95% CI 35.5−64.5, n=25) at four weeks, meeting a priori criteria of 50% at this point: however, throughout the trial did not reach the threshold (41.0%, 95% CI 31.3−51.3; n=41). Second, change in incidence (as a proportion) of HPS during daily activities was assessed. Primary caregivers were asked open-ended questions to record their activities during the past 24 hours, and if they did or did not use the HPS. Results are shown in **Table 19**, with activities categorised. Broadly, there was no change in use throughout the trial during food preparation/eating but use increased during other activities inside the home (such as breastfeeding) and outside, such as preparing enset and farming. A full table describing activities and HPS use or non-use is in **Chapter 5, S3**. Lastly analysing HPS use according to the time of day suggested use was consistently highest in the mornings, although evening use increased at the trial end (**S3**).

Table 19. Acceptability: Reported playspace use in the past 24 hours during different daily activities, at two and four weeks, and the change across time points.

| Acceptability: Reported HPS use during specified household activities by 24-hour recall and change in proportion of use across study time points (N=50) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Reported daily activity** | **Total reported activity*** | **Reported HPS use** | **Proportion of use**** | **Total reported activity*** | **Reported HPS use** | **Proportion of use **** | **Change in use** | **Change in proportion of use$^{\alpha}$** |
| | Two weeks | | | Four weeks | | | Across time points | |
| | n | n | % | n | n | % | n | % |
| **Prepared / ate a meal** | **150** | **139** | **92.7** | **172** | **139** | **80.8** | **0** | **-11.9** |
| Prepared breakfast | 45 | 40 | 88.9 | 47 | 42 | 89.4 | 2 | +0.5 |
| Prepared lunch/snacks | 56 | 54 | 96.4 | 51 | 48 | 94.1 | -6 | -2.3 |
| Prepared dinner | 49 | 45 | 91.8 | 49 | 43 | 87.8 | -2 | -4.1 |
| Ate a meal | 0 | 0 | 0.0 | 25 | 6 | 0.0 | 6 | 0.0 |
| **Prepared coffee** | **75** | **69** | **92.0** | **95** | **85** | **89.5** | **16** | **-2.5** |
| **Duties within the home** | **57** | **46** | **80.7** | **73** | **62** | **84.9** | **16** | **+4.2** |
| Cleaned the house | 47 | 40 | 85.1 | 55 | 47 | 85.5 | 7 | +0.3 |
| Washed clothes | 10 | 6 | 60.0 | 18 | 15 | 83.3 | 9 | +23.3 |
| **Duties outside of the home** | **43** | **35** | **81.4** | **49** | **43** | **87.8** | **8** | **+6.4** |
| Fetched water | 41 | 40 | 97.6 | 48 | 44 | 91.7 | 4 | -5.9 |
| Prepared enset | 30 | 25 | 83.3 | 20 | 19 | 95.0 | -6 | +11.7 |
| Chopped wood | 7 | 6 | 85.7 | 8 | 6 | 75.0 | 0 | -10.7 |
| Farmed / maintained shop | 6 | 4 | 66.7 | 21 | 18 | 85.7 | 14 | +19.0 |
| **Visits outside home** | **23** | **17** | **73.9** | **32** | **15** | **46.9** | **-2** | **-27.0** |
| Went to church / meeting | 4 | 1 | 25.0 | 4 | 0 | 0.0 | -1 | -25.0 |
| Went to market | 15 | 14 | 93.3 | 16 | 12 | 75.0 | -2 | -18.3 |
| Visited neighbours/ other | 4 | 2 | 50.0 | 12 | 3 | 25.0 | 1 | -25.0 |
| **Breastfed / fed baby** | **26** | **15** | **57.7** | **30** | **20** | **66.7** | **5** | **+9.0** |
| **Slept / rested** | **23** | **5** | **21.7** | **18** | **3** | **16.7** | **-2** | **-5.1** |

HPS, household playspace.
*Number represents reported incidence of that activity within the past 24 hours. Households (N=50) were asked an open-ended question about their daily activities during the past 24 hours. Not every activity was reported by every respondent.
**Calculated as the proportion of households who reported using the HPS during that daily activity.
$^{\alpha}$Calculated as the difference between the proportions of HPS use at two and four weeks.

**Modified Barrier Analysis**

Acceptability was further assessed through a semi-structured questionnaire as a modified Barrier Analysis. This assessed 12 categories of behavioural determinants, exploring all factors which would act as barriers or enablers during a definitive trial (S1). Full results are available in in S4. The first seven determinants quantitatively assess beliefs and behaviours relating to infant health and HPS use. The further six determinants explored attitudes and beliefs through open-ended questions. Many cited advantages, both related and unrelated to infant health, indicated good acceptability of the HPS. Caregivers frequently stated the HPS helped prevent ingestion of dirt and faeces (80.0%, n=40), 76.0% (n=38). Further, many suggested the HPS prevented injury from several causes, including from fire, drowning and animals. Over half of caregivers (mothers) asserted that the HPS eased their workload (56.0%, n=28), reduced time pressures (46.0%, n=23) and allowed them to carry out their duties without distraction. Mothers reported relief that the HPS alleviated fears and worries over their infant's safety (52.0%, n=26), and almost half believed their infant would physically grow better (42.0%, n=21). Approval within the community was high among neighbours (96.0%, n=48) husbands (40.0%, n=20), and both close (66.0%, n=33) and wider family (36.0%, n=18). Conversely, some caregivers mentioned that neighbours (8.0%, n=4) or friends (12.0%, n=6) were envious as the common reason for disapproval *('My friend who does not have one wants one too')*, or that money would have been preferable *('My colleague says better to give the child clothes or money for me')*. Barriers to use included the cost of cleaning materials (22.0%, n=11) – echoed in the *Access* determinant where caregivers frequently noted the expense of soap (56.0%, n=28) and cleaning materials, for example, brushes (24.0%, n=12). Importantly, having no older children to watch the infant was a barrier (32.0%, n=16) and relates to the burden of workload on women. A lack of toys was also a barrier (32.0%, n=16). Whilst the design appeared largely acceptable, some difficulties included fitting the rope connecting walls (38.0%, n=19; see **Chapter 5, Figure 14**).

### 6.10.3 Secondary outcomes: Infant health outcomes

**Table 20** shows changes in reported seven-day diarrhoeal prevalence and presumptive *Campylobacter* spp. across groups and time periods. Considering change in point prevalence, seven-day diarrhoea declined more markedly within the intervention group from 19 cases (38.0%) at baseline to 5 cases (10.0%) at four weeks, versus 22 cases (44.0%) to 16 (32.0%) amongst controls. Considering change in prevalence from baseline, the intervention group showed a reduced odds of reported diarrhoea versus controls (OR 0.57, 95% CI 0.40−0.83). Baseline prevalence of presumptive C*ampylobacter* was high, mirroring a similar prevalence at this site and others.[26,29] However from baseline, point prevalence showed no significant difference between groups or time points. Similarly, the intervention group had no reduced odds of a *Campylobacter*-positive stool versus controls from baseline. Colony counts from positive samples can be viewed in S5.

Table 20. Secondary health outcomes: Point prevalence across study time points and change in prevalence from baseline for seven-day diarrhoea and Campylobacter, intervention, and control groups.

| **Reported seven-day diarrhoea point prevalence across study time points** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Baseline | | | | Two weeks | | | | Four weeks | | | |
| | Intervention (n=50) | | Control (n=50) | | Intervention (n=50) | | Control (n=50) | | Intervention (n=50) | | Control (n=50) | |
| | n | % | n | % | n | % | n | % | n | % | n | % |
| No diarrhoea | 31 | 62.0 | 28 | 56.0 | 44 | 88.0 | 35 | 70.0 | 45 | 90.0 | 34 | 68.0 |
| Diarrhoea | 19 | 38.0 | 22 | 44.0 | 6 | 12.0 | 15 | 30.0 | 5 | 10.0 | 16 | 32.0 |
| **Presumptive *Campylobacter* point prevalence across study time points** | | | | | | | | | | | | |
| No infection | 23 | 46.0 | 24 | 48.0 | 33 | 66.0 | 32 | 64.0 | 36 | 72.0 | 36 | 72.0 |
| Infection | 27 | 54.0 | 26 | 52.0 | 17 | 34.0 | 18 | 36.0 | 14 | 28.0 | 14 | 28.0 |

| **Change in reported seven-day diarrhoeal prevalence after baseline*** | | | | |
|---|---|---|---|---|
| | Intervention (n=50) | | Control (n=50) | |
| | n | % | n | % |
| No diarrhoea** | 39 | 78.0 | 28 | 56.0 |
| Diarrhoea | 11 | 22.0 | 22 | 44.0 |
| **Change in presumptive *Campylobacter* prevalence after baselineβ** | | | | |
| No infectionα | 30 | 60.0 | 28 | 56.0 |
| Any infection | 20 | 40.0 | 22 | 44.0 |

*OR for intervention group 0.49 (95% CI 0.33−0.75)
**No diarrhoea: No reported diarrhoea at two or four weeks, OR no reported diarrhoea from baseline; Diarrhoea: Reported diarrhoea at two or four weeks, OR reported diarrhoea from baseline.
βInsignificant.
αNegative: No suspected *Campylobacter* at two or four weeks, OR always negative; Positive: Suspected *Campylobacter* prevalence at two or four weeks, OR always positive.

## 6.11 Harms

No adverse events were observed from HPS use in the intervention group. No household reported any safety concerns associated with use, aside from one household who mentioned the plastic mattress became hot under the sun. HPS use did not increase the risk of any adverse infant health outcome, where the direction of effect does not show an increased risk for the intervention group.

## 6.12 Discussion

The CAMPI trial is the first randomised, controlled feasibility trial of an HPS in rural, subsistence agriculture households in Ethiopia. The trial outcomes did not fully reach *a priori* criteria, but with adjustments a definitive RCT for efficacy is feasible. Results echo two similar studies. In the SHINE trial in Zimbabwe, an imported plastic HPS and locally-sourced plastic playmat were included in a WASH intervention to improve growth and anaemia. Whilst fidelity of delivery was high,[10] the WASH intervention did not prevent infection.[30] However, the analysis did not estimate a magnitude of effect from the HPS specifically. In Zambia, a community-built HPS was assessed alongside a plastic model for acceptability and feasibility.[129] Reported use was similar between the two types (ranging from 10 minutes to three hours), family and community reactions suggested acceptability was high and caregiver reports suggested the community-built space prevented infant ingestion of soil and animal faeces. Thus, growing evidence supports wide acceptability and feasibility across different contexts and further rigorous assessment of efficacy is merited.

Addressing barriers to appropriate use and cleaning of the HPS would improve these outcomes. Data here described a broadly consistent pattern over the four weeks, albeit with a small decline (**Table 17** and **Table 19**). The modified Barrier Analysis offered reasons for diminishing use and drops in compliance, including the expense of soap and other cleaning materials. Providing these alongside the HPS would be a key consideration for any future RCT to ensure good hygiene. Similarly, contextual WASH factors, such as water quality, availability, and unsafe storage (76.0%, n=38 in the intervention group; **Table 15**) must be considered which may result in increased bacterial transmission. Similarly, the team decided not to provide toys during the trial given the potential to become vectors for indirect faecal-oral transmission.[18,32] However, this was a frequently cited barrier for mothers whose infants became bored and cried: thus, providing toys or including stimulating features to the HPS is an important consideration. Alternatively, caregivers may be counselled on providing (non-porous), non-hazardous toys and on regular proper cleaning. Further, during early, critical growth periods there are other important considerations including psychosocial and neurodevelopment. Opportunities for linguistic, socioemotional, and cognitive development are critical and a future RCT should consider if an HPS reduces these opportunities through interruptions to normal play, exploration, and caregiver-infant interaction – all strongly related to contextual norms and traditions.

Through random spot checks of HPS use and change in time-use, the trial showed mixed acceptability, partly meeting *a priori* criteria (**Table 16** and **Table 19**). Reported daily use increased for certain activities, suggesting an increasing ease with incorporating the HPS into daily life. However increased use during certain activities (fetching water, farming) may indicate a complacency with infant safety inside the HPS and present a risk. These increases may account for the reduction in 'Appropriate use' at week four which included if the caregiver left the infant alone whilst outside. A key finding from the modified Barrier Analysis were the secondary effects of easing work burden, time restraints, and worries about infant health and safety for many mothers. Thus, in the short term, an HPS may hold many benefits including potentially improving women's empowerment through time availability and choice, reducing anxiety, and even freeing up time to spend with her infant. However, any negative long-term impacts will need to balance these. This includes a lack of infant supervision, and the risk of reinforcing women's roles as sole caregivers alongside a continuing responsibility for other domestic duties. This is reinforced by the GEE model (**Table 18**) where when the mother bore the duty of collecting water alone, the HPS was less likely to be used or cleaned properly. In many low-income countries, women's' 'triple work burden' in the productive, reproductive, and social domains impedes their well-being and may reduce engagement in childcare[33] – a pattern often inherited by older female siblings. This highlights a trade-off in encouraging more active parenting alongside existing home duties, and any intervention must ensure it does not further encumber women.

The CAMPI trial was not powered to detect any differences in health outcomes between groups and results should be interpreted accordingly. Beyond the lack of adequate power, substantial methodological limitations may affect validity: these include the reliability of caregiver-reported diarrhoea and a desirability bias within intervention households. However secondary infant health outcomes indicated the potential efficacy of an HPS and appropriateness of these outcomes for a future RCT. Diarrhoeal prevalence from baseline reduced among the intervention group whilst presumptive *Campylobacter* did not (**Table 20**). No further GEE analysis was performed to explore associated variables. However, aside from a potential lack of effect of the HPS on *Campylobacter* prevalence, other pathways not interrupted by the HPS likely contributed to pathogen transmission. This includes unsafely prepared (and reheated) food foods[34]; data on this indicated unsafe practices were common (S6) where across households only 28 safely prepared all meals at both time points (data not shown). All infants were given liquids other than breastmilk, including water, possibly contaminated through unsafe storage or other pathways. *Campylobacter* from domestic free-range poultry appears to present an infection risk to infants[5,26] and here poultry frequently shared living and sleeping areas (**Table 15**). However, questions remain on what, how and where infants contract *Campylobacter*, the role of domestic animals in transmission and survival time in the environment.[34] The methodology used to isolate *Campylobacter* spp. also holds limitations[26] and a definitive RCT should consider other, more sensitive techniques such as the use of ELISA or quantitative PCR. This may provide greater sensitivity to show a reduction in infant *Campylobacter* prevalence from HPS use. If with greater study power and sensitive techniques a reduction is still not seen, but where diarrhoea prevalence still lowers, it may be that the HPS is able to offer protection against other environmental pathogens. This may translate into a small but clinically meaningful effect on the infant infection burden and subclinical outcomes (EED) during this early period of development.

### 6.12.1 Progression to a definitive RCT

To improve playspace adherence and acceptance, a future definitive RCT should focus on directly addressing the barriers whilst promoting the enabling factors as identified in this feasibility trial. Whilst further behavioural 'modules' and developing caregiver knowledge might have improved outcomes, it is not always practical. During the sensitisation day the HPS was introduced in a 'scalable' manner to reduce work burden among households and HEWs who are already overworked. Rather, to achieve behavioural change it is pragmatic to directly address barriers and promote enabling factors. Knowledge alone is unlikely to prevent infant faecal-oral transmission without a material element which breaks contact, and an enabling technology may drive changes in behaviour but still requires addressing factors which support or obstruct change. Factors included in the composite variable Appropriate use responsible for a decline include another child sharing the HPS (S2). Given the potential to introduce contamination, this might be addressed by a visiting HEW as a risk factor. Similarly, Appropriate cleaning declined from every day/every other day to twice a week. The direction of effect and significance in the GEE model (**Table 18**) is an important consideration to improving this: cleaning behaviours will not change without access to soap. To improve time-use, toys (non-porous) might be provided with counselling from HEWs on regular cleaning. Factors not modifiable to counselling are important prognostic factors and might be included as strata in group randomisation in a full RCT.

Several contextual factors undoubtedly influenced this trial's operational success, including ease of recruitment and full retention. The study kebeles, within PIN outreach, may have resulted in higher acquiescence during recruitment and consent. High retention likely results from this plus a high number of data collectors for the sample. However, it is important to note that daily data collection was intense and required serious team dedication. A larger trial would likely experience higher drop out without equivalent input: a 95% CI estimate would be between 96−100% in a power calculation and 95−100% if repeated maintaining the same effort and ratio of study personnel. Over a longer time period, this is likely unsustainable.

Future sample size calculations must consider these number requirements for study personnel. Furthermore, as recipients of previous WASH interventions, the intervention group likely adopted the new intervention modality earlier than might be seen in other contexts, holding implications for external validity. Good uptake may also be seen in other contexts where NGOs have a known presence and have provided multiple interventions for many years, but this does limit the generalisability of findings to other contexts. Lastly it is important to note the extensive HPS design process and the underlying formative work. Good contextual understanding is critical for intervention success, which must be culturally acceptable, locally integrated and must consider contextual baseline demographic and WASH characteristics and health status which vary significantly.

Lastly is the consideration of for how long a future study might run. Whilst four weeks provided some insight into use and acceptability within a feasibility trial setting, a longer period would undoubtably indicate sustainability of these outcomes. ‘Sustainable change’ might also be better assessed by a high-quality mixed-methods design which might integrate direct observational periods as well as in-depth focus group discussions which would provide greater insight into reasons for use and non-use.

## 6.13 Conclusion

The CAMPI trial evaluated feasibility of an HPS and recommendations to progress to a future RCT in a rural, subsistence agriculture setting in Ethiopia. Not all *a priori* criteria were met. Overall, the HPS showed mixed engagement and adherence, good acceptability, and many reported secondary benefits. An HPS remains a viable option to help reduce direct faecal-oral transmission of pathogenic organisms and infant infection in these settings. A larger trial with longer follow-up is feasible to implement and should assess infant health outcomes as primary endpoints. Addressing identified barriers and promoting enabling factors would likely improve adherence and use.

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### 6.15 Author contributions

SB was mainly responsible for the trial design and oversight and principally wrote the manuscript. PH, AP and CG contributed towards study design and assisted in assessing the paper quality, writing and review. SN assisted with statistical analysis and in assessing paper quality and review. FW and MJ provided input with the study design, planning and logistics and management of the field team during the trial. MM, SHA and HB assisted in reviewing the paper and were valuable partners at Hawassa University College of Medicine and Health Sciences, overseeing laboratory practice.

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### 6.17 Declaration of interest

All authors have no conflict of interest to declare.

### 6.18 Data access

All of the individual participant data collected during the trial, after de-identification, will be available immediately following publication and with no end date, for any analysis purpose. Data are available indefinitely, accessible online at the Cranfield University data repository (uploaded following thesis completion).

The study protocol and informed consent form are also available upon request.

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## 6.20 Supplementary information

### S1. Modified Barrier Analysis methodology

### Background to a Barrier Analysis

A Barrier Analysis (BA) is the main type of formative research recommended in the Designing for Behavioural Change framework. It is described as the 'field research step' with a primary aim to identify what is preventing the target groups from practicing the targeted behaviours (the 'barriers') and what might encourage adoption (the 'motivators').[35] The full official training syllabus, published by Kittle BL, provides a practical guide.[36] Briefly, the standard BA method asks the target group a series of questions aiming to identify barriers and motivators, using a Doer/Non-Doer methodology (S1). This consists of interviewing the group who already do the behaviour and the group who have not yet adopted the behaviour. The motivators and barriers identified in the survey are categorised under 1 of 12 possible determinants. These determinants represent the perceptions, feelings, and beliefs of the target group and determine why they do or do not adopt a specific behaviour and are as follows: Perceived self-efficacy; Perceived social norms; Perceived positive consequences; Perceived negative consequences; Access; Cues for action/reminders; Perceived susceptibility/risk; Perceived severity; Perceived action efficacy; Perceived divine will; Policy and Culture. Analysing the difference between the Doers' and Non-Doers' responses indicates which barriers or enabling factors are the most important in determining that behaviour. Insights into these perceptions are used to further develop the content and strategies of the behavioural change activity. Such links are called 'Bridges to Activities'.

### Barrier Analysis method in the CAMPI feasibility trial

Given that there were no 'non-doers' in the CAMPI feasibility trial, intervention households were not analysed according to the standard Doer/Non-doer methodology as described above. Rather, the methodology was modified slightly to explore behaviours among all participants, without categorising them as Doers/Non-doers. The survey used in the modified BA is shown below. Intervention households were interviewed by the data collection teams, trained in the BA method, alongside a Health Extension Worker at week four of the feasibility trial. Following data collection, responses were entered into Excel. Questions 2−9 were entered into categories according to determinants and then categorised into themes which arose from the data. Those themes were summed and described in the results. Quantitative responses (questions 1, 10−16 in the table below) were summed in each answer category and also subsequently described in the result. As such, the determinants allowed for the description of barriers/enabling factors among all households which would improve adherence to a greater degree – given that all households used the playspace during the trial.

**S1. Barrier analysis as used in the CAMPI feasibility trial.**

| | | |
|---|---|---|
| 1 | Do you think that you use the play space for your child whenever you can? | Yes<br>No |
| 2 | What are the **advantages** of using the play space? | |
| 3 | What are the **disadvantages** of using the play space? | |
| 4 | What makes it **easy** for you to use the play space? | |
| 5 | What makes it **difficult** for you to use the play space? | |
| 6 | What makes it **easy** for you to keep the play space clean? | |
| 7 | What makes it **difficult** for you to keep the play space clean? | |
| 8 | Who are the people who **approve** of you using the play space for your child? | |
| 9 | Who are the people who **disapprove** of you using the play space for your child? | |
| 10 | How difficult is it to remember to use the play space for your child every time you could use it? | Very difficult<br>A bit difficult<br>Not difficult<br>Don't know |
| 11 | How likely do you think it is your child will get diarrhoeal disease within the next month? | Very likely<br>Quite likely<br>Not likely<br>Don't know |
| 12 | How serious would it be if your child had a diarrhoeal disease? | Very serious<br>Quite serious<br>Not serious<br>Don't know |
| 13 | How likely do you think it is your child will get diarrhoeal disease if you used the play space whenever you could? | Very likely<br>Quite likely<br>Not likely<br>Don't know |
| 14 | Do you think God approves of you using the play space? | Yes<br>No<br>Don't know<br>Specify: |
| 15 | Are there any community rules which prevent you from using the play space? *If yes,* what are they? | Yes<br>No<br>Don't know<br>Specify: |
| 16 | Are there any cultural rules that you know of against using the play space? *If yes,* what are they? | Yes<br>No<br>Don't know<br>Specify: |
| 17 | Ask the caregiver:<br>*Do you have any other comments about the play space, positive **OR** negative?* | |

**S2. Playspace use behaviours and infant hygiene and playspace cleaning practices included as part of composite variables 'Appropriate use' and 'Appropriate cleaning'.**

| **HPS use behaviours** | | | | | | |
|---|---|---|---|---|---|---|
| | Two weeks | | Four weeks | | Both time points | |
| | n (50) | % | n (50) | % | N (100)* | %** |
| Who watches the infant: Another child | 42 | 84.0 | 43 | 86.0 | 85 | 85.0 |
| Mother | 27 | 54.0 | 28 | 46.0 | 55 | 55.0 |
| Husband | 18 | 36.0 | 24 | 48.0 | 42 | 42.0 |
| A grandparent | 0 | 0.0 | 1 | 2.0 | 1 | 1.0 |
| Infant in HPS when leave house | 41 | 82.0 | 26 | 52.0 | 67 | 67.0 |
| Other child shares the HPS | 14 | 28.0 | 18 | 36.0 | 32 | 32.0 |
| Who shares the HPS: Mother to feed | 6 | 12.0 | 10 | 20.0 | 16 | 16.0 |
| Sister or brother | 4 | 8.0 | 4 | 8.0 | 8 | 8.0 |
| Another child | 2 | 4.0 | 6 | 12.0 | 8 | 8.0 |
| Twin | 1 | 2.0 | 1 | 2.0 | 2 | 2.0 |
| Infant given toys or items to play | 43 | 86.0 | 46 | 92.0 | 89 | 89.0 |
| Items given: Plastic cup | 32 | 64.0 | 33 | 66.0 | 65 | 65.0 |
| Plastic water bottle | 27 | 54.0 | 27 | 54.0 | 54 | 54.0 |
| Jerry can cover | 8 | 14.0 | 6 | 12.0 | 14 | 14.0 |
| Empty plastic container | 7 | 13.0 | 5 | 10.0 | 12 | 12.0 |
| Mobile phone | 6 | 12.0 | 6 | 12.0 | 12 | 12.0 |
| Small ball | 5 | 10.0 | 5 | 10.0 | 10 | 10.0 |
| Store-bought plastic toys | 2 | 4.0 | 6 | 12.0 | 8 | 8.0 |
| Book/paper | 2 | 4.0 | 2 | 4.0 | 4 | 4.0 |
| Reasons to remove infant: Infant hungry | 49 | 98.0 | 49 | 98.0 | 98 | 98.0 |
| Infant is crying (bored) | 44 | 88.0 | 46 | 92.0 | 90 | 90.0 |
| Infant has defecated/urinated | 39 | 78.0 | 37 | 74.0 | 76 | 76.0 |
| To clean the playspace | 30 | 60.0 | 26 | 52.0 | 56 | 56.0 |
| To wash/change infant | 25 | 50.0 | 30 | 60.0 | 55 | 55.0 |
| To breastfeed/feed | 11 | 22.0 | 15 | 30.0 | 26 | 26.0 |
| Infant is sleeping | 4 | 8.0 | 1 | 2.0 | 5 | 5.0 |
| To go out | 1 | 2.0 | 2 | 4.0 | 3 | 3.0 |
| **Infant hygiene and HPS cleaning** | | | | | | |
| **Observational data** | | | | | | |
| Infant visibly dirty upon arrival | 20 | 40.0 | 19 | 38.0 | 39 | 39.0 |
| Infant has dirty hands and nails | 28 | 56.0 | 24 | 48.0 | 52 | 52.0 |
| Visible dirt on mattress | 6 | 12.0 | 3 | 6.0 | 9 | 9.0 |
| Urine or faeces on mattress | 1 | 2.0 | 1 | 2.0 | 2 | 2.0 |
| Animals inside HPS (observed) | 1 | 2.0 | 0 | 0.0 | 1 | 1.0 |
| **Caregiver-reported data** | | | | | | |
| How often clean HPS: Every day | 30 | 60.0 | 16 | 32.0 | 46 | 46.0 |
| Twice a week | 9 | 18.0 | 17 | 34.0 | 26 | 26.0 |
| Every other day | 6 | 12.0 | 6 | 12.0 | 12 | 12.0 |
| Only when infant defecates/urinates | 3 | 6.0 | 11 | 22.0 | 14 | 14.0 |
| Only when it is dirty | 2 | 4.0 | 0 | 0.0 | 2 | 2.0 |
| Cleaning materials used: Water only | 5 | 10.0 | 2 | 4.0 | 7 | 7.0 |
| Water and soap | 45 | 90.0 | 48 | 96.0 | 93 | 93.0 |
| Animals seen inside HPS: Yes | 4 | 8.0 | 0 | 100.0 | 4 | 4.0 |
| Which animals? Cat | 2 | 50.0* | 0 | 0.0 | 2 | 2.0 |
| Poultry | 2 | 50.0* | 0 | 0.0 | 2 | 2.0 |

HPS, household playspace.
*Calculated as a cumulative total of both time points.
**Percent is of the cumulative total.

**S3. Reported playspace use and non-use during daily activities in the past 24 hours across daily time periods: at two and four weeks.**

| | Morning | | Afternoon | | Evening | |
|---|---|---|---|---|---|---|
| | Two weeks | Four weeks | Two weeks | Four weeks | Two weeks | Four weeks |
| Reported use of HPS | 154 | 153 | 119 | 153 | 93 | 105 |
| Reported non-use of HPS | 24 | 32 | 28 | 32 | 42 | 60 |

HPS, household playspace.
Figures are summed from reported daily activities table in S4.

**S4. Modified Barrier Analysis results among the study intervention group.**

| BA determinant and question | | Very… | | Quite… | | Not… | | Don't know | |
|---|---|---|---|---|---|---|---|---|---|
| | | n (50) | % | n (50) | % | n (50) | % | n (50) | % |
| *Cues for action/ reminders* | How **difficult** is it to remember to use the HPS every time you could? | 0 | 0.0 | 0 | 0.0 | 50 | 100.0 | 0 | 0.0 |
| *Perceived susceptibility/ risk* | How **likely** do you think it is your child will get diarrhoea within the next month? | 0 | 0.0 | 9 | 18.0 | 24 | 48.0 | 17 | 34.0 |
| *Perceived severity* | How **serious** would it be if your child had diarrhoea? | 40 | 80.0 | 7 | 14.0 | 2 | 4.0 | 1 | 2.0 |
| *Perceived action efficacy* | How **likely** is it your child will get diarrhoea if you used the HPS whenever you could? | 0 | 0.0 | 9 | 18.0 | 38 | 76.0 | 3 | 6.0 |
| | | **Yes** | | **No** | | **Don't know** | | | |
| | | n (50) | % | n (50) | % | n (50) | % | | |
| *Perceived divine will* | Do you think God approves of you using the HPS? | 48 | 96.0 | 1 | 2.0 | 0 | 0.0 | | |
| *Policy* | Are there any community rules which prevent you from using the HPS? | 0 | 0.0 | 50 | 100.0 | 0 | 0.0 | | |
| *Culture* | Are there any cultural rules that you know of against using the HPS? | 0 | 0.0 | 50 | 100.0 | 0 | 0.0 | | |

HPS, household playspace.

| BA determinant | BA question | Inductive theme | n (50) | % |
|---|---|---|---|---|
| *Perceived positive consequences* | What are the advantages of using the HPS? | Prevents ingestion of dirt/soil/dirty objects | 40 | 80.0 |
| | | Prevents injury (falling, fire, drowning, dust/ash, road) | 38 | 76.0 |
| | | Prevents injury from animals | 29 | 58.0 |
| | | Decreases/Eases mother's workload | 28 | 56.0 |
| | | Mother worries less for infant's health/safety | 26 | 52.0 |
| | | Eases time pressure for mother/stress | 23 | 46.0 |
| | | Improves infant's physical development | 21 | 42.0 |
| | | Infant/Clothes stay clean | 20 | 40.0 |
| | | Prevents ingestion of faeces | 20 | 40.0 |
| | | Infant feels happy playing inside/comfortable | 18 | 36.0 |

| | | | | |
|---|---|---|---|---|
| | | Prevents diarrhoea/Other disease | 14 | 28.0 |
| | | Protects from sunlight | 4 | 8.0 |
| | | Promotes infant's independence | 2 | 4.0 |
| *Perceived negative consequences* | What are the disadvantages of using the HPS? | No disadvantage | 26 | 52.0 |
| | | Cost of extra cleaning materials | 11 | 22.0 |
| | | Takes up space inside the home | 7 | 14.0 |
| | | Infant cries (from boredom) | 7 | 14.0 |
| | | Extra item to clean | 6 | 12.0 |
| *Perceived self-efficacy* | What makes it easy for you to use the HPS? | Easy to assemble/rope easy to tie | 27 | 54.0 |
| | | Weighs little/Easy to move (including mattress) | 25 | 50.0 |
| | | Good size/Takes little space inside | 22 | 44.0 |
| | | Door facilitates easy use | 14 | 28.0 |
| | | Safe design/Infant easily visible | 14 | 28.0 |
| | | Design encourages infant play (size/comfort) | 13 | 26.0 |
| | | Bamboo structure strong/Stable/Durable | 12 | 24.0 |
| | | Can be taken outside | 8 | 16.0 |
| | | Older children who can watch infant | 8 | 16.0 |
| | | Good width to slats to encourage standing | 4 | 8.0 |
| | What makes it difficult for you to use the HPS? | Difficult to rethread rope when dismantled | 19 | 38.0 |
| | | No older children to watch infant | 16 | 32.0 |
| | | Lack of toys | 16 | 32.0 |
| | | Difficult to move outside/Heavy without help | 8 | 16.0 |
| | | Rope may become loose/Structure falls | 4 | 8.0 |
| | | Nothing | 3 | 6.0 |
| | | Takes up space/House is small | 2 | 4.0 |
| | | No older children to watch infant | 2 | 4.0 |
| | | Plastic can get hot in sun | 1 | 2.0 |
| | | Height insufficient | 1 | 2.0 |
| *Access* | What makes it easy for you to keep the HPS clean? | Plastic covering easily cleaned | 39 | 78.0 |
| | | Mattress lightweight/Small to carry/Removable | 38 | 76.0 |
| | | Requires little water | 34 | 68.0 |
| | | Dries quickly (in/out of sun) | 16 | 32.0 |
| | | Bamboo stays clean/easy to wipe | 14 | 28.0 |
| | | Requires little soap | 13 | 26.0 |
| | | Plastic does not absorb smell/urine/dirt | 5 | 10.0 |
| | | Soap easy to buy/Inexpensive | 2 | 4.0 |
| | | Water easily available | 2 | 4.0 |
| | What makes it difficult for you to keep the HPS clean? | Lack of/Expense of buying soap | 28 | 56.0 |
| | | Water unavailable at times | 13 | 26.0 |
| | | Requires extra cleaning materials/Associated cost | 12 | 24.0 |
| | | Nothing | 6 | 12.0 |
| | | Material (rough bamboo/rope/open seams) | 5 | 10.0 |
| *Perceived social norms* | Who are the people who approve of you using the HPS? | Neighbours | 48 | 96.0 |
| | | Immediate family (parents, grandparents, siblings) | 33 | 66.0 |
| | | HEW/HDA/Other government worker | 24 | 48.0 |
| | | Husband | 20 | 40.0 |
| | | Friends of parents | 18 | 36.0 |
| | | Aunts/Uncles/Family-in-law | 18 | 36.0 |
| | | Community members/Guests/Passers-by | 11 | 22.0 |
| | | Labourer/Customers | 3 | 6.0 |
| | Who are the people who disapprove of you using the HPS? | Nobody | 37 | 74.0 |
| | | Friends of parents | 6 | 12.0 |
| | | Neighbours | 4 | 8.0 |
| | | Community members/Colleagues/Customers | 3 | 6.0 |

BA, Barrier Analysis; HPS, household playspace.

**S5. Number of samples positive for presumptive *Campylobacter* spp. under each category of colony count.**

| | Intervention (n=50) | | | | | Control (n=50) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0-100 | 101-250 | 251-999 | >1000 | >2000 | 0-100 | 101-250 | 251-999 | >1000 | >2000 |
| Baseline | 2 | 2 | 14 | 6 | 3 | 3 | 10 | 13 | 0 | 0 |
| Two weeks | 0 | 1 | 14 | 2 | 0 | 4 | 4 | 8 | 1 | 1 |
| Four weeks | 2 | 6 | 4 | 2 | 0 | 3 | 5 | 6 | 0 | 0 |

**S6. Feeding of fresh or reheated foods prepared as recommended, across study groups and time points.**

| **Baseline** | | | | | | |
|---|---|---|---|---|---|---|
| | Intervention (n=50) | | Control (n=50) | | Total (N=100) | |
| | n | % | n | % | n | % |
| Morning meal | 30 | 60.0 | 43 | 86.0 | 73 | 73.0 |
| Midday meal | 34 | 68.0 | 38 | 76.0 | 72 | 72.0 |
| Evening meal | 33 | 66.0 | 42 | 84.0 | 75 | 75.0 |
| All safely prepared | 25 | 50.0 | 31 | 62.0 | 56 | 56.0 |
| **Two weeks** | | | | | | |
| | Intervention (n=50) | | Control (n=50) | | Total (N=100) | |
| | n | % | n | % | n | % |
| Morning meal | 31 | 62.0 | 38 | 76.0 | 69 | 69.0 |
| Midday meal | 41 | 82.0 | 38 | 76.0 | 79 | 79.0 |
| Evening meal | 37 | 74.0 | 39 | 78.0 | 76 | 76.0 |
| All safely prepared | 19 | 38.0 | 28 | 56.0 | 47 | 47.0 |
| **Four weeks** | | | | | | |
| | Intervention (n=50) | | Control (n=50) | | Total (N=100) | |
| | n | % | n | % | n | % |
| Morning meal | 37 | 74.0 | 36 | 72.0 | 73 | 73.0 |
| Midday meal | 30 | 60.0 | 30 | 60.0 | 60 | 60.0 |
| Evening meal | 31 | 62.0 | 37 | 74.0 | 68 | 68.0 |
| All safely prepared | 21 | 42.0 | 24 | 48.0 | 45 | 45.0 |

Feeding of fresh or reheated foods ’prepared as recommended’ if: Meals were prepared less than 2 hours before eating (not reheated); Meals were prepared less than 2 hours before eating which were reheated to ‘almost boiling’; Meals were prepared more than 2 hours before eating but reheated to ‘almost boiling’. ‘Not prepared as recommended’ if: Meals were prepared less than 2 hours before eating but only heated to ‘warm’; Meals were prepared more than 2 hours before eating and reheated to ‘warm’.

# 7 Discussion

In 2018, the WASH sector was surprised by the results from three trials (WASH Benefits Kenya[1] and Bangladesh[2] and SHINE, Zimbabwe[3]) which showed inconsistent or no effect of key WASH interventions on infant diarrhoea and linear growth. In 2019, the four-year MapSan trial also demonstrated no effect of improved shared sanitation on the prevalence of enteric infections.[4] The null findings were challenging as comparable WASH interventions are frequently implemented in similar rural, low-income contexts with the aim of improving IYC health. Regardless, findings do not suggest WASH is ineffective at improving outcomes but rather serve to remind the field of the knowledge gaps that remain in terms of the transmission of enteric pathogens, causes of infection (both symptomatic and asymptomatic) and the high hygiene thresholds necessary to improve diarrhoea and growth.[5–7] The findings from this thesis reinforce the trial results by identifying ‘blind spots’ in conventional WASH programming and interventions designed to improve IYC health. These blind spots are discussed here as contributions to the research field. Following, the discussion considers the feasibility of an HPS as a material intervention within WASH scope and its potential to reduce infection risk. Finally, limitations of the body of work are presented followed by suggestions for future research. This includes a discussion of the scope and boundaries of WASH where limitations with the framework may explain the failure of programmes and interventions to improve infant health.

## 7.1 Research contributions

### 7.12 Objective 1

Firstly, among the contributions to the field addressed objective 1: To review current evidence surrounding infant infection, malnutrition, and environmental enteric dysfunction in relation to domestic animal husbandry. This scoping review considered current evidence surrounding infant infection (in particular, infection from zoonoses), malnutrition and EED and the contribution of domestic animals to infection risk (**Chapter 2**). Addressing objective 1, the review highlighted the role of WASH conditions in optimal child growth, and the potential of interventions to effectively disrupt pathogen exposure. The scoping review underlined that addressing the contribution of animals to domestic contamination from zoonotic (enteric) pathogens may be necessary to address growth failure and other poor infant health outcomes. The review was among the first linking WASH, nutrition, ECD and animal husbandry which called for WASH interventions to focus on aspects that pertain specifically to infants. Whilst the review primarily aimed to consider EED and the relationship with nutritional deficiencies and pathogenic infection, it questioned whether EED as an entity should be a focus of prevention. Alongside the difficulties (and expense) of measuring EED and the uncertainty of causality with growth failure and diarrhoea, focusing on EED as an outcome may overlook other, meaningful, and tangible effects of interventions – such as the benefits of improved WASH and/or nutrition on childcare, parent-child interaction or improved dietary diversity. It might also mitigate the need to address risk factors contributing to infection, such as infant exposure to domestic animals. That is not to say EED measures are without value: for example, EED biomarkers as outcomes *may* serve as a valuable indication of whether WASH trials are serving to adequately 'clean up' the environments in which IYC live and play. As a cause of EED, infection can be reduced by WASH interventions that achieve the necessary threshold of hygiene to prevent transmission. Thus, it was argued that WASH interventions which seek to prevent EED might better focus efforts on addressing specific pathways through which faecal-oral (and thus pathogen) transmission occurs in the first two years of a child's life.[8] This avoids fixating on 'curing' a specific (sub)clinical condition which is multifactorial in nature and cause.

A second contribution from this chapter is the further identification and assessment of the risk factors and transmission pathways which contribute to infant infection in rural households, leading into objective 2. Whilst the positive association between WASH programmes and improvements in IYC health is evident,[8–10] **Chapter 2** suggests that many programmes lack the necessary multifactorial approach to address multiple elements of pathogen transmission in rural, subsistence contexts.[11] Whilst the BabyWASH approach advocates for the consideration of age-related behaviours and risk factors which increase infection risk,[12,13] research groups and implementing bodies within WASH and infant health often do not consider this during trial design.[14–18]

### 7.13 Objective 2 and objective 3

Contributions from objectives 2 and 3 – 2. To identify specific risk factors and transmission pathways that contribute to infant infection in rural Ethiopian households; and 3. To better understand how domestic animals and household WASH facilities (ownership and use) affect contamination across different transmission pathways and infant infection risk, as well as the effect of domestic animals on WASH facilities – are addressed together.

As demonstrated in the first phase of formative research (**Chapter 3**), normal developmental behaviours expose the infant to a wide range of pathogens in contaminated environments that should not contain this burden of enteric pathogens. Further, in LMICs, IYC are exposed to environmental reservoirs that have levels of contamination from enteric pathogens or other pathogenic organisms (e.g., domestic floors) with easily accessible highly contaminated vectors (e.g., animal faeces) than in high-income countries which do not share the same burden of enteric pathogens. The fieldwork also highlighted the importance of floors and fomites to infant infection risk (**Chapter 3**). The second formative research (**Chapter 4**) also highlighted contaminated floors as a risk factor for both direct and indirect faecal-oral transmission and thus enteropathogen infection (**Figure 6** and **Figure 7**). Again, these are frequently under-emphasised or omitted pathways in conventional WASH trials.

Furthermore, behaviours – and thus primary exposure and transmission routes – change dramatically from birth through to early childhood, requiring a systematic and dynamic approach to addressing infection risk. For example, as IYC age, the frequency of mouthing hands decreases when infants are not eating but increases during eating.[19] Mouthing behaviours also alter depending on whether the IYC walks or crawls. Similarly, longitudinal research into *Campylobacter* infection and growth shows a high infection prevalence very early in life, with an increasing prevalence over the first year,[20] indicating infection risk changes with developmental stage. The second phase of formative research into C*ampylobacter* infection and associated risk factors (**Chapter 4**) demonstrated the importance of infant age in opening up risk factors and transmission pathways (i.e., as the infant starts to crawl). This stresses the importance of infant age and developmental stage in infection burden and transmission and in the development of subclinical infection (and thus the development of EED). Thus further, gross motor developmental milestones are important considerations for assessing reductions in infection via a reduced pathogen burden and pathogen exposure during the first few years of life. These should be considered as strata during trial sample design and microbiological sampling in broader future interventions.

Thus, a key consideration from the two phases of fieldwork is the need to carefully consider the age of IYC enrolled in WASH trials. This concerns both the ‘critical window’ between birth and two years and the behaviours and developmental stages that infants experience in that time. Longitudinal studies showing associations between enteropathogen carriage and linear growth have faced limitations where infants less than two were underrepresented in cohorts, limiting the ability to test whether associations were mediated by age.[20,21] This age group are most at risk in terms of exposure behaviours and gut and immune immaturity during this 'first thousand day' period when both linear and cognitive growth are formative.[22] It must be considered that infection from specific pathogens (including *Campylobacter*) or other sequelae might be a marker, rather than a cause, of reduced linear growth. As such an assessment of carriage and growth in a longitudinal (WASH) study designed to reduce enteropathogen exposure may better distinguish this.[20] Similarly, results from the formative research phase two (**Chapter 4**) and the CAMPI feasibility trial (**Chapter 6**) support similar research in this field endorsing pathogen carriage and infection as valuable outcomes to WASH interventions focused on infant health.[23–26] The prevalence of enteropathogenic infection (or carriage) allows researchers to understand if interventions can interrupt transmission, as well as to elucidate the effects of specific pathogenic infection on both acute (diarrhoea) and more chronic manifestations of malnutrition (growth failure, EED biomarkers).

Thirdly, a further contribution is an improved understanding of the impact of faecal contamination from animal-related pathogens on infant infection risk (objective 3). Zoonoses and other animal-related diseases underlie 10% of disability-adjusted life years (DALYs) lost in low-income countries each year. This constitutes a quarter (26%) of DALYs lost from all infectious disease.[27] As reviewed in **Chapter 2**, the impact of infant zoonotic infection on linear growth is not understated in the literature. However, studies which look at health impacts of animal exposure do not often consider whether livestock are generally allowed to enter within and share domestic environments – nor do WASH trials assess this. Similarly, domestic contamination from animal-related pathogenic organisms and infant exposure to animals and their faeces has not been a consideration of WASH trials. Thus, a primary outcome in this thesis was to further understand importance of zoonotic pathogen contamination within the home and the transmission of zoonoses as further evidence that animal management must be a consideration of WASH interventions. The first and second phase of formative research (**Chapter 3** and **Chapter 4**) addressed objective 3 and demonstrated how domestic animals within the household affect pathogen contamination across different transmission pathways and infection risk, and that WASH facilities ownership and use do not mitigate this. It has been suggested that pathogenic contamination by animals likely happens at water sources.[28] Conversely these results suggest the proximity of animals contributes substantially to pathogenic contamination of living spaces. Further, findings from the two phases of fieldwork support research by other groups (George M et al,[29] Ercumen A et al,[30] Kaur M et al,[31] El-Tras WF et al,[32] Lowenstein C et al,[33] Ngure F et al,[14] Vasco K et al,[24] Reid B et al[18]) indicating infection and diarrhoea are apparently increased in contexts of close domestic animal proximity due to faecal exposure and the burden of zoonotic pathogens. Phase 2 formative research (**Chapter 4**) focused specifically on *Campylobacter* and added evidence that this zoonotic pathogen is frequently isolated from infant faeces in rural Ethiopia,[35–37] contributing to the *Campylobacter*-stunting hypothesis. This reinforces the need to address this particular zoonosis from backyard poultry (and other carriers such as cattle) which must be a key consideration for any WASH intervention aiming to improve infant health (see the relationship in **Figure 7**).

A further aspect of objective 3 was to understand the impact of domestic animal husbandry on household WASH facilities and use. The fieldwork phases (**Chapter 3** and **Chapter 4**) showed that household WASH facility availability or use did not contribute to a reduction in pathogen contamination across the home nor in the likelihood of infant infection when animals were present. Further results demonstrated that even with high sanitation access and other WASH facilities, faecal contamination was common across different transmission pathways. This supported the hypothesis that WASH interventions are not sufficient in scope nor depth as they do not attempt to block zoonotic or other faecal pathogens, resulting in many contaminated transmission routes that ultimately reach the home (**Figure 6**). Similarly, a key contribution was the suggestion from the fieldwork that domestic animals might indeed hinder the effectiveness of WASH intervention components (in **Chapter 3** and **Chapter 4**). Recent reviews have described a negative impact of animal presence on WASH inputs, or an increased negative impact where WASH conditions are poor.[11,38,39] Due to the vector-borne nature of certain pathogens, unprotected water sources or poorly stored water can facilitate breeding.[11] Thus contaminated water brought into the home, alongside animal faeces transferred by feet, may contaminate many transmission pathways (**Figure 7**), leading ultimately to both direct and indirect faecal-oral ingestion of pathogenic bacteria and other enteric pathogens by infants. Thus, even where improvements in secondary barriers are in place (i.e., improved handwashing, water quality and sanitation) a residual burden from zoonotic pathogens might be expected when animal management is not considered. This shows how domestic animals can hinder the effectiveness of WASH measures.

Further, WASH interventions designed to control human faeces will not see improvements in infant health (or at least suboptimal gains) without efforts to control animal faeces in the same living environment.[39] The WHO 2018 Guidelines admit that few studies have evaluated animal control methods on sanitation efficacy, including decreasing cohabitation with animals, providing scoops for animal faeces, or controlling animal movement.[40] There are difficulties with this. Rural livelihoods depend on animals as a major source of income and as an alternate source in emergencies, and certain measures that support disease control objectives may not be feasible in practice. For example, pig-corralling is recommended for the control of cysticercosis but this is economically unfeasible for low-income households.[11,41] In rural Zimbabwe, mothers were counselled on risk factors for infant infection and could choose to try one or more improved practices of animal management.[42] No households wanted to corral poultry, nor did they choose to upon renegotiation; this was unequivocally due to economic reasons where poultry would not be able to freely scavenge and would require treatment for parasites. In Burkina Faso, focus group participants were keen to separate poultry from living quarters and recognised the associated health risks, but a 'lack of means' was cited as a barrier.[15] However several study households had been experimenting with poultry housing solutions. Similarly, preventing animal access to water sources for household use prevents contamination with animal faeces. However, there is an inherent trade off with providing both livestock and humans with clean water which poses a challenge for many rural communities where water is scarce. Further, as discussed in the introduction, in LMICs many guidelines for biosecurity in household poultry are impractical, have low adoption rates[42] and are undesirable.[42] The SELEVR trial in Burkina Faso is a poultry value chain programme involving poultry flock management, including housing, to increase production and improve maternal and child nutritional status.[44] The authors admit that little attention has been paid to the prevention of infection or growth failure through improved poultry-related hygiene. Similarly, they admit the WASH field has a large evidence gap regarding the importance of animal faeces on infant health, where it has focused on containing human excreta. They note this is not inconceivable given that *'…examining the links between poultry husbandry and child nutrition also requires researchers to design rigorous research across traditional disciplines which is in itself a challenge'*.[44] Further, lower-income contexts in particular may present difficulties with containing poultry: specific barriers include the cost of construction materials and treatment costs of sick birds.[11,45] Basic requirements for housing poultry include space, ventilation, light and protection: the design and materials must not promote parasite infestations and allow good ventilation and easy cleaning to prevent infection transmission.[45] As such, it would become necessary to educate farmers on how to build sturdy, elevated poultry houses for night-time sheltering as well as improved understanding of animal husbandry practices and disease prevention and control. Other challenges include feed access and cost when animals no longer scavenge[46,67] and fears of theft.[48] Natural predators are also a challenge in rural areas. These are not insurmountable challenges, and WASH interventions seeking to reduce animal pathogen transmission must be mindful of the many competing and interdependent priorities for households in relation to their domestic animals.[49]

### 7.14 Objective 4 and objective 5

Taking a different approach from interventions which have attempted to corral animals, a contribution to the WASH field came from objective 5 which aimed to assess the potential for an HPS to reduce the risk of infection in such households, and to a. Assess feasibility to inform a future definitive trial and b. Describe effects on other livelihood-related outcomes. An HPS offers the opportunity for a protective and 'hygienic barrier' to block infant contact with animal faeces.[39] Addressing objective 5, the CAMPI trial (**Chapter 6**) sought to understand the feasibility of an HPS as a WASH intervention component. The HPS demonstrated good acceptability and mixed adherence, which was mostly encouraging. Whilst the trial did not show a reduction in infant faecal *Campylobacter* versus controls (although was not powered to do so), a difference in diarrhoeal prevalence was seen between groups. As such it remains unclear as to whether an HPS alone as a 'primary barrier' (by way of preventing direct faecal contact) is sufficient to reduce zoonotic infection. Whilst studies suggest that that animal contact is most important to the transmission of *Campylobacter,*[50] other routes to infant infection must also be considered, including caregiver hand and food hygiene and the contamination of fomites given to the infant. More broadly, the design and development of the HPS highlighted how important are the community and beneficiaries of the intervention throughout these processes. The use of mixed-methods work allowed the team to understand motivations and barriers to the potential use of an HPS. As importantly it reminds the WASH community the importance of ensuring communities are technically supported to be able to reduce infection. Further, it highlighted the role of engaging caregivers (particularly women) in decision making; not only should caregivers be party to intervention design but the trial demonstrated how interventions will have an impact on family members before on more intractable outcomes such as growth failure. Further, interventions do not necessarily need to improve linear growth to have an effect: interventions will have positive, meaningful, and observable effects before this improves. As noted by Brown et al. '…*for most of the beneficiaries the advantages and motives for the adoption of* [WASH] *measures are not directly health-related, but improvements in quality of life, including factors related to privacy, comfort, status, dignity, protection from harassment and savings in cost and time*'.[51] The CAMPI feasibility trial demonstrated many secondary benefits (e.g. injury and harm prevention, reductions in maternal anxiety, stress and time burden) – important given that these factors may inadvertently increase infection risk. This includes maternal time burden and lack of time to clean up the living space, time to fetch water, hygienically prepare food, housing structure and crowding.[52] Thus a positive impact on these may ultimately reduce undernutrition and thus improve infant health by directly contributing to poverty reduction.[46,51] This aside, the CAMPI trial was the first randomised, controlled feasibility trial of an alternative method to prevent infant faecal-oral exposure. Whilst providing primary insights into acceptability and adherence, the study also offers a valuable base for further research into the potential of an HPS to reduce infant infection.

### 7.15 Objective 6

This body of research suggests that domestic animal husbandry practices must become a key consideration for WASH interventions, particularly those focused on improving infant health. Whilst 'secondary' barriers to block transmission of pathogens from animal faeces (personal, household and food hygiene, water quality and safe storage) might limit some exposure to both human and animal faeces, 'primary' barriers which address animal faecal contamination (e.g. sanitation and animal husbandry practices which limit animal faecal contamination of water sources) have largely not been considered in traditional WASH intervention design.[39] It is thus in the interest of WASH interventions to address the issue of domestic animal management and to integrate this into the WASH framework[49] if this is to be systematically considered. WASH interventions have the potential for this: most, if not all, zoonotic pathogens causally related to diarrhoea or growth failure (including the Neglected Zoonotic Diseases such as schistosomiasis[11]) are also related to the three components of WASH in terms of prevention and/or treatment. Given good sector knowledge about pathogen transmission through the environment and into homes, WASH interventions plausibly can, and should, contribute to the control of zoonoses through the provision of infrastructure that removes both human and animal waste. This can be via sanitation infrastructure, the provision of consistent and safe water (purified within the home), handwashing and hygienic preparation and storage of food, the careful management of animal faeces (including considering the relationship to wastewater and irrigation), and animal corralling or penning (or indeed, providing play spaces which demarcate a hygienic environment for infants). However, issues abound here regarding what is seen as the 'upper boundary' or maximum holistic viewpoint when it comes to what WASH aims to deliver, and further the limitations of the framework on which many interventions are based (referring specifically to the F-diagram). These limitations might underlie the continuous stream of trials and analyses attempting to estimate and attribute WASH efficacy to infant health outcomes which show varying, inconsistent effects. This section thus concludes summarising the contributions to research by addressing objective 6: To discuss limitations of the WASH framework and the scope of WASH interventions to improve infant health outcomes.

As a primary criticism, the original F-diagram, although fundamental to WASH research and programming, was developed to illustrate transmission routes of faecal-oral pathogens from the viewpoint of human excreta and does not consider the contribution to contamination from animals inside and around the home. This is something which much research discusses[38,39,53] although it is rarely operationalised. Whilst the WHO 2018 Guidelines for Sanitation and Health suggest that the management of domestic animals should be coordinated alongside WASH interventions to 'maximise the health benefits of sanitation' and recommends animals should be restricted from entering domestic spaces,[40] the guidelines do not encompass animal management. The modified F-diagram presented in the guidelines recognises animals as mechanical vectors and further, that the multiple, complex interactions between sanitation and animals was a poorly understood factor in trials that did not achieve expected health outcomes. However, the guidelines admit: *'Although many enteric bacteria are zoonotic... the safe disposal of animal faeces is beyond the scope of these guidelines'.*[40] Whilst this is perhaps understandable where animal faeces management lies beyond the remit of the guidelines, it might be argued this is short-sighted and a reflection of the limitations of the scope of WASH and the guidelines that are created around it.

Similarly, the fact that many white documents and guidelines do not attempt to integrate animal husbandry practices within their scope may hint at a broader issue which lies in the construct of WASH and how it has reduced within its operational capacity. Whilst the F-diagram is a useful tool which frequently underpins WASH interventions and which captures immediate exposures, in doing so it excludes the broader background state, or overall levels of environmental hygiene. It is widely acknowledged that transmission may be simple or may involve multiple steps across pathways, and so interventions are most likely most effective when considering the broader environment and contextual risks.[Dod] Whilst some research calls for a focus on the key transmission pathways which contribute to infant infection,[38,54,55] it might be argued that in highly contaminated environments, this approach would not achieve the hygiene levels that are necessary to see improvements in growth. It is possible that achieving improvements in IYC health is unlikely with small-scale, fragmented interventions – no matter how well-designed. Regarding the four recent trials,[1–4] it is likely that the interventions did not interrupt all transmission pathways substantially to significantly reduce environmental contamination and thus prevent infant exposure to faecal pathogens. This questions the theory that a risk-factor or an 'exposure profile'[54–56] approach to reducing contamination might be sufficient. More broadly it questions if the current framing, concept, and delivery of WASH is appropriate and adequate – and indeed if WASH still serves its original purpose of blocking faecal-oral transmission where primary aims are to improve infant health.

Paradoxically, whilst trials are not able to (or not bold enough) to deliver comprehensive interventions, there appears an overconfidence in the infant health improvements that are expected within their scope and timeframe. Interventions which focus on largely intractable outcomes such as stunting ignore the multifaceted nature of the condition. Infection causes undernutrition (see **Figure 2**), as does poor dietary quality and quantity – but at the heart is the negative relationship between these factors which is reinforced in highly unhygienic conditions. Thus, interventions remain stubbornly narrow and fragmented without considering the wider environmental landscape and social and biological systems of human beings. This includes many interrelated, synergistic relationships such as those between nutrition and infection[57] (**Figure 3**), the age- and behaviour-related pathways that predispose infants to greater infection risk (as described in Chapter 3 and Chapter 5) and the substantial contribution of animal faeces to each transmission pathway (Chapter 3 and Chapter 5). Primarily, of main concern is the impact of overall poor environmental hygiene and living conditions on disease, as shown historically in upper-income countries. As mentioned, disease was once considered an indicator of poor societal and environmental conditions and it became evident that to improve health necessitated cleaning up the environment.[58] In lower-income countries today, environmental contamination is pervasive and multiple risk factors contribute to the burden: these risk factors go beyond conventional programmatic conceptions of water supply, latrines, and handwashing. As such, it seems untenable that with the current framework, WASH alone can sufficiently prevent infection to the level needed to improve health. That is, as described in the previous section, WASH (in its programmatic definition) is necessary but not sufficient to reduce infection burdens: it is clear WASH needs to evolve to sufficiently interrupt contamination pathways and have an aggregate and sustainable impact on infant (and public) health.

Thus, the inefficiencies of WASH and deployed interventions lie within the WASH construct, where each component of water, sanitation, and hygiene themselves are limited. Where each component is underpinned by a very young understanding of faecal-oral disease transmission, the scope to act is thus also constrained. Interventions must consider that multiple pathogens are transmitted through multiple environmental reservoirs. Although single interventions may reduce exposures, reductions may be insufficient to improve health.[56] Essentially, it may be argued that the concept of WASH has become narrowly defined and uprooted from a broader set of thinking on the importance of the physical environment for human (infant) health. Focusing on only one (or a few) dominant transmission pathways overlooks the governing environment and may be a 'Band-Aid solution' without considering the broad background state. Whilst the WASH acronym is a useful category for training and organising the sector and serves to encompass these aspects of public health into a practical framework. It might be contested that this argument here, which highlights the need for much more intensive, extensive, and holistic programming for improved infant health, should not determine how the sector organises the response to it. Ultimately, however, improving population health for the poorest, where risk factors for transmission are increased, will necessitate critical improvements and reforms in material living standards and in overall environmental hygiene.[6–8] At the crux of this is how we define the WASH concept. If the basis of WASH intervention design is blocking faecal-oral transmission, then a failure to show improvements in health is not a failure of WASH but how it has been reduced.

Further, although reference has been made to the 'BabyWASH' coalition as a recent concept which attempts to merge the sectors of WASH, ECD and nutrition, the creation of initiatives such as the BabyWASH coalition bring forth the issue of fragmenting 'aspects' of WASH into further sectors which may not help the sector in designing and deploying necessarily extensive interventions. It might be argued that BabyWASH should not act as a 'baby-focused bolt-on' to WASH interventions, but should serve to call for, and as a reminder to, those designing WASH interventions to reconsider what is necessary to improve infant health. WASH interventions that are predicated on infant health grounds must necessarily consider what is really required to achieve the high hygiene threshold clearly required to improve infant health.[11,59] This requires reassessing is delivered in terms of WASH, and indeed the WASH framework, if we are not achieving anticipated results.

This brings the discussion toward the recent push for 'Transformative WASH'.[59] Trial findings prompted calls to test interventions which 'radically reduce faecal contamination in the household environment', termed Transformative WASH.[59] What exactly is Transformative WASH is as of yet unclear: principally, it refers to a set of interventions which 'radically' and comprehensively clean up the community and domestic environments. This means delivering each component of WASH in tandem of substantial scale and quality. This would include, but is not limited to, improved water quality and quantity, improved sanitation, drainage, handwashing facilities with soap, the separation of animals and their faeces from living environments, food safety and hygiene along the food chain – all at the household and community levels. Thus, Transformative WASH is necessarily comprehensive and multifaceted (and expensive). Whilst this approach is an important and beneficial step, it may be that this new concept is still not sufficiently broad and something more encompassing is needed: Transformative WASH may be less pertinent than the older, broader concept of environmental hygiene. Both historical and accumulating recent evidence suggest this is more useful and relevant to improving human health than that of 'WASH' alone, even when delivered 'holistically'. This includes, but is not limited to: 1. Household and communal infrastructure, not only in terms of WASH facilities but also improvements in housing quality[60] and flooring[61,62] which supports domestic hygiene; 2. Other sources of faecal contamination within the home, particularly from domestic animals). As noted by WHO and UNICEF, 'transformation is also needed in the implementation environment, collectively referred to as systems', including where WASH interventions must include greater investment and capacity throughout the system.[63] – also, delivery will need to be at the scale of administrative areas, with programmes covering entire districts, municipalities, cities and provinces.[63]

As we attempt to understand and implement Transformative WASH, it may be pertinent to consider both historical and accumulating recent evidence and consider that a broader concept of environmental hygiene is more relevant, and necessary, for the prevention of faecal-oral disease. Taking responsibility for improvements in population health thus necessitates a focus on overall environmental hygiene as individual health will unlikely improve without it. Researchers, practitioners, donors and most importantly, governmental bodies need to acknowledge the wider environment to bring about a radical shift in hygienic living conditions if we are to transform the health of the poorest. An 'environmental hygiene' paradigm means taking a preventative approach to controlling faecal-oral disease. This approach looks beyond the F diagram and does not focus on dominant transmission pathways or risk factors, nor deliver isolated interventions, but considers broader background conditions and existing infrastructure to substantially improve living conditions in lower-income settings.

## 7.2 Limitations of the research

Both the first and second phases of formative research (**Chapter 3** and **Chapter 4**) held limitations within their methodologies. These are discussed here. Firstly, there can be discussion around the use of the term 'formative' for the first two phases of fieldwork. Where formative research does not test hypotheses per se, data and findings from formative research 'can provide working hypotheses to explain successes or failures, particularly when the implementation and evaluation plans are grounded in a conceptual framework'.[64] This sort of 'implementation-focused formative data' provide evidence for components of a conceptual framework as was described within the review chapter and insights towards the hypotheses for future interventions. Thus, whilst the term may not capture the nature of the studies perfectly, the approach was key to the success, design, interpretation, and evaluation of the final trial, as well as for the replication of the process (whilst bearing in mind limitations now discussed and recommendations for future research). Perhaps more importantly, small sample sizes limited the ability to test associations with infant health outcomes (or other sociodemographic factors) and may not have fully captured variability in pathogen contamination across pathways. Regardless, it served to emphasise levels across the domestic environment – urging that WASH interventions are better geared to address such extensive contamination. In general, small sample sizes affect validity and generalisability. A larger sample size which also compared households *without* domestic animals living in proximity would have contributed towards testing the central hypothesis, although such households would have been difficult to find.

Observation periods in the first fieldwork (**Chapter 3**) provided insight into contextual factors opening certain pathogen transmission pathways, including dirty floors, fomites, water, and the presence of animal faeces. However, these observations were over a relatively short time period which may not capture variation in infant activities/behaviours. Observational data can also present biases, especially when the researcher is present. This includes participant bias (or 'response bias') and social desirability bias where participants are aware of what the researcher is investigating, or anticipates finding, and holds implications for how participants behave.[65] This presents difficulties where survey results can still show internal validity. Examining the extent of the bias present in responses by incorporating a socially desirable scale in the survey[66] might have helped mitigate this. Similar studies have attempted to overcome this by piloting the use of video recording.[67] Here, video 'activity' data were combined with surface sample microbiology to develop 'example exposure profiles'. Such methods may allow for a more accurate estimation of microbial exposure which reduces recall bias. Applying this method over a specified time period (a day or longer), alongside mapping of microbial load and frequency of exposure, provides a more accurate and valuable map of pathogen transmission. Regardless, it is important to bear in mind a takeaway from the thesis which reminds the sector of the high 'hygiene thresholds'[6,7] necessary to see improvements in infant health. Whilst it is important to understand pathogen burdens across different transmission roues within the home, this may be less important than understanding what is necessary in terms of intervention design to reduce the overall burden and exposure.

However, the two phases of fieldwork only captured part of infant infection risk. Contaminated food[68] and drinking water[69] as well as other fomites, such as utensils,[51,70] are important (possibly primary) transmission pathways which were not measured. Food hygiene is a likely important pathway in some contexts[71]: some estimates suggest approximately 70% of all diarrhoea is caused by contaminated foods, with pathogen loads exceeding those in drinking water.[51] Measuring these pathways would have provided greater insight into the overall pathogen burden. In certain contexts, such as Ethiopia, it is common to eat using hands and thus transmission pathways start to cross over (as shown in the unpublished research in **Chapter 4**). The CAMPI feasibility trial collected some data on food reheating practices; across households only 28 safely prepared all meals at both time points (data not shown; see Table S6 in **Chapter 6**). Further analysis suggested that infant diarrhoeal prevalence was associated with an increased waiting time between food preparation and feeding (OR 3.04, p=0.04) but not with *Campylobacter* prevalence.[72] However data collected did not include information on food storage practices or on other modes of contamination (such as from utensils or hands). Further, the faecal contamination of food crops from domestic animals (through use of faeces and wastewater for fertiliser, irrigation and washing) is a dominant source of pathogen contamination in the home.[73,74] Food safety has a clear programmatic link between WASH and nutrition that may have an important role to play in reducing infant enteropathogen exposure when considered as part of a wider WASH intervention package.

The formative fieldwork showed some difficulties in ascertaining correct use and upkeep of WASH facilities, including latrines, handwashing stations and soap. In some contexts, latrines may be present, but they are often not used by all household members or kept clean.[11] As mentioned in **Chapter 4**, in rural communities it can be difficult to accurately assess latrine and soap use. Further, in this setting where PIN provided latrines households may have more likely responded positively to enumerators (hired by PIN) and when PIN staff were present. Latrines were checked for use, but it is possible that all family members did not use them – particularly children. Similarly, households were asked to show soap to confirm handwashing, but it is not certain it was always used. Further observational data and a more detailed understanding of motivators and barriers would help explain use or non-use. Relatedly, the formative fieldwork did not investigate child faecal disposal practices. This is an essential component of the sanitation chain[75] but has not been consistently addressed in WASH interventions.[40]

Other limitations involved pathogen measurement. The primary fieldwork (**Chapter 3**) used the water filtration method to identify TTCs (as faecal indicator bacteria). This method determines presence of faeces but cannot determine origin. That is faecal indicator bacteria do serve, as their name suggests, as an indicator of where there is faecal contamination within the environment. However, they may not be pathogenic, and the method does not allow to distinguish between human or animal faeces. The second formative study (**Chapter 4**) sought to test different methodologies to detect *Campylobacter* spp. in clinical samples in order to inform the upcoming CAMPI feasibility trial. Further, studies demonstrating household spread of *Campylobacter* between poultry (and other domestic animals) and infants using advanced DNA sequencing methods are lacking,[75] toward which this research hoped to contribute. *Campylobacter* is a fastidious Gram-negative bacterium which is difficult to isolate and there is no gold standard or accepted routine method for isolation from samples.[76] Laboratory diagnosis of infection requires culture-dependent and/or culture-independent methodologies. **Chapter 4** and **Chapter 6** used the culture method to isolate *Campylobacter* spp. The culture media used was externally validated and demonstrated good sensitivity and specificity. However, the use of culture-based testing without validation holds limitations, particularly high specificity but low sensitivity[25,26] with substantial under-detection. Considering culture-independent methods, DNA or RNA can be isolated from samples and an organism's 'genetic signature' or 'marker' can be verified using sequencing techniques or genus- or species-specific PCR amplification of the gene of interest (e.g., the 16S rRNA gene). Genetic sequencing of *Campylobacter* spp. virulence genes provides high discriminatory power to identify and differentiate clusters of related strains both within and between different environmental samples. The ELISA and Lateral Flow Assay (LFA) tests use immunological screening to detect antibodies. Both PCR (and quantitative PCR, qPCR) and ELISA demonstrate high sensitivity and specificity but low positive predictive values.[25,26] The LFA also demonstrates high sensitivity and specificity.[77] As such molecular or serological tests provide a rapid and reliable alternative for the laboratory diagnosis of *Campylobacter* spp. – such that time-consuming culture may no longer be required for diagnosis.[77] These are likely best in combination.[25,77] Reasons why these techniques could not be adopted within the fieldwork is further discussed later in this section.

A further limitation of the fieldwork pertaining to domestic animal husbandry is the lack of data capturing relationships between animal ownership, assets and income, dietary quality and diversity and infant health. These factors might explain the heterogeneity among studies examining relationships between animal exposure and infant health, where findings vary between animal, rurality, country and by outcome.[78–82] This research did not collect data on infant dietary quality nor estimate household economic status, but much research documents the role of animal husbandry in household income elasticity, rural livelihoods and wellbeing[82,83] and the importance of animal source foods (ASFs) in infant nutritional status.[83–85] This is a reciprocal relationship. The dense nutrition ASFs provide is associated with improved child growth.[85] Increased livestock ownership may mean greater assets and income, increased feeding of ASFs to infants in place of purchasing cheaper, less nutritious foods and therefore improvements in infant health (by way of reduced disease susceptibility),[83] and lower healthcare-associated costs.

Alternatively, poor health may also be related to the environment in which animals and humans co-reside which more effectively harbours and transmits enteropathogens.[82] One study examining WASH and cysticercosis in pigs showed an increase in cysticercosis *after* a CLTS intervention – perhaps due to continuing open defecation (persons infected with tapeworms intermittently shed infective eggs in their faeces).[86] The authors did not discuss if new latrines led to the safe separation of both humans and animals from human faeces.[11] This was not analysed here in the formative fieldwork or the CAMPI trial: however in fieldwork phase one open defecation was estimated at one in five persons (**Chapter 3**, see **Table 7**) which may well contribute to animal disease. This level of detail is an important objective for future research to assess human and animal pathogen transmission.

### 7.3 Reflecting on fieldwork challenges as a cornerstone of international research

Whilst methodological limitations associated with the fieldwork have been presented, broader challenges offer wider lessons. Such challenges are rarely described and discussed in peer- reviewed papers.[87] However, international research, by virtue of its positioning within cross-cultural settings, increases the risk of potential issues from unforeseen contextual conditions.[88] Researchers engaged in such partnerships can encounter problems arising from the theoretical and practical gap between a well-designed and confident research proposal and 'on-the-ground realities'.[89] However, this is not always disadvantageous to the research and sharing encourages flexibility, reassessment and adjustment.[88] Thus finally this section reflects on challenges faced during the second phase of formative research (**Chapter 4**). It discusses difficulties regarding local capacity, access and partnership building in a context of local civil and political unrest and infrastructure failure. It also touches on the importance of reflexivity and flexibility, such that instead of glossing over 'failures' the necessarily evolving nature of a project is seen and embraced.[89]

In preparation for the upcoming feasibility trial (**Chapter 6**), it was necessary to determine how to best measure *Campylobacter* within Ethiopian field conditions in terms of sensitivity, specificity, ease, and budget. Three methods (selective culture, qPCR and LFA) aimed to test environmental and clinical samples. Prior laboratory work tested DNA extraction methods, refined DNA sequences and piloted *Campylobacter* detection with

LFA. However, difficulties in the field meant obtaining qPCR and DNA sequencing data was impossible. This included access to facilities which had to be re-negotiated upon arrival – a stressful process which led to a substantial loss of time (and thus data). Where access to a new laboratory was not permitted, key pieces of equipment were not available and 'improvising' equipment (such as a vortex) was time consuming. Infrastructure failure constituted the largest challenge. For indeterminate and extended periods wireless internet connections were ceased and alongside frequent power cuts, expensive and irreplaceable reagents were wasted. Although culture analysis was satisfactory, the laboratory only held glass, non-ventilated dishes not conducive to culturing *Campylobacter* and many samples were indeterminable. This might have meant it was not possible to determine the best protocol for measuring *Campylobacter* within Ethiopian fieldwork conditions. However, the difficulties faced were not unique nor rare and did highlight future potential future hurdles. Issues of access and other practicalities often force researchers to shift the overall research scope[89] thus the pilot study did indeed fulfil the aim by suggesting that without necessary practical arrangements, a larger, controlled trial with substantial time pressures and significantly more daily samples would be unfeasible. Whilst this experience highlights that the relationship between proposal and project should be dynamic and fluid[88] it also highlights the importance of pilot studies, which are not always feasible but often significantly influence the later full-scale project.[89]

Further challenges concerned study partnerships. Recent years have seen a huge increase in the number of international partnerships and collaborations across universities, particularly across the so-called 'north-south' divide.[90] International partnerships can benefit both groups from knowledge transfer across these topics and by improving visibility and recognition and the sharing of equipment and ideas. However, this can form an 'endogenous self-perpetuating outcome of science, with substantial costs and no commensurate benefits'.[91] Further, a format can be assumed where the 'southern' collaborator essentially assists in data collection but contributes little to study design, hypothetical discussions or knowledge generation.[91] As noted, *'Implicit in [the] enthusiasm for research collaboration… are a number of assumptions: 1. that the concept of 'research collaboration' is well understood'*.[92] Here, where partnership expectations, outputs and contributions were not defined prior to starting, opportunities to develop skills and ideas were lost. This was limited by available time following negotiations, and data collection was prioritised over partner engagement and training. Later in preparation for the feasibility trial, a Memorandum of Understanding clarified deliverables, responsibilities and a mutual exchange of payment, teaching and skills training for study personnel, laboratory access and co-authoring papers.

The process and results of data collection are often presented in a way that denies the disorder often experienced. Within the 'field', there are multiple physical components (study personnel, logistical arrangements, materials, costs, and settings) which require constant negotiation. Almost all fieldwork requires changes in the pre-planned schedule, methods and/or research design. As such, fieldwork requires reflexivity, flexibility and to continually negotiate 'local realities'[89] for a strong, mutually beneficial partnership and to fulfil project aims. Regrouping, reflecting, accepting errors and changing plans are 'four cornerstones' of good fieldwork.[88,89] Importantly, the 'field' itself is not self-contained or static and not discrete from 'everyday life',[93] but an evolving place that is shaped by the dynamics between collaborators and what each brings.[88] As such an important aspect of reflexivity and flexibility is avoiding the imposition of standards or expectations and to allow the cultural dynamics between partners to exist and to inform the collaboration. The researcher must be ready and willing to negotiate the many unknowns in new projects, and further to allow that to feedback into initial plans as an integral (and essential) part of the research process.

## 7.4 Research in context

The feasibility trial in this thesis demonstrated the potential for an HPS, as one novel household-level WASH intervention component, to help prevent infant geophagy in lower-income settings where infants are exposed to floors contaminated with faeces and their pathogens. Although an HPS will not interrupt other major transmission routes, as discussed, it might alleviate a slight portion of the infection burden enough to have a small but meaningful impact on enteric infections and the development of EED early in life. The secondary benefits seen in the study are also major contributors towards infant nutritional status where the HPS may directly benefit the primary caregiver – in this context usually the mother. Thus, an HPS is plausible as a material component of a WASH intervention but will not be sufficient alone to reduce levels of infant infection.

A major consideration of this research is the narrow focus on the faecal-oral route as a mode of disease transmission. This thesis explores the hypothesis that a reduction in pathogen exposure could lead to improvements in infant health outcomes and focuses on faecal-oral transmission as a main driver of pathogen exposure. However, as mentioned in the introduction, faecal-oral transmission constitutes as just one subcategory of communicable water-supply and sanitation-related disease,[94] and not the only route to infant infection (albeit forming the basis for the design and delivery of most WASH interventions). Others include water-based diseases such as schistosomiasis, water-related insect vector diseases such as malaria and non-faecal-oral water-washed diseases such as trachoma, where research describes a relationship with undernutrition.[95] Mara and Alabaster present water- supply-related disease as just one principal category in an environmental classification of 'housing-related diseases'.[94] The authors remind that housing provides 'essential shelter and services', which includes water and sanitation but also waste storage and collection and food preparation and storage. These components contribute to infant infection (particularly food preparation and storage,[68,71] as mentioned in the limitations section) Thus whilst faecal-oral transmission of pathogenic organisms may contribute greatly to infant infection and poor health outcomes, it is necessary to bear in mind that this constitutes just one area of communicable disease that WASH seeks to improve. There is a greater theoretical protection that WASH can provide, both from other types of water-supply- and sanitation-related disease, but also in the broader housing environment. Indeed, Mara and Alabaster note the contribution of animal faeces within the home to disease.[94]

Therefore, considering the household playspace as a material component of a WASH intervention, it is practical to examine it alongside Mara and Alabaster's environmental classification of disease[94] to understand whether any benefits might be expected. This early classification has helped frame WASH as it is known today where interventions seek to remediate one or more areas. Table 21 below incorporates the environmental classification framework, and explores potential positive benefits of the HPS for different disease categories plus where it may have an additive effect and when no effect is likely. This aids the WASH field in identifying when an HPS might provide benefits to infant health and what other intervention components would be necessary to make a meaningful difference. In summary, Table 21 suggests that an HPS might offer some protection from communicable disease in groups relating to 1) Building related diseases, including from: insect- and rodent-vector diseases, geohelminths; animal faeces, bites and stings; 2) Water-supply related diseases including from water-based protection from contaminated surface water in the home and contaminated floors) and water- related insect-vector diseases (when used in conjunction with a bed net); 3) Sanitation-related diseases as protection from contaminated surface water in home and contaminated floors.

Regarding non-communicable disease, an HPS holds potential to from 1) Dust (when used with a roof or netting, as some households installed during the TIPs trial in **Chapter 5**); 2) Accidents from unsupervised play e.g., burns, electrical shocks, drowning, traffic accidents, poisoning; 3) Possible protection from sudden infant death syndrome (SIDS) or injury from close-confinement sleeping (if HPS is used as a cot). An HPS is unlikely to impact communicable or non-communicable disease areas where other major intervention components are required to interrupt transmission, such as foodborne-excreta related diseases and foodborne zoonoses due to unsafe food preparation and storage. Most of the potential benefits from an HPS will likely come when the surrounding domestic environment provides improved water quantity and quality and safe sanitation. This exercise demonstrates the complex relationship between housing and health and highlights the many considerations within the domestic environment for WASH interventions aiming to improve infant health. Researchers, practitioners, donors and governmental bodies concerned with providing WASH to households and communities need to acknowledge structural limitations of the WASH framework to bring about a radical shift in hygienic living conditions if we are to transform the health of the poorest. This means taking a preventative attitude to controlling faecal-oral disease which might look beyond the F-diagram and does not focus on dominant transmission pathways or risk factors, nor delivers isolated interventions, but considers what is necessary to deliver against the broader background conditions and current environmental infrastructure to substantially improve living conditions in lower-income settings.

Table 21. Possible benefits of a household playspace as mapped against an environmental classification of housing-related disease. Adapted from Mara and Alabaster.[94]

| Principal disease category | Communicable disease | Conceived benefit from, or effect of, an HPS | Non-communicable disease | Conceived benefit from, or effect of, an HPS |
|---|---|---|---|---|
| 1. Disease related to defects in buildings and the peri-domestic environment | Building-related insect vector diseases; peri-domestic insect-vector diseases | Possible protection against lice, fleas, bed bugs and ticks; possibly against malaria in conjunction with a net | Building-related insect vector diseases | Unlikely |
| | Building-related rodent-vector diseases | Possible protection against diseases from rats and other rodents | Dust-, smoke- and damp-induced diseases | Possible protection against dust with a roof; unlikely protection against damp or smoke |
| | Geohelminthiases | Possible protection during play from ingestion of soil contaminated with eggs or larvae | Building-related carcinoma | Unlikely |
| | Diseases due to animal faeces | Likely protective during play against disease from direct/indirect faecal-oral transmission | Accidents | Likely protective against accidents from unsupervised play e.g. burns, electrical shocks, drowning, traffic accidents, poisoning |
| | Diseases due to animal bites | Likely protective during play against injury from domestic animals; potentially from rodents and stings | Diseases due to traffic fumes | Unlikely |
| | | | Overcrowding | Possible protection from SIDS or injury from close-confinement sleeping |
| 2. Diseases related to defective water supply | Faecal-oral (waterborne and water-washed) diseases | Unlikely | Water quality-related diseases | Unlikely |
| | Non faecal-oral water-washed diseases | Unlikely | | |
| | Water-based diseases | Possible protection during play from decreased contact with contaminated surface water | Water-related carcinomas | Unlikely |
| | Water-related insect-vector diseases | Possible protection against malaria in conjunction with a net | | |
| 3. Diseases related to defective sanitation | Non-bacterial faecal-oral diseases | Possible protection during play against direct/indirect transmission from contaminated surface water and floor surface | None known | n/a |
| | Bacterial faecal-oral diseases | | | |
| | Geohelminthiases | | | |
| | Taeniases | Unlikely | | |
| | Water-based helminthiases | Possible protection during play against contaminated surface water | | |
| | Excreta-related insect-vector diseases | | | |
| | Excreta-related rodent-vector diseases | | | |
| 4. Diseases related to defective refuse storage and collection | Refuse-related insect-vector diseases | Possible protection during play against contaminated surface water | None known | n/a |
| | Refuse-related rodent-vector diseases | | | |
| 5. Diseases related to defective food storage and preparation | Foodborne excreta-related diseases | Unlikely | Food related carcinoma | Unlikely |
| | Foodborne zoonoses | Unlikely | | |
| | Diseases from foodborne microbial toxins | Unlikely | | |
| | Airborne water-based diseases | Unlikely | | |

HPS, household playspace; SIDS; infant sudden death syndrome.

### 7.5 References

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# 8 Conclusion

Through multiple stages of an initial review, two phases of formative research, the participatory design process of an HPS and a randomised controlled feasibility trial, this thesis highlights key ‘blind spots’ in conventional WASH programming. These omissions and their implications might explain why WASH trials have largely not improved certain infant health outcomes. Further, they may help inform future interventions for greater health gains.

Firstly, interventions must consider the age- and behaviour-related factors which increase infection risk – including related transmission pathways such as domestic floors and fomites (toys). WASH currently lacks the multifactorial approach needed to address these routes to infection. Second is the importance of animal faecal contamination on domestic hygiene and infection risk. Where contamination might mitigate the benefits of improved WASH, the traditional F-diagram with its focus on human excreta and related pathways should be reconsidered. WASH interventions can plausibly contribute to the control of zoonoses and this must become an integral element of WASH guidelines. Lastly, researchers have called for the testing of other WASH- related intervention components alongside vaccine development to prevent infection.

The CAMPI feasibility trial demonstrated the potential for an HPS as one such component. With mixed adherence and good acceptability, an HPS remains a viable option to reduce direct faecal-oral transmission and infant infection – if recommended adjustments are made. The study concluded a full randomised trial was merited which would provide further insight into adherence and acceptability and would be powered to detect an effect on infection and diarrhoeal prevalence. Providing soap and other cleaning materials and possibly (non-porous) toys would be critical to ensure sustained adherence and use. Through multiple other benefits, the trial demonstrated the importance of ‘soft’ outcome measures in WASH trials. This reminds those in the field that such ‘secondary’ outcomes should not be relegated, and that interventions will have meaningful impacts before any effect on more intractable outcomes (for example, growth or diarrhoea). These other benefits from the HPS are intrinsic to infant nutrition, and so trials might incorporate measures of time allocation and engagement in childcare to further assess impacts on infant health.

## 8.1 Implications for WASH programming and directions for future research

The final thesis objective was to describe implications of the research body for current WASH programming. As such, this section provides recommendations to how WASH interventions might be deployed within rural areas to help prevent infant infection. Overall, research findings emphasise the high thresholds of hygiene and development necessary to improve infant health, and the necessary intervention components to block multiple pathways of infection transmission. This goes further than an 'exposure profile' approach which may lead to further fragmentation of the field and not sufficiently reduce the pathogen burden to have any clinically or significantly meaningful effect. A similar takeaway from the WASH Benefits trials stated that *'Despite high implementation fidelity and uptake of interventions, the children who received the WASH interventions in our trials still experienced very high enteropathogenic exposure and infection, showing that environmental faecal contamination remained pervasive despite these interventions'*.[1] Although the BabyWASH approach aims for close integration of related sectors, it is proposed in practitioner guidelines as 'an additional component.'[2] The creation of initiatives such as the BabyWASH coalition highlight the inconsistency of current WASH interventions on infant health outcomes, and also what is needed to improve infant nutritional status. However, it also highlights the issue of fragmenting 'aspects' of WASH into further sectors which may not help the sector in designing and deploying necessarily extensive interventions. It might be argued that BabyWASH should not act as a 'baby-focused bolt-on' to WASH interventions, but should call for interventions to reconsider the whole WASH package and framework to deliver what is necessary to improve infant health. This aligns with the recent push toward 'Transformative WASH' or 'WASH++'[1,3] which calls for much greater improvements in hygiene to reduce malnutrition and infection.

The thesis builds a picture of domestic hygiene in a rural, subsistence agriculture context and the limiting effect on infant health. Whilst isolated interventions are unlikely to effectively block the full spectrum of transmission routes to infants, together they might achieve a higher hygiene threshold. More broadly, this research body highlights the importance of infant age and mobility thresholds in studies demonstrating causality. As infants age, risk factors and transmission pathways will change, affecting the aetiology and outcomes of infection. These are important strata in terms of study design and study variables. Whilst it is not exactly clear how much cleaner the household environment must become to reduce infection, it is increasingly evident that the necessary quality, scope, and scale of WASH interventions is extensive. Whilst WASH (in its programmatic definition) is clearly necessary it may not be sufficient alone to reduce infection. Hence the framework must evolve. This includes incorporating improved flooring, housing, and animal management – necessary elements of a 'Transformative WASH' approach. Further, WASH interventions to control human waste will lose health benefits if they do not contain animal feces in the same environment. Research which is attempting to achieve overall reductions in pathogenic contamination within the home must recognise domestic animals as mechanical vectors and address this as part of the sanitation chain.

Further research into the issue of animal contamination is required. It is increasingly evident that animal faeces contribute to certain disease processes and poor health outcomes in infants. However, evidence gaps remain on how, when, where and why zoonotic pathogens reach infants in the domestic environment and how best to prevent this. A clearer understanding of the true burden of disease from animal excreta within different infrastructure and behavioural contexts is critical for improved health outcomes. Research must clarify how zoonotic pathogens move through the home and contaminate transmission pathways, as they pertain to each area of WASH (Table 21). A broader study that seeks to measure pathways and risk factors in terms of pathogen contamination, origin, burden, and health effects (and additive effects between different pathways) would be productive. More sensitive, specific detection measures such as qPCR and/or ELISA would inform on pathogen species and prevalence, distinguish species and identify clusters of related strains.

Domestic animals are an intrinsic part of rural livelihoods and crucial assets for income and dietary quality and diversity. Thus, the interactions between animal ownership, husbandry practices and economic and health benefits versus trade-offs are essential further research relating to the WASH field if interventions are to improve infant health. Of further importance are the motivators and barriers which determine behaviours surrounding animal husbandry practices. This includes knowledge of exposure risks, and preventative behaviours and practices, gender- and age-specific activities and responsibilities and animal housing and containment. This will determine 'hot spots' of infant contact with animals and their faeces and help delineate transmission pathways, and thus how WASH interventions might achieve the greatest impact in terms of reducing the pathogen burden. This will help develop innovative interventions which limit exposure. These factors require investigation at both the household and community levels. Whilst household behaviours may affect individual infection risk, animal faecal contamination is significant at the community level. This concerns contamination in food markets and of soil and community water sources which affects the overall disease burden. Lastly, food safety has a clear programmatic link between WASH and infant health and must be considered in interventions to reduce pathogen exposure. Programs must consider the sanitation chain from latrines through to serving food, as well as contamination at water sources from animal as well as human faecal waste. This is often overlooked (or not comprehensively considered) in WASH intervention design and constitutes a transformative approach to block pathogen transmission more effectively.

Future research must be bold and clear on how it is comprehensively ‘cleaning up’ domestic and community environments to improve infant health. Without a transformative approach that considers the many transmission routes plus broader background conditions (as captured in Table 21), interventions may continue to show inconsistent and insignificant effects. Continuing to assess health impacts might be premature if an intervention is not truly ‘transformative’. Taking responsibility for improvements in health necessitates a focus on much higher and extensive levels of hygiene as population health will unlikely improve without it.

## 8.2 References


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