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Eggs: A High Potential Food for Improving Maternal and Child Nutrition

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Maternal & Child Nutrition

Aims and Scope

Maternal & Child Nutrition is a forum for the dissemination of the latest research and innovation in all aspects of practice and policy that impinge on nutrition and its outcomes in women and their children, both in early and later life. Drawing from global sources, the Journal provides an invaluable source of up-to-date information for health professionals, academics and service users with interests in maternal, infant and child nutrition.

The scope of *Maternal & Child Nutrition* includes pre-conception, antenatal and postnatal maternal nutrition, women's nutrition throughout their reproductive years, and fetal, neonatal, infant and child nutrition, up to and including adolescence.

Topics covered include:

- Nutritional needs of mothers and their children in health and illness
- Physiological, socio-cultural, psychological, economic and political aspects of the nutrition of mothers and their children
- Infant and young child feeding, including breastfeeding and complementary feeding
- Research directed at the translation of scientific findings into programmatic and policy initiatives to improve maternal and child nutrition
- Implementation and effectiveness of culturally acceptable, cost-effective and sustainable programmes aimed at improving health
- Evaluation of inter-agency initiatives and programmes
- Health promotion and health education initiatives
- Food safety, and related environmental and regulatory issues
- Studies relating nutrition to health or disease risk in mothers and their children
- Role of nutrition in healthy groups and in high risk and vulnerable groups
- Development of research methods and validation of measures

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Eggs: A High Potential Food for Improving Maternal and Child Nutrition

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SUPPLEMENT ARTICLE

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Preface

Malnutrition remains the single largest killer of children under five worldwide (Black et al., 2013). The estimated cost to the global economy could be as high as $3.5 trillion per year or 11% of global GDP (FAO, 2013). This deficit reflects the loss of productivity from child mortality, impaired cognitive function, and staggering health care expenditures. Investing in global nutrition not only saves lives but also provides a high return on investment: every $1 invested in nutrition programmes generates $16 of returns (IFPRI, 2014). The Children's Investment Fund Foundation (CIFF), the world's largest philanthropy that focuses specifically on improving children's lives, has invested over $300 million in nutrition in developing countries since 2002. CIFF's nutrition portfolio is diverse, ranging from large-scale programmes that deliver nutrition solutions to evidence generation, targeted advocacy, and resource mobilisation for nutrition.

Successful nutrition-sensitive food-based approaches have the potential to provide entire communities with year-round availability of micronutrient-rich foods, as well as sustain livelihoods through agricultural income-generating activities (FAO & CABI, 2013). To this end, CIFF has actively moved towards investments that help partners test different approaches to food production, dietary diversification, and biofortification, including new and innovative sustainable social business models for delivering nutrition solutions.

CIFF has a particular interest in food-based nutrition solutions such as poultry and eggs. At the International Congress of Nutrition (ICN) 2017, CIFF sponsored a symposium entitled: "Cracking the egg potential to reduce childhood stunting and improve rural livelihoods." This supplement provides an overview of the current evidence on eggs, and how we can best utilise this evidence to improve the lives of children around the world.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

SG wrote the first draft of the preface; SA and AH critically revised and provided overall supervision.

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SUPPLEMENT ARTICLE
Introduction

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Eggs: A high potential food for improving maternal and child nutrition

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Recent research has demonstrated that egg consumption can have a dramatic impact on preventing stunting and possibly on the cognitive development of young children (Iannotti, Lutter, Stewart, et al., 2017; Iannotti, Lutter, Waters, et al., 2017). This leaves us with the question: How do we best utilize this new evidence to help improve the lives of children around the world? This supplement tackles this question by providing a set of nine papers that progress from the role of eggs in improving maternal and child nutrition to a scenario-based analysis of possible pathways to reaching one billion low-income households with access to eggs. The first paper provides an overview of the role of eggs in the diet of maternal and child nutrition and updated data on egg consumption (Lutter, Iannotti, & Stewart, 2018), while the second summarizes how social marketing was used in a randomized controlled trial of eggs early in the complementary feeding period to foster brand loyalty and high compliance, as well as empowerment of participants and policy change in Ecuador (Gallegos et al., 2018). The third and fourth papers examine how a controlled intervention to foster poultry production affected child dietary diversity and nutritional status in Ghana (Marquis et al., 2018) and Zambia (Dumas, Lewis, & Travis, 2018), while the fifth paper reviews successes and lessons learned from a project on small-scale poultry production to increase egg production and household egg intake in four diverse African contexts (Nordhagen & Klemn, 2018). A novel approach to use chicken eggshells to improve dietary calcium intake in rural sub-Saharan Africa is reported in the sixth paper (Bartter et al., 2018), while the seventh paper reports on business models for poultry production in East Africa and India (Beesabathuni, Lingala, & Kraemer, 2018). The multiple roles, systems and challenges, and options for sustainable poultry production through a Planetary Health lens are reviewed in the eighth paper (Ayers et al., 2018), and the supplement closes with a paper on how universal access to eggs might be achieved through large-scale poultry production (Morris, Beesabathuni, & Headey, 2019).

The promotion of eggs should be seriously considered in maternal and child health and nutrition programmes. Nutritionists also need to team up with livestock specialists, agricultural economists, ministries of agriculture, academic institutions, non-governmental organizations, and private sector poultry and egg producers to understand and foster economically and environmentally viable pathways to improve small-, medium-, and large-scale egg production. There are complex trade-offs—health, environment, and animal welfare—which need detailed discussion in every country. However, as this supplement demonstrates, eggs in the context of a healthy diet may be an efficient, sustainable, and scalable approach to improve maternal and child nutrition and rural development.

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SUPPLEMENT ARTICLE

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The potential of a simple egg to improve maternal and child nutrition

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Abstract

Evidence is mounting about the benefits of eggs for child nutrition and potential benefits for women during pregnancy and birth outcomes. Maternal consumption of eggs during lactation may also enhance the breast-milk composition of certain nutrients, thus contributing to the nutrition and potentially also to the development of breastfed children. Relative to single nutrient supplements, eggs deliver nutrients and other hormone or immune factors in compounds that may be more readily absorbed and metabolized. In addition to macronutrients, eggs contain a number of micronutrients, such as choline, that are known to have brain health promoting effects. Among children less than 2 years of age, consumption nearly universally increases with age. Large regional differences exist; the prevalence of egg consumption among African children is less than half that of most other world regions and threefold less than in Latin America and the Caribbean. Among women of reproductive age, egg consumption is strongly related to socio-economic status in a dose–response fashion with women in the lowest wealth quintile eating the fewest eggs and those in the highest wealth quintile eating the most. Cultural factors likely play a role in around consumption of eggs during pregnancy, lactation, and early childhood, though most reports are anecdotal in nature and few high-quality data exist. Well-informed social marketing and behaviour change communication strategies have led to large increases in egg consumption among young children. Economic barriers that limit access are likely to be far more important than cultural ones in explaining low consumption.

KEYWORDS

brain development, breast milk, child nutrition, eggs, maternal nutrition

1 | INTRODUCTION

Chickens eggs are ubiquitous globally and well known to be highly nutritious, yet are generally not widely consumed among children and women of reproductive age in low- and middle-income countries (Iannotti, Lutter, Bunn, & Stewart, 2014; Lutter, Iannotti, & Stewart, 2016). Yet evidence is mounting about their benefits to child nutrition and potential benefits for women during pregnancy and birth outcomes. The Lulun Project, a randomized controlled trial conducted among young undernourished children in the Ecuadorian Andes, showed dramatic effects on growth and stunting reduction after consuming eggs for just 6 months (Iannotti, Lutter, Stewart, et al., 2017). It also showed significant effects on biomarkers of choline and docosahexaenoic acid (DHA) status, two nutrients associated with cognitive development, raising the question whether eggs early in the complementary feeding period might also

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contribute to child development (Iannotti, Lutter, Stewart, et al., 2017).

Building on our previous review (Iannotti et al., 2014), here, we highlight the contribution of eggs to maternal and child nutritional requirements, how maternal consumption of eggs may influence breast-milk composition, how specific of key nutrients in eggs likely contribute to brain development, and the role of cultural beliefs and egg taboos around egg consumption. We also provide recent national and regional data on egg consumption among young children in low- and middle-income countries.

Key messages

- Eggs provide an exceptional protein source as well as fatty acids and a large range of vitamins, minerals, and bioactive compounds that could potentially improve birth outcomes, child nutrition, and brain development.
- Relative to single nutrient supplements, eggs deliver nutrients and other hormone or immune factors in compounds that may be more readily absorbed and metabolized.
- Egg consumption is low among women of reproductive age and young children with the lowest intakes in the African region, India, and among children 6 to 8 months of age in all regions.
- Cultural factors play a role in many nutrition practices, including around consumption of eggs during pregnancy and early childhood, though most reports are anecdotal.
- Carefully conducted social marketing and behaviour change communication strategies have led to large increases in egg consumption among young children.

2 | RESULTS

2.1 | Contribution of eggs to the nutrient requirements of young children and pregnant and lactating women

Eggs are holistically designed for reproduction and nutritive support for the chicken embryo from conception to the time it hatches. As such, they provide the sole source of immune protection and nutrients until the chick can survive independently in the environment. The distinctive parts of the egg—the yellow yolk, white, and shell—differ in both composition and biological function. Although the yolk's composition is primarily nutritive, the purpose of the white serves mainly as a defence mechanism against pathogens. The shell is a semipermeable membrane to allow for air and moisture to pass through its pores, and has as a thin outermost coating that helps keep out bacteria and dust.

One egg has, on average, only 75 calories but 7 g of high-quality protein, 5 g of fat, and 1.6 g of saturated fat, along with vitamins, minerals, and carotenoids. The egg is also high in disease-fighting dietary bioactive compounds such as lutein and zeaxanthin, which may reduce the risk of age-related macular degeneration, the leading cause of blindness in older adults (Wallace, 2018). Animal models show lutein and zeaxanthin also help to protect against oxidative stress (Bian et al., 2012).

Eggs are particularly high in choline, an important precursor of phospholipids, which are needed for cell division, growth, and membrane signalling (Caudill, 2010; Zeisel & Niculescu, 2006). Inadequate intake during pregnancy has been associated with neural tube defects (Shaw, Carmichael, Yang, Selvin, & Schaffer, 2004), changes in brain structure and function in the offspring (Zeisel & Niculescu, 2006) and adverse pregnancy outcomes (Vollset et al., 2000). Choline may influence gene expression, including epigenetic effects, during pregnancy because of its role as a methyl donor (Jiang et al., 2012). Choline supplementation during late pregnancy resulted in significant changes in expression of genes regulating placental vascularization and angiogenesis (Jiang et al., 2012). This suggests that choline may affect placental development and remodelling, required for placental perfusion and nutrient transfer, particularly with respect to Docosahexaenoic acid (DHA). Brain development and memory may be enhanced by the choline content of eggs (see later section).

During pregnancy and early childhood, cells of the fetus and child grow in size and number at a rapid rate, requiring a steady and increasing source of nutrients. The high quality of essential macronutrients provided by eggs can contribute to optimizing these processes. Protein quality plays an important role during this period. An ideal food during this period is one with a high digestible indispensable amino acid score (FAO, 2013) with eggs and milk having the highest scores. Although protein deposition in maternal and fetal tissues increases throughout pregnancy, most occurs in the third trimester. A single estimated average requirement for protein covers all pregnancy, which does not take into consideration changing needs as a pregnancy progresses. Protein requirements may be 14% to 18% greater than the current recommendation according to recent research (Elango & Ball, 2016). Eggs are also an important source of essential fatty acids. DHA, in particular, is critical for early brain growth and visual acuity (Hoffman et al., 2004; Riediger, Othman, Suh, et al., 2009). Limited evidence suggests that essential fatty acids during pregnancy might have benefits for birthweight and length and gestational age (Huffman, Harika, Eilander, & Osendarp, 2011). Early in pregnancy, maternal cholesterol plays an important role in placental hormone biosynthesis, implementation, and vascularization; low levels may result preterm birth and other adverse birth outcomes (Edison et al., 2007).

For a number of key nutrients, eggs provide a large proportion of the Recommended Dietary Allowance (RDA) or adequate intake (AI) for young children as well as pregnant and lactating women (Table 1). For a healthy infant between 7 and 12 months of age, one 50-g egg provides 57% of the RDA for protein. It provides 88% and 98% of the AI for vitamin B_{12} and choline, respectively. It provides between 25% and 50% of the AI for pantothenic acid, vitamin B_6, folate, phosphorus, and selenium and slightly over 20% of the requirement for zinc. For a breastfed infant consuming an average

TABLE 1 Nutrient content of one large egg and proportion of adequate intake (AI) or recommended dietary allowance (RDA) level for healthy breastfed infants aged 7–12 months and two large eggs for pregnant and lactating women

Nutrient	Unit of measure	Large egg (50 g)	% AI/RDA for healthy infant 7–12 months provided by 1 large egg	% AI/RDA during pregnancy provided by 2 large eggs	% AI/RDA during lactation provided by 2 large eggs
Energy	kcal	72	—	—	—
Protein	g	6.28	57.3	17.7	17.7
Lipids (total)	g	4.75	—	—	—
Linoleic acid (18:2n−6)	g	0.77	16.7	11.8	11.8
a-Linolenic acid (18:3n−3)	g	0.02	4.0	2.9	3.1
DHA (22:6n−3)	g	0.03	—	—	—
Carbohydrates	g	0.36			
Vitamins					
Vitamin A, RAE	ug	80.0	16.0	20.8	12.3
Thiamin (B_1)	mg	0.02	6.7	2.8	2.8
Riboflavin (B_2)	mg	0.23	57	32.6	28.5
Niacin (B_3)	mg	0.04	1.0	0.4	0.3
Pantothenic acid (B_5)	mg	0.77	42.8	25.7	22.0
Vitamin B_6	mg	0.09	28.3	8.9	8.5
Vitamin B_{12}	ug	0.44	88	33.8	31.4
Folate DFE	ug	24	30	8.0	9.6
Choline	mg	146.9	97.9	65.3	53.4
Vitamin C (ascorbic acid)	mg	0	0	0	0
Vitamin D (D_2 + D_3)	ug	1.0	10.0	13.3	13.3
Vitamin E (a-tocopherol)	mg	0.52	10.4	6.9	5.5
Vitamin K	ug	0.2	0.8	0	0
Minerals					
Calcium	mg	28	10.8	5.6	5.6
Copper	mg	0.04	18.2	8.0	6.2
Iodine	ug	0	0	0	0
Iron	mg	0.88	8.0	6.5	19.6
Magnesium	mg	0.6	8.0	3.4	3.9
Manganese	mg	0.01	2.3	1.4	1.1
Phosphorus	mg	99.0	36	28.3	28.3
Potassium	mg	69.0	9.9	2.9	2.7
Selenium	ug	15.4	77	51.3	44.0
Sodium	mg	71.0	—	—	—
Zinc	mg	0.64	21.3	11.6	10.7

Note. DFE, dietary folate equivalents; DHA, docosahexaenoic acid; RAE, retinol activity equivalents. For infants, calculations used the RDA for protein, iron, and vitamin D and the AI for all other nutrients. For pregnant and lactating women, calculations used the AI for vitamin K, choline, pantothenic acid, manganese, and potassium and the RDA for all other nutrients. AIs/RDAs from the Food and Nutrition Board, Institute of Medicine, National Academies. For thiamin, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12}, pantothenic acid, and choline (1998); for vitamin C, vitamin E, and selenium (2000); for vitamin A, vitamin K, copper, iodine, iron, manganese, and zinc (2001); potassium and sodium (2005); and calcium and vitamin D (2011). (Institute of Medicine, Food and Nutrition Board, & National Academy of Sciences).Institute of Medicine, Food and Nutrition Board, & National Academy of Sciences. Dietary Reference Intakes (DRIs): Estimated Average Requirements. http://www.nationalacademies.org/hmd/~/media/Files/Activity%20Files/Nutrition/DRI-Tables/5Summary%20TableTables%2014.pdf?la=en, accessed March 15, 2018.

amount of breast milk (World Health Organization [WHO], 1998), one 50-g egg provides 29% of energy needs. For pregnant women, two 50-g eggs provide 18% of the RDA for protein. They provide between 20% and 35% of the AI/RDA for vitamin A, riboflavin, pantothenic acid, vitamin B_{12}, and phosphorus. They also provide more than 50% of AI/RDA for choline and selenium. For lactating women, a same amount of eggs provide between 20% and 35% of requirements for riboflavin, pantothenic acid, vitamin B_{12}, iron, and phosphorus. They provide 53% and 44% for choline and selenium, respectively.

2.2 | Eggs and nutrient composition of breast milk

Maternal consumption of eggs during lactation may also enhance the breast-milk composition of choline and other water-soluble vitamins, thus contributing to child nutrition and potentially the optimal development of breastfed children. A mother's intake of water soluble vitamins largely affects the concentration of nutrients in breast milk. To a lesser extent, breast-milk concentration is influenced by intake and stores of fat-soluble vitamins (WHO, 1998). Micronutrients have been classified into two groups, according to the effect of maternal intake and the status of the micronutrient content of breast milk (Allen, 2012). In Group 1 are those affected by maternal status including thiamin, riboflavin, vitamin C, vitamin D, vitamin B_6, vitamin B_{12}, choline, vitamin A, iodine, and selenium. In Group 2 are those not affected by maternal status including folate, calcium, iron, copper, and zinc. During lactation, low maternal intake or stores of micronutrients in Group 1 reduces the amount in breast milk, which may negatively affect a child's growth and possibly development. As noted above, breast milk is particularly rich in choline, the concentration of which doubles after birth (Homes, Snodgrass, & Iles, 2000). Adequate intake of Group 1 micronutrients is necessary to ensure breast-milk adequacy and eggs are high in several of these, including choline, riboflavin, and vitamin B_{12}.

Fatty acids in breast milk are also extremely sensitive to maternal consumption and body composition, with implications for infants' neurological development (Innis, 2014). The transfer of n–6 (omega-6) and n–3 (omega-3) fatty acids from the maternal diet into breast milk occurs with little interconversion of 18:2n–6 to 20:4n–6 or 18:3n–3 to DHA. There is also little evidence of regulation by the mammary gland to maintain individual fatty acids constant with varying maternal fatty acid nutrition. A recent study among Chinese women showed that supplementation of DHA during pregnancy increases the concentration of polyunsaturated fatty acids in breast milk (Deng et al., 2016).

2.3 | Eggs and brain development and function

Finding from the Lulun Project in Ecuador suggests consumption of eggs during early childhood could contribute to healthy brain development and function (Iannotti, Lutter, Waters, et al., 2017). In the Lulun Project, children in the egg intervention group had significantly higher concentrations of biomarkers associated with improved child development and important physiological processes in the brain. Choline concentrations were increased by an effect size of 0.35 and DHA by 0.43. Although child development outcomes were not assessed, qualitative research findings pointed to increases in child activity levels and social interactions with caregivers and others (Waters et al., 2018). However, inasmuch as these findings were reported by mothers and caregivers in the intervention group, the study team acknowledges the potential for performance bias.

The nutrient composition, and likely more importantly the nutrient matrix of the egg, has potential to impact brain growth and development. Relative to single nutrient supplements, eggs may deliver nutrients and other hormone or immune factors in compounds that are more readily absorbed and metabolized. The concept of food synergies may be applied here to understand how egg nutrients and other factors act in concert to contribute to growth and development (Jacobs & Tapsell, 2007). The protein content of eggs, held up as the standard for amino acid composition for decades, may contribute to meeting protein needs of mothers and children but eggs also package minerals such as iron or zinc in bioavailable forms.

Here, we highlight particular nutrients found in eggs and their role in brain development as evidenced in the literature, though again in recognition that matrices of multiple assembled nutrients together likely impact outcomes. DHA, although not as highly concentrated in eggs compared with fish foods, was significantly increased in the Lulun Project. This essential fatty acid contributes to neurogenesis, neurotransmission, myelination, and synaptic plasticity, among other processes (Weiser, Butt, & Mohajeri, 2016). Evidence shows the importance of DHA through the lifespan for cognition and visual acuity (Uauy & Dangour, 2006). Another long-chain fatty acid, arachidonic acid (ARA), is derived from linoleic acid found more highly concentrated in eggs. ARA contributes to signalling and hippocampal plasticity. Its role in potentiation may arise from the production of docosatetraenoic (adrenic) acid from ARA (Hadley, Ryan, Forsyth, Gautier, & Salem, 2016).

In addition to macronutrients, several micronutrients are known to have brain health promoting effects (Goyal, Iannotti, & Raichle, 2018). Choline is an important precursor for the neurotransmitter, acetylcholine, and sphingomyelin, a lipid molecule that surrounds neuronal axons for insulation and signal transduction purposes. Animal models have demonstrated choline's role in hippocampal development and function, whereas in humans, studies indicate its importance for long-term memory and cognition (Zeisel, 2006). A recent trial in the United States showed that maternal choline supplementation in the third trimester improved infant information processing speed (Caudill, Strupp, Muscalu, Nevins, & Canfield, 2017). Vitamins A (as retinol) and B_{12}, both present in eggs and with established functions in brain development, were not increased in the Lulun Project. Selenium was not assessed in Lulun, but in view of its high concentration in eggs providing over 75% of daily requirements for infants 7–12 months and role in brain development and thyroid metabolism, more studies could examine its effects. Iron and zinc, although provided in small quantities in eggs, could contribute to brain development. Iron participates in myelination synthesis, neurotransmitter metabolism, and neurotransmitter metabolism (Beard & Connor, 2003). Zinc activity in the brain is known to be primarily at the synaptic cleft, in glutamatergic processes, but also in critical roles in DNA and RNA synthesis and transcription and enzyme activity, among others (Levenson & Morris, 2011). Deficiencies in both iron and zinc during childhood are known to compromise child development.

Eggs and other animal source foods (ASF) have long been part of the hominid diet, beginning approximately during the juncture in evolution when brain size increased compared with other primates (Eaton & Iannotti, 2017). Sea bird eggs in particular are considered part of the shore-based paradigm that explains rapid brain growth arising from lacustrine and marine foods during the Palaeolithic period (Cunnane & Crawford, 2014). With the advent of agriculture and rapid industrialization in the past two centuries, the proportion of ASF in the diet relative to cereals and processed foods has decreased especially in low- and middle-income countries. The evolutionary history of eggs and brain growth may contribute to the rationale for ensuring eggs in the diets of mothers and children. Although we have focused on maternal and young child nutrition, eggs also have the potential to improve brain development and functioning throughout the lifecycle (Wallace, 2018).

2.4 | Egg consumption among young children and women of reproductive age

Egg consumption in the previous 24 hr among young children is highly variable, though two broad patterns are discernable (Figure 1; Appendix S1). Consumption nearly universally increases with age

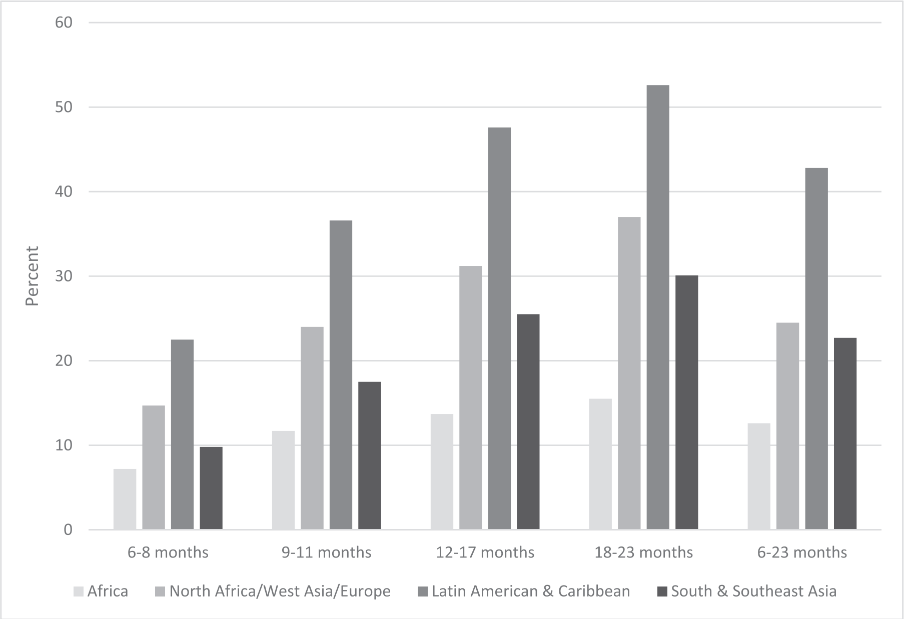

FIGURE 1 Regional prevalence (%) of egg consumption in the previous 24 hr among children less than 2 years of age, based on nationally representative surveys conducted 2006–2017 and weighted for age-specific population size of countries represented. Consumption data calculated from ICF International, the DHS Program, Demographic and Health Surveys (DHS StatComplier, accessed March 12, 2018). Population estimates to construct weighted regional averages from United Nations, World Population Prospects: The 2017 Revision

across all regions. Large regional differences are also apparent; the prevalence of egg consumption among African breastfed children is less than half that of most other world regions and threefold less than the region of Latin America and the Caribbean.

Few data are available on egg consumption among women of reproductive age as questions about food intake in the preceding 24 hr were only asked in a subset of Demographic and Health Surveys conducted between 2007 and 2010 for women who had given birth in the last 3 years and were dropped in subsequent surveys. Among this group, egg consumption was strongly related to socio-economic status in a dose–response fashion with women in the lowest wealth quintile eating the fewest eggs and those in the highest wealth quintile eating the most (United States Agency for International Development, Dec 2014; Figure 2). However, the differences in consumption by wealth quintile were also quite variable; for example, although the difference between the lowest and highest quintile in Ghana ranged from 13.8% to 31.8%, in Tanzania, it only ranged from 3.1% to 9.4%.

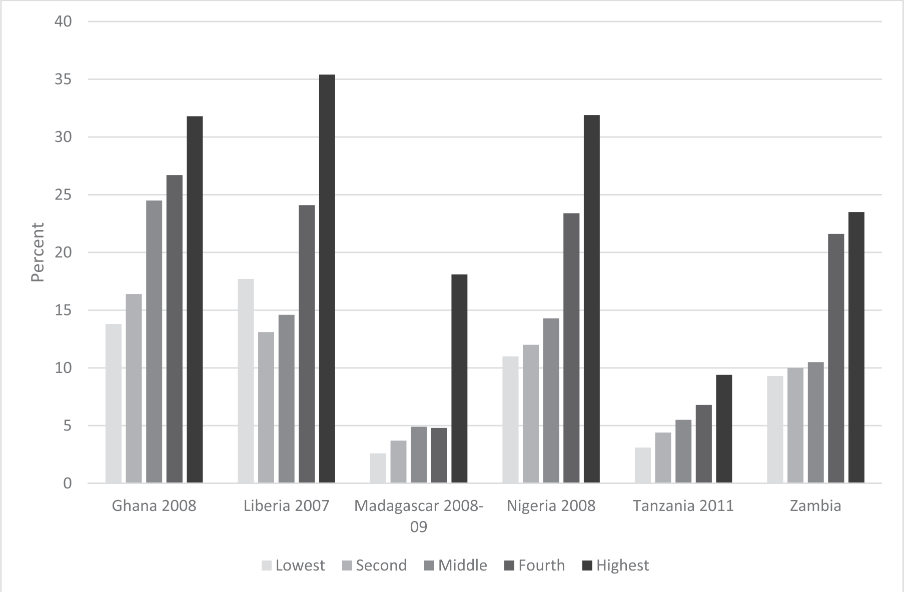

FIGURE 2 Prevalence (%) of egg consumption in previous 24 hr among women age 15–49 years who gave birth in the last 3 years by household wealth quintile, based on nationally representative surveys conducted 2007–2010. United States Agency for International Development (Dec 2014) nutrition status of women and children. A 2014 update on nutritional status by socio-economic and water, sanitation, and hygiene indicators collected in Demographic and Health Surveys. Rockville, Maryland USA. ICF International

2.5 | Cultural and belief barriers around egg consumption

Cultural factors play a role in many nutrition practices, including taboos or beliefs around consumption of eggs during pregnancy, lactation, and early childhood, though most reports are anecdotal in nature and few quantitative or qualitative studies on the subject exist. In Bangladesh, the 2007 Demographic and Health Survey showed that 75% of children 2 to 3 years had consumed eggs, fish, or poultry the preceding day whereas only 10% of infants 6 to 7 months had consumed these foods, showing that beliefs about what and when young children should receive ASF, including eggs, are extremely important (Jimerson, 2017). Among pregnant women in Nepal, religion has been cited reason for not eating eggs (Christian et al., 2006).

In rural Zambia, Dumas et al., (this supplement) report that over 90% of women agreed eggs were good for infants and young children, 82% agreed they were good for pregnant women, and 90% agreed they were good for lactating women. Taboos restricting egg consumption by certain individuals, most commonly pregnant women, were only voiced by only 8% of women.

It is likely that cultural barriers and egg taboos may be overcome with well-informed and carefully conducted social marketing and behaviour change communication strategies (Pelto, Armar-Klemesu, Siekmann, & Schofield, 2013) and evidence to support this is available for young children. In a recent large-scale intervention in Bangladesh that heavily promoted egg consumption for young children 6 to 24 months, consumption among children in the intensive intervention group increased from 18% to 48% compared with only 19% to 31% among those in a nonintensive group (Menon et al., 2016). Qualitative research conducted during the Lulun Project in Ecuador revealed cultural beliefs that eggs can cause gastrointestinal problems in young children and increase cholesterol (Waters et al., 2018). However, with provision of eggs and a social marketing campaign, egg consumption among young children over the course of 6 months increased 128% in the intervention group (from 40% to 91%) compared with only 33% in the control group (45% to 60%; Iannotti, Lutter, Stewart, et al., 2017). In rural Sichuan, China, an intervention that promoted giving young children a hard-boiled egg yolk resulted in a higher percentage of mothers in the intervention group reporting that egg yolk should be the first food for infants and 24-hr dietary recalls showed a significant increase in consumption by the young child (Guldan et al., 2000). However, the study also showed a wide gap between knowledge and behaviours; although 65% of mothers in the intervention group reported that egg yolk should be the first food given, only 37% actually gave it to their infants aged 4 to 6 months. No studies were found that promoted consumption of eggs among pregnant and lactating women.

Concerns about egg allergies in high-income countries resulted in complementary feeding guidelines that recommended delaying their introduction until after the first year likely also discourage giving eggs to young children elsewhere in the world. Since 2003, several authoritative guidelines have recommended the introduction of eggs at 6 months (Greer et al., 2008; PAHO/WHO, 2003) and a recent systematic review reported early introduction of eggs to be associated with reduced egg allergy (Ierodiakonou, 2016). Notwithstanding, this information has yet to be reflected in complementary feeding guidelines in some low- and middle-income countries. This was also the case in Ecuador, though as a result of the Lulun Project, the Ministry of Public Health updated its feeding guidelines to recommend earlier introduction of eggs (Ministerio de Salud Publica de Ecuador, 2016).

Economic barriers that limit access are likely to be far more important than cultural ones in explaining low consumption of eggs among women and young children. Cost was the primary limitation to routine egg consumption in rural Zambia (Hong, Martey, Dumas, & Travis, 2016). Prior to an intervention that increased flock size and eggs production, households in rural Zambia sold eggs or chickens rather than for consumption (Dumas et al., 2016). A recent analysis showed that eggs are a very expensive source of calories in low-income countries with caloric prices of these foods very strongly associated with consumption patterns among young children (Headey & Hirvonen, 2017). Economic aspects poultry and eggs are the subject of the paper by Morris et al., in this supplement.

3 | DISCUSSION

The consumption of eggs during pregnancy, breastfeeding, and early childhood has the potential to improve birth outcomes, breast-milk composition, and child nutrition and brain development. At the same time, consumption by women of reproductive age and young children is low, especially for infants 6 to 8 months of age and in the African region. Although both cultural and economic reasons likely explain this, inasmuch as consumption increases with child age, it is likely that consumption among older infants could increase to at least that of young children as these households clearly have some access to eggs. This is especially important given that the Lulun Project found that daily consumption of eggs for 6 months starting at 6–9 months led to an increase in linear growth by a length-for-age z-score of 0.63 and a reduction of 47% in stunting as well as increases in biomarkers associated with cognitive development.

Given the relationship between socio-economic status and egg consumption, consumption is also likely to increase as household incomes rise. In India, consumption among breastfed children 6 to 23 months of age increased nearly threefold between DHS surveys conducted between 2005–2006 and 2015–2016, from 4.7% to 13.3% (an increase of 183%). In Cambodia, the percentage point increase between 2005 and 2014 was twofold, from 17.4% to 35.9%. In contrast, in Nepal, the percentage point increase was extremely modest, from only 9.5% in 1996 to 13.2% in 2016. Clearly, in addition to overall efforts to improve household incomes, efforts to increase egg availability and access are also needed.

Vegetarian populations may particularly benefit when religious beliefs do not preclude egg consumption. In India, one third of the 1.25 billion inhabitants are vegetarian. In the 2006–2006 DHS, egg consumption among Indian women of reproductive age who had given birth in the previous 3 years was only 3%, the lowest of any country for which nationally representative data exist. According to mother's report, 15% of newborns to have been smaller than average and 6% very small for a total of 21%.

Inasmuch as the consequences of poor nutrition not only have life-long consequences for a child but also for the economic development of a country (Kim, 2015), the potential contribution of eggs to brain development is particularly noteworthy. Eggs provide the most concentrated source of choline, which is essential for a myriad of processes critical for brain development. The unique egg matrix that includes macronutrients, micronutrients, and hormone and immune factors may act in concert to not only promote growth but also child development.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

CKL was responsible for conceptualizing the paper and writing most of the first draft. LLI wrote the section on brain development and commented on the paper. CSP reviewed and extensively commented on the paper.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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SUPPLEMENT ARTICLE

WILEY | Maternal & Child Nutrition

The Lulun Project's social marketing strategy in a trial to introduce eggs during complementary feeding in Ecuador

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Abstract

The Lulun Project incorporated a social marketing strategy that accompanied a randomized controlled trial (RCT) of a food-based intervention that introduced eggs into the complementary feeding diet of Ecuadorian infants. This strategy was designed to promote behaviour change, in this case, egg consumption, through voluntary prosocial behaviour, empowerment, and brand loyalty. A three-phase social marketing strategy (design, campaigns, and evaluation) contributed to our successful RTC by applying techniques drawn from marketing, publicity, design, and communications. To develop the strategy, we conducted (a) market research focused on culturally based norms, values, and local expectations; (b) a situational assessment based on the four Ps of social marketing (people, product, place, and price); and (c) fostered a creative process to develop the project's brand and communication plan. The strategy combined a communication plan, brand, and activities that were implemented in four campaigns: outreach, recruitment, promotion, and closing. Our evaluation showed that the social marketing strategy was instrumental in promoting the RCT's objectives and responding to unforeseen events and community concerns regarding the RCT. The strategy resulted in high compliance, low attrition, and infant feeding policy change, including Ecuador's Ministry of Public Health new complementary feeding guidelines for introducing eggs early in complementary feeding. Use of social marketing techniques, like those in our study, could be key for scaling up this food-based intervention—or others like it—in Ecuador and beyond.

KEYWORDS

behaviour change, Ecuador, egg intervention, infant and child nutrition, randomized controlled trial (RCT), social marketing

1 | INTRODUCTION

Stunting affects the poorest and most vulnerable populations throughout the world. The recent Sustainable Development Goals call for reducing stunting and wasting in children <5 years by 40%, which would affect 90 million children worldwide (UNICEF, WHO, & World Bank Group, 2015). Stunting is a serious public health problem in Ecuador, affecting 25.2% of children <5 years, with only modest reductions in the past three decades (Freire et al., 2014). Applied research can play an important role in providing evidence for cost-effective food-based alternatives to fortified complementary foods, lipid-based nutrient spreads, and micronutrient powders, which have had mixed results related to problems of adherence, cost, scalability, and sustainability (Bhutta et al., 2013).

The Lulun Project was a randomized controlled trial (RCT) conducted in 2015 in five rural parishes in the highland province of Cotopaxi, Ecuador, where the prevalence of stunting among children from 0 to 23 months is 30% (Freire et al., 2014). Its purpose was to test the efficacy of introducing eggs on a daily basis in children 6 to 9 months of age on linear growth and other outcomes (Iannotti et al., 2017). The project represented a culturally appropriate food-based intervention that reduced stunting by nearly 50% (Iannotti et al., 2017; Waters et al., 2018). The social marketing strategy described here contributed to the project's success.

Approximately 22% of the inhabitants of Cotopaxi province are indigenous by self-identification (INEC, 2010). Lulun in Kichwa (or Quechua) means "egg," thus harkening to a locally accessible food that is a culturally appropriate part of the diet (Ferraro, 2008; Hastorf, 2003; Waters et al., 2018; Weismantel, 1998). Eggs represent an appropriate food-based nutritional intervention because they provide nutrients that are important for healthy growth and development (Iannotti, Lutter, Bunn, & Stewart, 2014). In the past, the consumption of eggs by infants was limited because Ecuador's Ministry of Public Health (MPH) recommended that whole eggs should only be introduced at 12 months of age (Waters et al., 2018).

The social marketing strategy applied a transdisciplinary approach designed to promote the Lulun Project's main objective: egg consumption in infants from 6 to 9 months. The strategy addressed six key points:

- Gaining trust among mothers/caregivers in order to be able to take baseline and end line measurements (especially providing blood samples, still a taboo in some indigenous communities).
- Addressing negative rumours that may spread in the communities (e.g., that the blood was being collected to be sold and that eggs are bad for young children).
- Developing project identity and a brand in order to instil loyalty in both the intervention and control groups.
- Addressing perceptions of inequity among mothers/caregivers of children in the control group.
- Promoting local empowerment in the communities in order to motivate effective and sustainable behaviour change
- Ensuring that the social marketing strategy would contribute to effects beyond the RCT (Gallegos, Waters, Salvador, Chapnick, & Iannotti, 2014).

Key messages

- Social marketing can be a methodological innovation in nutrition research, programme implementation, and policy change.
- A three-phase social marketing strategy (design, campaigns, and evaluation) used techniques drawn from marketing, publicity, design, and communications.
- The strategy was informed by culturally based norms, values and local expectations, and the four Ps of social marketing: people, product, place, and price.
- The transdisciplinary approach engendered participants' empowerment and promoted brand loyalty resulting in voluntary prosocial behaviour.
- The strategy addressed community concerns about blood collection and inequity and led to high compliance, low attrition, and minimum spillover effects.

2 | SOCIAL MARKETING: PROMOTING BEHAVIOUR CHANGE

Social marketing strategies are designed to promote specific behaviour changes to gain and retain loyal and satisfied customers. Unlike commercial marketing that focuses on selling goods or services for profit, social marketing promotes voluntary behaviour that benefits society (Dovidio, Piliavin, Schroeder, & Penner, 2006; Kotler & Lee, 2008) by addressing specific problems (Kotler, 2011). The relevance of social marketing to public health and nutrition is well-recognized (Gordon, McDermott, Stead, & Angus, 2006; Grier & Bryant, 2005; Hastings & Haywood, 1991; Stead & Gordon, 2009), particularly with respect to project and policy design, implementation, and evaluation (Andreasen, 1997; Farquar et al., 1985; Fox & Kotler, 1980; Mitchell, Madill, & Chreim, 2015; Williams & Girish, 2015). Social marketing strategies are the basis for campaigns that are designed to advance project objectives (Grier & Bryant, 2005; Snyder, 2007). Complex projects often involve several strategies; each of which may incorporate one or more campaigns. Kotler and Zaltman (1971) proposed a model based on the four Ps of marketing to be included in social marketing strategies: product, place, price, and promotion. Two other Ps have subsequently been added: people and policy change (Andreasen, 2002; Gordon et al., 2006).

The *product* involves behaviour change or maintenance of psychosocial factors such as motivation and self-esteem. *Place* refers not only to physical space but also to communication channels. Examples include elements that connect people and products such as project staff, and promotional items such as calendars, caps, or shirts with project logos. In addition to the cost of project inputs and activities, *price* incorporates intangible resources and efforts as well as opportunity costs (e.g., the cost of attending project workshops vs. performing household tasks). *Promotion* includes advertising using different channels to promote empowerment and brand loyalty. Finally, *policy* change occurs when the intervention produces modifications in regulations, guidelines, or laws (Gallegos et al., 2014).

The six Ps of the Lulun Project's social marketing strategy are shown in Table 1. The RTC began after a situational assessment to analyse people, product, place, and price. Successively, a communication plan, campaigns, and branding were developed to promote the project. Advocacy for policy change was incorporated into project activities and the evaluation plan.

3 | METHODS

The strategy's design consisted of (a) market research (Andreasen, 2002), which included formative research in project communities, and (b) a creative process, which consisted of the concept and medium by which the messages were conveyed (Kinder, 2014). The creative process led to the creation of the project's brand, a mascot, promotional items, participatory activities, and a communication plan.

TABLE 1 Six Ps of the Lulun Project social marketing strategy

People	Eligible caregiver–infant pairs (n = 163). Community leaders, stakeholders, field staff, and researchers.
Product	*Behaviour 1:* Intervention children (n = 83) who consume one egg a day for 6 months. *Behaviour 2*: Caregivers of intervention children who feed them daily with an egg. *Behaviour 3*: Control children (n = 80) who maintain their regular diet for 6 months. *Behaviour 4*: Caregivers of control children who keep them on their regular diet.
Place	Andean region, Ecuador, central highlands; Mainly disperse rural communities in mountain terrain; Scarce and deficient means of transport; Main channels of information: elected councils, community meetings, and the public health system; and The Lulun Project staff; The presence in the field of the Lulun Project's brand.
Price	Monetary cost for the project's activities, instruments and other inputs. Physical and intellectual efforts of the project staff. Cost assumed by the participants (particularly opportunity costs).
Promotion	Communication plan: design of the message and the selection of communication channels. Implementation of four campaigns which tackled each RCT's stages (e.g., outreach and recruitment) Branding: project identify (name, mascot, symbols, and design) combined with promotional items and activities
Policy change	The Lulun Project brand was reflected explicitly at the different levels of change: • Local health facility relaxed their rules regarding egg consumption of project participants. • The intervention escalated from a local project to a nationwide policy. • The national policy led to new nutritional guidelines for egg consumption after the exclusive breastfeeding period.

Evaluation of the social marketing campaign incorporated information from the RCT and a qualitative assessment (Iannotti et al., 2017; Waters et al., 2018).

3.1 | Market research

Market research began with the identification of the target audience, followed by the conceptualization of different levels of influence (individual, intervention and control groups, and community). Subsequently, formative research and a situational assessment based on people, product, place, and price were conducted (Table 1). This phase concluded with field validation of the creative process.

3.1.1 | Target audience

Project participation was defined in terms of caregiver–infant pairs. After recruitment, participants were randomly divided into intervention and control groups. The intervention group received seven eggs each week for 6 months during household visits, whereas members of the control group were visited but did not receive eggs. Members of both groups participated in social marketing activities, received promotional items, and were monitored for health problems and supported in cases of health emergencies. In this sense, families in both groups developed a sense of a united community, in which people take care of each other and also have fun together. Mothers and infants in both groups received wool caps, bracelets, cooking aprons, and notebooks, which were designed to promote brand loyalty and empowerment. In addition to caregivers (85% of whom were mothers), the project promoted the involvement of other stakeholders, particularly local elected officials, religious and informal community leaders, grassroots organizations such as cooperatives and neighbourhood associations, local non-governmental organizations, and local MPH personnel (Iannotti et al., 2017).

3.1.2 | Levels of influence

The project's communication plan and activities were directed at each level and included radio spots, advertising posters, and workshops (Gallegos et al., 2014). Implementation began at the individual level because it is there that the psychosocial experience starts (Bandura, 1985; Bronfenbrenner, 1977). At the group level, the emphasis was on creating a sense of belonging, solidarity, and behaviour change for the common good. In turn, sociocultural factors, including indigenous identity, were promoted at the community level, where people are bound together by ethnicity, geography, culture, and history (Waters & Gallegos, 2014), with shared notions about aesthetics, values, and worldviews (Durkheim, 1982), and sociocentric as the central norm (Kirmayer, Brass, & Tait, 2000).

3.1.3 | Formative research

Field-based formative research analysed local expectations, beliefs, and attitudes using questionnaires and open-ended interviews in order to better define social marketing activities and communication channels.

3.1.4 | Situational assessment

The situational assessment defined the chain of events and interrelationships among them, producing a map of people, product, place, and price that informed the social marketing strategy. This assessment helped ensure timely delivery of eggs to infants in the intervention group for incorporation in their daily diet, while at the same time, optimizing inclusion of control group members.

3.2 | Creative process

The creative process included the development of the project's brand and mascot as part of the communication plan; both symbolized the project in a way that was recognized and appreciated by the target audience. This process was shaped by empirical evidence on cognition

FIGURE 1 Lulun Project's logos: Elegant style (left side) and minimalist black and white style (right side)

and language (Bandura, 1985; Brown, 2013; Gombrich, 1999; Jung, 1981; Rolf, 2013) and was guided by an understanding of the desired outcome and the characteristics of the target population (indigeneity, rurality, sociocentrism, and labour-intensive, gendered agriculture).

3.2.1 | Brand

A brand impacts cognition by establishing connections with knowledge and beliefs (Peter & Olson, 2005) and by evoking emotions and influencing individual self-monitoring and motivation (Crocker et al., 2013; Hoffman, 1984). The brand is a fundamental component of a communication strategy because it becomes the name and visible face of the project. A well-designed brand produces positive attitudes in the target audience (Peter & Olson, 2005). The brand should be consistent with the purpose of the project, inspire trust in the community, reflect shared norms and values, and raise public interest. Using the Kichwa word for egg (lulun), the project created a connection between the community's indigenous heritage and contemporary norms and values by using an effective representation of the project's central feature. Eggs are an accessible part of the local diet and traditional medicine. The word "Project" stressed the potential improvement children's nutrition through the RTC. The brand not only portrayed the project in a culturally appropriate form but also converted participants and their communities into protagonists rather than passive beneficiaries. The combination of Kichwa and English words reflected local knowledge and the contribution of western science. Even for non-Kichwa speakers, the sound "lulun" is phonetically pleasing and, along with the English word "Project," has a friendly sound.

Creation of a brand based on an effective representation or logo makes use of familiar images and acceptable colours. The Lulun brand was created using versions of the logo in different colours: a simple, elegant version was used in formal communications such as letters and business cards, whereas a more colourful version was used to promote project activities. Figure 1 portrays two versions.

The Lulun logo combines two distinctive features. An egg (the central focus of the project) is wrapped in a cloth, reflecting the way women carry infants on their backs using their ponchos, which keeps the infants snug and facilitates breastfeeding. The cloth's design incorporates a *chakana*, an Andean cross that represents interconnections and a spiral that represents an indigenous concept of time that integrates the past, present, and future. This logo underscores indigenous worldviews, the relationship between the community and the project, and the importance of past, present, and future in human nutrition.

3.2.2 | Mascot: From brand to hero

In order to represent itself as a change agent and promote active participation and empowerment, a mascot was created to portray both project staff and community members. Figure 2 presents Luluma, an adaptation of the *Aya Huma* (devil's head) as a provider of eggs. Aya Huma is an Andean symbol of leader, counsellor, and protector who dances and celebrates with the community. Luluma was both a printed image and a costumed member of the project staff. In Figure 2, Luluma carries a basket of eggs.

FIGURE 2 Luluma in white background

3.2.3 | Communication plan

The communication plan was the project's cornerstone. Social marketing campaigns traditionally emphasize message content (Snyder, 2007). An effective communication plan should include the design of messages and the selection of communication channels (Kotler & Armstrong, 2008). The Lulun Project communication plan incorporated three message attributes: content, configuration, and tone (Kotler & Armstrong, 2008). *Content* included relevant information that was conveyed in the project area. The *configuration* of a message refers to length, word order, and selection of ideas; it involves a sender, a receiver, a communication channel, and a reaction (Kotler & Armstrong, 2008). In our project, messages were designed to reach the target audience using colloquial terms to convey interest in well-being and effectively communicate the project's content and objectives. Information about the Lulun Project was communicated through traditional information channels such as word of mouth and community celebrations. *Tone* incorporates the sound of messages and the emotions that may be evoked. The tone of the Lulun Project was designed to be consistent with project content, configuration, and concept to expresses a sense of a united community. Based on content, configuration, and tone, the narrative revolved around well-being, health, a united community, and consumption of eggs as an accessible means of improving infants' nutrition (Kotler & Armstrong, 2008).

4 | IMPLEMENTATION: CAMPAIGNS

Based on the social marketing strategy, project implementation consisted of four campaigns, as shown in Table 2 (LeppäNiemi & Karjaluoto, 2008). The first P (people) included staff; some of whom were local residents, including a nutritionist with experience with children in vulnerable populations. Others had previously worked in the project area, which allowed the project to build on existing community relationships and trust (Hoffman, 2000).

TABLE 2 Strategy of the Lulun Project

Input	Output	Outcome
Strategy design	Market research + Creative process	Lulun Project social marketing manual: Mapping of people, product, place, and price; Concept, brand, and mascot; Definition of social marketing activities; Communication plan. Manual of corporate identity: Branding and design of promotional items
Implementation	1. Publicize the project	Outreach and rapport building
	2. Call for participation	Recruitment and baseline construction
	3. Egg-based intervention	Intervention group compliance; Controls marginal treatment contamination; Low attrition
	4. Project closing	Endline construction; Fair compensation for controls caregivers
Evaluation	1. Intervention integrity	RCT objectives achieved
	2. Behavioural change	Two sets of specific behaviours (see Table 1: Product)
	3. Policy change	Internal policy of the health centre; National policy for public health system; New nationwide nutritional guidelines

Staff members not only delivered eggs and visited members of the intervention and control groups but also monitored potential side effects of egg consumption, including allergic reactions. In addition, they assisted families with unrelated medical emergencies, accessing regular health care services and providing transportation for elderly and disabled residents. They also promoted capacity building by training local authorities in project development and stimulated the local economy through the purchase of eggs and office supplies (e.g., pens, pencils, binders, and photocopies).

Campaigns are based on social marketing strategies that incorporate community-based activities (Snyder, 2007). Each campaign used specific communication channels, project narratives, branding, and activities and were designed to address participants' needs while invoking indigenous traditions and symbols that were attractive and meaningful to multiple stakeholders in the project area. The campaigns promoted key project activities, including meetings with the parish council, community leaders, and local health authorities; and workshops and special events including project inauguration, community meetings, and celebrations.

It was important that community members felt the project's presence through the prominent use of its brand and mascot in various forms. For example, the project vehicle bore the logo, so that the staff's presence could be readily recognized (see Figure S4). Additional examples included (a) business cards and name badges used by project staff; (b) rollups with the logo and the representation of Luluma used in all activities; (c) mobile recordings, posters, and other promotional material announcing project activities; (d) videos and photographs shown in public events; (e) a Web page; (f) branded aprons used during cooking workshops; and (g) project notebooks used during workshops and information sessions.

The first campaign promoted the project during its initial stages and included the diffusion of publicity using mobile audio messages, posters, and calendars. The second campaign supported participant recruitment and included entertainment for children at data collection sites and photographs of each child. The third campaign motivated caregiver empowerment by dividing participation into discrete, easily executable achievements that reinforced a sense of accomplishment (Andreasen, 2002; Reeve, 2001). Mothers/caregivers in the intervention group were motivated to feed their infants a whole egg every day; consumption was monitored using cards that featured the project's logo (see Figure S3). The monitoring cards also tracked participation in the control group so that each household visit represented a small achievement and allowed for a gift at the end of the project. This campaign also included workshops on topics of interest to mothers, which while not focusing on egg consumption, reinforced motivation and sense of belonging. In addition, social media was incorporated into the project, and promotional items, such as the wool caps, were distributed among participants in both groups. During the intervention's concluding months, a fourth campaign was implemented to support final data collection. This campaign focused on door-to-door nutritional counselling and follow-up for families in the intervention and control groups.

Each component of the strategy was designed to instil a sense of loyalty to the project's brand, empower participants and promote project adherence (Chaudhuri & Holbrook, 2001). Additionally, a symbolic relationship was established by converting a brand into an institution that surpassed the boundaries of the RTC.

5 | RESULTS: EVALUATION

The evaluation of the social marketing strategy was based on fieldwork monitoring reports, RCT data, individual interviews, focus group discussions, and documentation provided by the MPH. Four interrelated results were found. First, the Lulun Project became a brand that was well recognized in the study communities, particularly by participating mothers/caregivers. Second, participants were empowered, expressed as the belief in their capacity to become a change agent. Third, the strategy influenced behavioural change (see "product" in Table 1) that was shaped by prosocial values such as prioritizing the good of the community, improving infant nutrition, and a belief that children are the future. Fourth, the Lulun Project influenced child nutrition policy at local and national levels.

Brand loyalty was reflected in high treatment compliance in the intervention group and low spillover effects in the control group (Iannotti et al., 2017). This result was monitored through weekly household visits and in qualitative research that analysed attitudes and practices (Waters et al., 2018):

> *The project is good, because thanks to the project we went to the cooking workshops. It is good that they delivered eggs, we [child in the control group] did not receive the eggs but my nephew [in the intervention group] was given eggs daily (Focus group discussion with caregivers of control children).*

> *The egg is attractive, it is a delicious and comparing bread and eggs, I prefer eggs. (Interview with female community leader)*

Specifically, mothers in the treatment group indicated that eggs are a healthy alternative to sweets and carbohydrates and are a better alternative than past feeding practices (Waters et al., 2018). As one participant stated:

> *I always carry an egg in my bag and when the baby is hungry I give it as a snack instead of giving him a candy (Focus group discussion with caregivers of intervention children).*

The positioning of the brand represented a competitive advantage in the project's market. An unanticipated byproduct of brand loyalty was the reduction in the intake of sugary foods in the intervention group (Iannotti et al., 2017), which revealed an important change in food preferences and understanding of the nutritional value of eggs, especially those that are fertilized and considered more nutritious than industrially produced eggs:

> *Well, I really did not know about the eggs, like most people around here, [now we know] that feeding with eggs is good (Focus group discussion with caregivers of intervention children).*

> *[When] my mother's chickens lay eggs, they are the chicken and the rooster's egg, (those are) the ones that we eat most. (Focus group discussion with caregivers of intervention children)*

Empowerment was reflected in an attrition rate of only 7%, regular attendance in social marketing activities, participation in social media, and testimonies expressed during household visits. Furthermore, the project overcame negative perceptions about eggs, as expressed by one focus group participant.

> *[An egg] does not have cholesterol. It has been shown that the egg has nothing bad. (Focus group discussion with caregivers of intervention and control groups)*

Accordingly, project activities were structured in such a way that they stimulated both behaviour maintenance among control group members and behavioural change in the intervention group, thereby converting an isolated activity (feeding one whole egg to an infant), to a habit (a whole egg every day) and ultimately, to a routine practice in each household (a full egg a day should be given to infants beginning at 6 months to improve their nutrition). A focus group participant explained her feeding strategy:

> *He eats the whole egg. First thing in the morning he eats [the egg], and then the rest I put in the juice and he drinks the blend (Focus group discussion with caregivers of intervention children).*

Behaviour change in the intervention group resulted in a significant increase in growth compared with the control group (Iannotti et al., 2017), and positive perceptions about the effects of the intervention, as illustrated by one participant:

> *The egg is truly effective, and it is good for our children. Thank you for promoting campaigns to help people to know more about the egg (Focus group discussion with caregivers of intervention and control groups).*

The Lulun Project also influenced the local health facility to change its recommendations regarding the introduction of eggs from 12 to 6 months:

> *I went to the health center; I have him checked every month. The doctor told me that the egg is good for him, that I should give it to him every day and not to miss that (Focus group discussion with caregivers of intervention and control groups).*

> *The research of the colleague here: they are trying to incorporate the egg for the priority group [infants from the area], specifically to start giving the whole egg from early ages (Interview with local public health physicians).*

A final result was that the MPH changed the national complementary feeding guidelines to promote the introduction of whole eggs earlier in the complementary feeding period (MPH, 2013). Table 2 shows the strategy inputs, outputs, and intervention outcomes.

6 | DISCUSSION

The Lulun Project developed, implemented, and tested a social marketing strategy that accompanied a RCT to evaluate an egg intervention among infants in the rural Ecuadorian highlands. The strategy was aligned with the RCT's objectives and planned according to a communication plan, branding, and social marketing activities. It responded to a vision of empowering participants to become agents of change and project owners, fostered by brand loyalty. Brand loyalty was evoked as a symbolic construct based on images and words that acquired personal and consensual meanings and hence motivated individual and collective behaviour (Blumer, 1969; Durkheim, 1982).

The simultaneous focus on empowerment and brand loyalty constituted a departure from classical views of behaviour change. A fundamental premise of symbolic interactionism theory is that the meaning that people acquire about the world around them influences their behaviour (Blumer, 1969). In this context, the RCT was not about introducing a new behaviour per se but rather changing the way eggs were defined and their contribution to infant nutrition. Hence, the project brand symbolized a redefinition of eggs during the complementary feeding period. Empowerment was key to overcoming psychological barriers to participation, such as potential suspicion that researchers might collect data for their own purposes and then leave nothing for the participants.

The social marketing strategy facilitated project promotion, motivated community members, and enhanced participation of caregiver–infant pairs, which was fundamental for reaching the required sample size and for overcoming cultural obstacles to blood collection and anthropometric measurements, and beliefs that eggs are not good for infants. The strategy was also critical to the equitable inclusion of control group members, who did not receive eggs.

The project competed with the food industry and non-governmental organizations, which also sought attention, participation, and community acceptance for their products/services. It also competed with health providers, who used established MPH guidelines for introducing eggs into complementary feeding regimens at a later age.

Finally, community-based interventions often face unforeseen events that can affect implementation or data collection, and a strong social marketing component can be instrumental in addressing these challenges. In our study, Cotopaxi, the world's highest active volcano located less than 3 miles from the project area erupted for the first time in 150 years during the final phase of data collection. This event resulted in a temporary relocation of many families. Another unforeseen event was initial opposition by health providers, who were unwilling to accept an innovative nutritional practice because they had always recommended the introduction of whole eggs at 12 months.

The results presented here are consistent with evidence provided in the human psychology literature, upon which the Lulun Project's social marketing strategy was based (Ajzen, 1991; Hoffman, 1984; Myers, 2005; Reeve, 2001). Considering the convergence of the social marketing, public health, and nutrition literature (Gordon et al., 2006; Grier & Bryant, 2005) in the context of RCTs (Biglan, Ary, Smolkowski, Duncan, & Black, 2000; Morrison, 2001), the Lulun Project's experience was consistent with other examples of successful behaviour change interventions designed to combat chronic malnutrition (Fabrizio, van Liere, & Pelto, 2014) based on the incorporation of a social marketing strategy.

Our results suggest that there are very promising opportunities for RCTs in public health and nutrition and for food-based interventions that incorporate social marketing as a central part of the intervention.

7 | CONCLUSIONS

The Lulun Project fulfilled participants' expectations and mobilized behaviour change, thereby ensuring a successful RCT. Positive behaviour change was converted into a habit that has the potential to spread throughout the project area and beyond. The project's brand was key to achieve behaviour change because it became associated with familiar symbols and expressed through colloquial language. Furthermore, the Lulun Project became an institutionalized element that later was converted into public policy. Brand loyalty and empowerment, which are overlapping psychosocial factors, were crucial to the intervention.

The conceptual elements presented here have theoretical and methodological value for expanding the subdiscipline of social marketing. At the same time, the RCT constitutes an example of applied social marketing that may be useful for researchers, practitioners, and policy makers interested in nutrition interventions. Finally, the integration of the social marketing into the project intervention can be scaled up in Ecuador and elsewhere.

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CONFLICTS OF INTEREST

No conflicts of interest to declare.

CONTRIBUTIONS

CAG and JMS designed the social marketing strategy, with important contributions from WFW and LLI and feedback from AMC, CKL, and CPS. CAG, WFW, JMS, and AMC implemented the strategy; CAG was responsible for conceptualizing and writing the manuscript with substantial input from WFW, JMS, and LLI. WFW, AMC, CKL, CPS, and LLI reviewed and suggested modifications in the final version.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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SUPPLEMENT ARTICLE

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Small-scale egg production centres increase children's egg consumption in rural Zambia

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Abstract
Animal source foods can efficiently enhance dietary quality, but they remain inaccessible and unaffordable for many women and young children in remote, low-income communities. We piloted an intervention in which 20 groups established egg production centres (EPCs) in their rural Zambian communities to increase the availability of eggs in the local food system. In a repeated cross-sectional design over 1 year (midline [4 months after the start of egg production] and endline [11 months]), we evaluated programme impact on household egg acquisition within those communities and on egg consumption and height-for-age *z* score (HAZ) among young children (6–36 months) using multilevel linear, logistic, and truncated negative binomial regression techniques. At midline, households in project areas were significantly more likely to consume eggs than those in control areas (OR 2.08, 95% CI [1.56, 2.78]), particularly those located within 250 m of the EPC. Similarly, children living in project communities were significantly more likely to consume eggs at midline than those in control areas (OR 5.53, 95% CI [2.90, 10.58]). Although increased over baseline, egg acquisition and consumption decreased by endline because of depressed egg production over time. There was no impact on children's HAZ, likely because of the short follow-up time and relatively modest "dose" of egg consumption. Although productivity can be improved, the EPC programme offers a novel approach to improving access to eggs in rural communities, and optimization of the production practices and marketing is needed to ensure that egg consumption translates to improved dietary quality, growth, and health.

KEYWORDS
animal source foods, child nutrition, eggs, food systems, nutrition-sensitive agriculture, stunting

1 | INTRODUCTION

Animal source foods (ASF) are an efficient mechanism for meeting children's dietary requirements, because relatively small amounts can make large contributions to their nutrient intake (Allen, 2003, 2012; Dror & Allen, 2011; Murphy & Allen, 2003; Neumann, Harris, & Rogers, 2002). There is strong evidence that the incorporation of ASF into the diets of young children can improve dietary quality, micronutrient intake, and nutrition outcomes (Allen, 1993; Allen, Backstrand, & Stanek, 1992; Darapheak, Takano, Kizuki, Nakamura, & Seino, 2013; Grillenberger et al., 2006; Herrador et al., 2014; Iannotti, Lutter, Stewart, et al., 2017a; Iannotti, Lutter, Waters, et al., 2017b; Krasevec, An, Kumapley, Bégin, & Frongillo, 2017; Krebs et al., 2011; Lien et al., 2009; Long et al., 2011; Neumann et al., 2013). However, the poorest families in low and lower middle income countries often rely on low-quality, plant-based diets consisting primarily of starchy staples (Allen, 1993, 2012; Arimond & Ruel, 2004; Black et al., 2008), and novel approaches are needed to improve ASF availability and consumption in these settings.

Small-scale livestock production is one approach to improving the physical and economic accessibility of ASF in rural, low-income communities, and poultry production is particularly promising for a number of reasons. First, village (or backyard) poultry production is already a familiar livelihood activity for more than 85% of rural families in sub-Saharan Africa (Gueye, 2000a). Second, it is estimated that more than 70% of chicken owners are women (Gueye, 2000a, 2000b; Wong et al., 2017), and women's empowerment and control over agricultural resources are important mediators of child nutrition outcomes (Ruel et al., 2013). Third, backyard poultry production has a low cost of entry and maintenance (Alders & Pym, 2009; Gueye, 2000a). Finally, eggs are an appropriate first complementary food (Iannotti, Lutter, Bunn, & Stewart, 2014), and feeding young children just one egg per day can have dramatic effects on their growth (Iannotti, Lutter, Stewart, et al., 2017a) and micronutrient status (Iannotti, Lutter, Waters, et al., 2017b).

Despite the great potential of village poultry, research evaluating the impact of poultry-based interventions has historically shown only modest impacts on child nutrition outcomes (Appendix S1). In rural Zambia, a package of interventions that effectively increased flock sizes had no effect on chicken or egg consumption. Instead, smallholders demonstrated a strong preference for leaving eggs from village chickens to hatch, increasing flock sizes, and allowing them to more readily sell birds as needed (Dumas et al., 2016). This phenomenon has been reported elsewhere (de Bruyn et al., 2017; Dumas et al., 2017; Gueye, 2000a; Olney, Vicheka, Kro, & Chakriya, 2013) and is a major limitation to the use of village poultry as a tool for increasing egg availability and consumption. Additionally, there is an emerging concern that free-ranging poultry can negatively affect child nutrition outcomes by exposing them to zoonotic pathogens that cause clinical disease (e.g., diarrhoea; Zambrano, Levy, Menezes, & Freeman, 2014) or environmental enteric dysfunction (Gelli et al., 2017; George, Oldja, Biswas, Perin, Lee, Ahmed, et al., 2015; George, Oldja, Biswas, Perin, Lee, Kosek, et al., 2015; Headey & Hirvonen, 2016; Marquis et al., 1990; Ngure et al., 2013).

As an alternative to village poultry, we designed and implemented a novel poultry intervention utilizing semi-intensive egg production practices to increase the availability of eggs in communities in rural Zambia. This pilot aimed to evaluate the impact of an egg production centre (EPC) programme over its first year on (a) household egg acquisition, (b) egg consumption among young children (6–36 months of age), and (c) child height-for-age *z* score (HAZ). We hypothesized that, compared with control areas, households and children in communities with an EPC would be more likely to acquire and consume eggs after implementation of the programme but that there would be little to no effect on HAZ in the short follow-up time.

Key messages

- Household acquisition of eggs increased significantly as a result of the programme, particularly among households located closest to the EPCs and when egg production was high.
- Children were significantly more likely to eat eggs as a result of the programme but only when egg production within the EPCs was high.
- There was no impact on child HAZ in the first year of the programme.
- Semi-intensive egg production practices may be a viable approach to increasing egg availability in some rural food systems, but programme delivery and system productivity should be refined and optimized to maximize benefits from replication or scaling up.

2 | METHODS

2.1 | Study setting

This research was conducted in rural farming communities of the Luangwa Valley (Appendix S2), located in Zambia's Eastern Province. Four traditionally defined areas, or chiefdoms, were purposively selected, and 24 rural communities within those chiefdoms were purposively selected to receive the pilot egg production intervention. Participating communities were selected by the implementing organization, Community Markets for Conservation (COMACO, a local non-governmental organization; www.itswild.org), based on their location within the COMACO intervention area, subjective evaluation of community need, and resource availability. Due to time and resource constraints, 20 of these 24 communities ("project areas") were randomly selected to participate in this impact evaluation. Twenty additional communities were identified by our implementing partner as suitable matched controls based on their Chiefdom and a subjective assessment of their size, density, and proximity to major roads, schools, markets, and protected areas, criteria deemed likely to affect local markets and food availability. Control areas were a median of 5.2 km from their matched project areas (range 1.6–17.5 km) and approximately 1 hr walking (range 26–210 min) to minimize risk of spillover.

2.2 | Programme description

A complete description of the programme, including training materials and protocols, is available elsewhere (Dumas, 2017). Briefly, four to five smallholder farmers from each of the 24 project areas were recruited as "egg producers" and were trained in hen health, biosecurity, food safety, and business management. Individuals were eligible for selection if they were members of a COMACO Poultry Producer group (focused on improving village chicken production), had a history of successfully adopting recommended agricultural practices, and were vulnerable to food insecurity and poverty based on the assessment of COMACO evaluators, itself incorporating input suggested from consultation with chiefdom or village leaders.

The design of the EPC was adapted from a previous, smaller pilot project in the area (Dumas et al., 2016). Each of the EPCs was stocked with 40 layer hens—considered to be a manageable number of hens for first-time egg producers, that would fit within a reasonably small facility, and yet would produce a reasonable number of eggs for the local markets—and egg production began in September 2015. During egg production, COMACO extension staff monitored production records and intervened where necessary to address production concerns; however, each of the egg producer groups worked together as the owners and operators of their EPC and were ultimately responsible for their own businesses, including marketing eggs, purchasing feed, and maintaining records. Egg prices were determined by each egg producer group based on the local market, but the most common egg price was 1 ZMW (~US$ 0.096).

2.3 | Data collection

In a repeated cross-sectional study design, data were collected at four time points selected to represent the dry and rainy seasons in the years prior to and during the intervention: June 2014 (Baseline 1; dry season; n = 906 households), December 2014 (Baseline 2; rainy season; n = 886), December 2015 (midline; rainy season; n = 885), and June 2016 (endline; dry season; n = 869). Distinct dry and rainy season evaluations were important because of pervasive food and income scarcity during the "hungry season," which coincides with the rainy season, and which was expected to significantly modify food acquisition and consumption. Each field site was marked with a GPS point; for project areas, this global positioning system (GPS) location was at the site of the EPC. A sampling frame of eligible households in each field site was generated through in-home visits. Inclusion criteria were (a) there was a child 6–36 months residing in the household, and (b) the dwelling was located ≤1.5 km from the field site GPS location. The 20 eligible households nearest to each field site GPS location were recruited and enrolled in the study, and all eligible children 6–36 months of age in enrolled households were included. The sampling and enrolment procedures were repeated at each of the four time points.

At each enrolled household, the research staff administered questionnaires over approximately 45 min, assessing household characteristics (household composition, asset ownership, food security, etc.) and the child's diet, animal source food consumption, recent morbidities, and breastfeeding history (WHO, 2010). Anthropometric measurements were then taken on both the child and his or her mother (weight, height or length, and mid-upper arm circumference) following standard procedures (Cogill, 2003). Height and weight measures were taken using standardized seca 872 electronic scales with mother or child function and seca 213 portable stadiometers (seca GMbH & Co., Hamburg, Germany). For both height and weight, two measures were taken; a third measure was taken if there was a difference of at least 0.5 kg or 1.0 cm between the first two measures (Cogill, 2003). The mean of the two most similar measures was defined as the child's height and weight. Data were collected by pairs of trained research staff, and responses were recorded either on paper forms (June 2014) or in GPS-enabled tablets using ODK Collect (v.1.4.10, Open Data Kit, https://opendatakit.org; all other time points).

2.4 | Outcome measures

We assessed the impact of the EPC programme on three outcomes of interest following our programme impact pathway. *Household egg acquisition* (Outcome 1) was operationalized as a dichotomous variable indicating whether or not anyone in the household consumed any eggs in the 7 days prior to the survey, as recalled by the mother of the eligible child. Because meals, especially for women and children, are typically consumed from a communal dish, determining the exact number of eggs consumed by an individual is difficult. Therefore, *children's egg consumption* (Outcome 2) was operationalized in a two-step process: first, as a dichotomous variable indicating that he or she did or did not consume any eggs in the 7 days prior to the survey and second, as the number of times that he or she consumed eggs over the past 7 days. This does not attempt to quantify the number of eggs consumed by an individual. A 7-day recall period, rather than 24 hr, was determined a priori to be most appropriate for both household and child egg consumption given the low average egg consumption in Zambia as a whole (3.3 kg per capita/year = 59 eggs per capita/year = 1.13 eggs per capita/week; FAO, 2013), a country that is significantly wealthier on average than the study area. *Children's nutritional status* (Outcome 3) was measured by HAZ, where the reference population was based on the WHO Child Growth Standards (WHO Multicentre Growth Reference Study Group, 2006).

2.5 | Covariates and descriptive variables

Household economic welfare was assessed with an asset index generated using principal components analysis, which collapses a large number of observed variables into a single measure (Filmer & Pritchett, 2001; Sahn & Stifel, 2003). The first component was retained as both a continuous variable and a categorical variable (low, medium, and high) to create a measure of relative household wealth (Appendix S3). Household food security was assessed by the Household Food Insecurity Access Scale (Coates, Swindale, & Bilinsky, 2007), a nine-item questionnaire that captures the frequency of experiences of inadequate household food access over the past month, scored from 0 (food secure) to 27 (severely food insecure).

Child morbidities were operationalized as dichotomous variables and included having any fever, diarrhoea (>3 stools in a day or abnormally soft or watery stool), vomiting, or rapid or difficult breathing with coughing in the past 14 days, as recalled by the child's primary caregiver (CSO et al., 2015), or malaria diagnosed by a health professional in the past 14 days. Caregivers were also asked questions about the child's breastfeeding and complementary feeding history, with questions and indicators following WHO recommendations (WHO, 2010).

At baseline, the child's mother or primary caregiver was asked multiple-choice questions (with response categories informed by qualitative formative research) about the household's primary source of eggs, travel time to that source, and barriers to more frequent egg consumption. To understand prevailing attitudes and beliefs about the social acceptability of eggs for particular individuals, they were asked to indicate their level of agreement with a series of statements using a 5-point Likert-type scale with a visual aid. They were also asked if "there are any people who are not supposed to eat eggs because of traditional or cultural reasons," and if so, who.

2.6 | Statistical analyses

Data were cleaned and analysed in Stata (Stata/IC version 14.0, StataCorp, College Station, Texas). Bivariate analyses were performed to identify differences between the treatment and control groups at baseline (considered significant if $p < 0.05$).

2.6.1 | Household egg acquisition

To investigate programme impact on household acquisition of eggs, the probability that a household consumed any eggs over the past 7 days was modelled using four-level random-intercept logistic regression with random-effects for chiefdom, matched field site pairs, and field site (i.e., community; Appendix S4). Level 1 covariates controlled for differences in household characteristics (Appendix S5). The interaction of time point and group (project vs. control community) was the "treatment effect" and preintervention and postintervention data were compared across the same season.

2.6.2 | Children's egg consumption

Because the frequency of children's egg consumption was highly zero inflated and right skewed, two-stage models were used (Afifi, Kotlerman, Ettner, & Cowan, 2007; Hu, Pavlicova, & Nunes, 2011). In the first stage, we used multilevel random-intercept logistic regression to model the probability that a child consumed any eggs in the past 7 days. To account for the survey design, random effects were included for chiefdom, matched field site pairs, field site, and household (Appendix S4). In the second stage, we conducted zero-truncated negative binomial regression to model the number of times a child ate eggs in the past 7 days within the subsample of those individuals who consumed any eggs. Stata does not support multilevel truncated negative binomial regression, so standard errors were clustered at the field site level, which had the largest variance component in the model fit in the first stage. In addition to geographic random effects, models at both stages included covariates at the level of the household, woman, and child (Appendix S5).

2.6.3 | Children's HAZ

To examine the impact of the intervention on children's HAZ, we fit multilevel mixed effect models using the maximum likelihood estimation method. To account for the survey design, nested random effects were included for chiefdom, field site pairs, communities, and households, and fixed effects were included to control for differences in household and individual characteristics (Appendix S5).

2.6.4 | Sample size calculation

The sample size for the survey at each time point was estimated to examine the impact on HAZ in children 6–36 months of age. The desired effect size was set at 0.33 standard deviations, which is smaller than the magnitude of the effect of a recent dairy intervention (0.54 standard deviations; Rawlins, Pimkina, Barrett, Pedersen, & Wydick, 2014) and approximately half the effect of a recent egg feeding trial on child HAZ (0.63 standard deviations; Iannotti, Lutter, Stewart, et al., 2017a). The sample size calculation considered a power of 80% and alpha of 0.05, with an estimated HAZ variance of 1.69. To adjust for geographic clustering, a design effect (DE) was included, where DE = 1 + ICC (n−1) (Rutterford, Copas, & Eldridge, 2015), and ICC = the intraclass correlation for HAZ in rural areas of low-income countries, estimated to be 0.035 (Fenn, Morris, & Frost, 2007). The sample size per cluster, n, was set at 20 children aged 6–36 months, deemed a reasonable number of children likely to live within 1.5 km of the EPC. This resulted in a required sample size of 405 children at each time point in each group (project and control), or 810 total children per time point and 3,240 children across all four time points.

2.7 | Ethical standards

All procedures, protocols, and research materials underwent an internal review process at the implementing organization, COMACO, and were approved by the Institutional Review Board at Cornell University (Protocol ID#: 1402004456). The study is registered at ClinicalTrials.gov (ID#: NCT02516852). Approval was obtained from area chiefs prior to initiating research activities, and all participants provided individual written informed consent at the time of enrolment. For illiterate participants, the interviewer read the consent forms in full, took a thumbprint from the participant, and acquired a witness signature confirming that informed consent was appropriately obtained.

3 | RESULTS

3.1 | Baseline characteristics

With few exceptions, the characteristics of children, mothers, and households in project and control areas did not differ significantly at Baseline 1 (Table 1). The preintervention characteristics of households and women did not vary meaningfully by season. However, in the rainy season, children were overall less likely to eat a minimally diverse diet (37.8% vs. 51.4%, $p < 0.001$), experienced fewer morbidities (75.4% vs. 90.3%, $p < 0.001$), and had lower weight-for-height z scores (0.10 vs. 0.29, $p < 0.001$).

Egg acquisition by households and consumption by children did not vary by group at baseline (Table 1). Eggs were mostly commonly sourced from the family's own flock of village chickens (48.0%) or purchased from road-side stalls (31.0%). Despite high prevalence of village chicken ownership, per capita household egg consumption was very low, and women cited cost and physical availability as the primary barriers to routine consumption of eggs in their household (Hong, Martey, Dumas, Young, & Travis, 2016). The majority of women liked eating eggs (94.0%), and they valued eggs primarily for their nutritional value (57.4%) and taste (20.1%). Most women agreed or strongly agreed that eggs are good for infants (91.8%) and young children (93.8%); slightly fewer agreed or strongly agreed that eggs are good for pregnant (82.3%) or lactating women (89.9%). Only 7.8% of women responded that they believed in taboos restricting egg consumption by certain individuals, most commonly pregnant women (n = 41).

3.2 | Outcome 1: Did households access more eggs as a result of the programme?

In project communities, the odds that a household acquired any eggs in the 7 days prior to the survey increased dramatically after

TABLE 1 Characteristics of participating households, women, and children in project and control communities in the Luangwa Valley at Baseline 1

	Baseline 1 (dry season)	
	Control	Project
Household characteristics	*n* = 390	*n* = 409
Household size, mean (±*SD*)	5.7 (2.0)	5.8 (2.1)
Female headed (%)	13.1	13.9
Head of household completed primary school (%)	56.0	61.3
Socio-economic status (tertiles of asset index)		
Lowest (%)	36.2	34.4
Middle (%)	33.9	33.9
Highest (%)	29.9	31.7
COMACO membership (%)	**21.9**	**40.1**
Any livestock ownership (%)	68.0	62.4
Chicken (%)	**64.4**	**55.5**
HFIAS, mean (±*SD*)	10.4 (6.9)	9.9 (6.6)
Food secure (HFIAS = 0), %	8.0	9.6
Mildly FI (1 ≤ HFIAS ≤9), %	37.3	39.2
Moderately FI (10 ≤ HFIAS ≤18), %	41.7	39.5
Severely FI (19 ≤ HFIAS ≤27), %	13.1	11.8
Number of eggs eaten, per capita in the past 7 days, mean (±*SD*)	0.6 (1.1)	0.6 (1.1)
Travel time to access eggs, mean minutes (±*SD*)	12.1 (17.5)	14.4 (23.2)
Women's characteristics	*n* = 396	*n* = 413
Age (year), mean (±*SD*)	27.9 (8.6)	28.1 (7.9)
Completed primary school (%)	**32.1**	**39.5**
Dietary diversity,[a] mean (±*SD*)	4.1 (1.2)	4.2 (1.3)
Underweight (%)	8.7	5.8
Overweight (%)	12.0	11.7
Children's characteristics	*n* = 426	*n* = 434
Age (months), mean (±*SD*)	20.1 (8.7)	20.3 (8.9)
Gender, % female	52.8	51.8
Dietary diversity,[b] mean (±*SD*)	3.6 (1.3)	3.7 (1.3)
Minimum dietary diversity met (6–23 months), %	47.3	55.6
Any eggs in past 7 days (%)	40.1	37.3
Number of times eating eggs, past 7 days, mean (±*SD*)	0.8 (1.3)	0.8 (1.3)
Currently breastfeeding (%)	50.5	47.7
At least one morbidity in past 2 weeks (%)	91.6	89.1
Fever (%)	**77.4**	**71.1**
Diarrhoea (%)	**56.6**	**49.0**
Malaria diagnosis (%)	54.2	47.7
HAZ, mean (±*SD*)	−1.76 (1.18)	−1.72 (1.18)
WHZ, mean (±*SD*)	**0.21 (1.18)**	**0.37 (1.02)**
WAZ, mean (±*SD*)	−0.77 (1.17)	−0.67 (1.05)
Stunted (<2 *SD* below mean) %	41.8%	39.1%

Note. Bolded values indicate that the test statistic for the chi-squared or *t* test is significant at $p < 0.05$. COMACO: Community Markets for Conservation; HAZ: height-for-age *z* score; HFIAS: Household Food Insecurity Access Scale; SD: standard deviation; WAZ: weight-for-age *z* score; WHZ: weight-for-height *z* score.

[a]Ranging from 0–9 food groups, based on the Women's Dietary Diversity Score (WDDS; Arimond et al., 2010; Kennedy, Ballard, & Dop, 2011).

[b]Ranging from 0–7 food groups, dietary diversity was defined here as the number of food groups consumed in the 24 hr prior to the survey, where the food groups were (a) grains, roots, and tubers; (b) legumes and nuts; (c) dairy products; (d) flesh foods; (e) eggs; (f) vitamin A-rich fruits and vegetables; and (g) other fruits and vegetables (WHO, 2010).

production began in the EPCs (Figure 1a and Table 2). By endline, 10 months after egg production began, the odds of household egg acquisition had decreased (likely due to depressed egg production at the time of the endline survey; Figure 2), but remained significantly higher compared to Baseline 1. In contrast, in control communities, the only significant change in the probability of egg acquisition

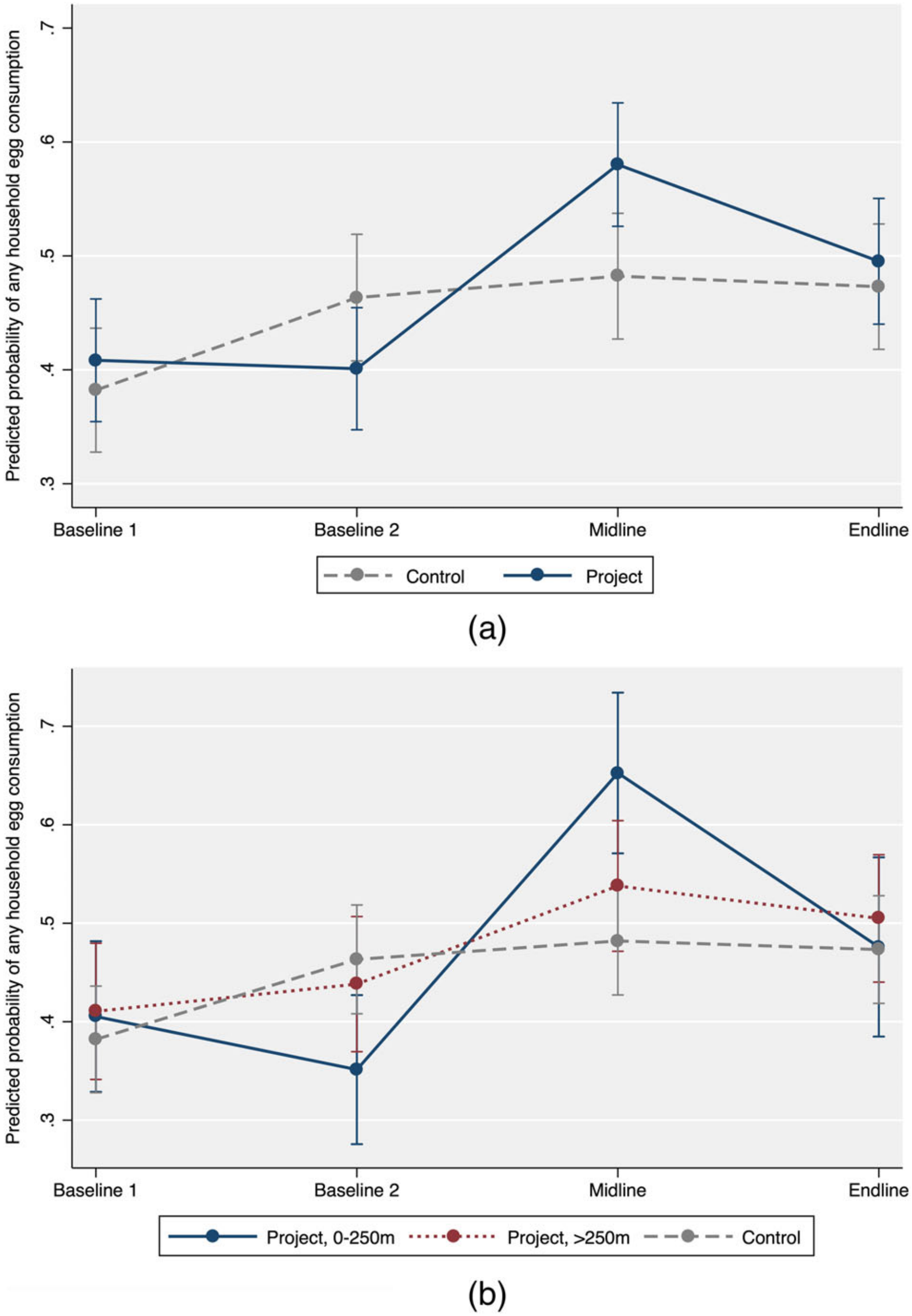

FIGURE 1 (a) Predicted probability and 95% confidence intervals of household egg acquisition in the 7 days prior to the survey in project (solid navy) and control (dashed grey) communities. (b) Predicted probability and 95% confidence intervals of household egg acquisition in the 7 days prior to the survey in households in project communities within 250 m of an egg production centre (EPC) (solid navy), in households in project communities greater than 250 m from an EPC (dotted maroon), and control (dashed grey) communities with no EPC

occurred between the two baseline time points and can therefore not be attributed to the programme.

Within project communities, there were significant differences in the impact of the intervention on household egg consumption based on their proximity to the EPC (Figure 1b). At midline, households located within 250 m of the EPC were significantly more likely to consume eggs than households in control communities (OR 2.03, 95% CI [1.03, 2.16]), whereas households located greater than 250 m from the EPC were not. By endline, however, there was no difference between either group and the control.

3.3 | Outcome 2: Did the programme increase children's egg consumption?

In project communities, but not control communities, the odds that a child consumed any eggs increased significantly from Baseline 2 to midline after the start of the EPC programme (Figure 3a and Table 2). There was no significant difference in the odds of children's egg consumption at endline relative to Baseline 1 in either group. In contrast to analyses at the household level, the odds of children's egg consumption within project areas did not significantly differ by

TABLE 2 Odds ratios and contrasts comparing the four outcomes of interest at each time point in project versus control areas ("project versus control") and within group over time ("project areas" and "control areas")

	Household egg acquisition		Children's egg consumption				Children's HAZ	
	OR	95% CI	OR	95% CI	β[b]	95% CI	β[c]	95% CI
Project versus control								
Baseline 1[a]	1.12	0.82, 1.53	0.66	0.35, 1.24	−0.04	−0.30, 0.22	0.01	−0.19, 0.21
Baseline 2[a]	0.77	0.57, 1.05	0.63	0.35, 1.18	−0.20	−0.50, 0.10	0.02	−0.18, 0.22
Midline	**1.49**	**1.10, 2.03**	**2.29**	**1.22, 4.29**	0.02	−0.27, 0.31	−0.06	−0.26, 0.14
Endline	1.09	0.81, 1.48	1.57	0.84, 2.90	−0.20	−0.49, 0.08	−0.12	−0.32, 0.08
Project areas								
Rainy season (midline vs. Baseline 2)	**2.08**	**1.56, 2.78**	**5.53**	**2.90, 10.58**	**0.59**	**0.31, 0.87**	−0.16	−0.33, 0.01
Dry season (endline vs. Baseline 1)	**1.41**	**1.06, 1.88**	1.42	0.79, 2.54	0.27	−0.09, 0.62	0.07	−0.11, 0.25
Control areas								
Rainy season (midline vs. Baseline 2)	1.07	0.80, 1.43	1.52	0.85, 2.72	**0.37**	**0.02, 0.71**	−0.08	−0.26, 0.10
Dry season (endline vs. Baseline 1)	**1.45**	**1.08, 1.94**	0.60	0.33, 1.09	**0.43**	**0.21, 0.66**	**0.20**[d]	**0.02, 0.38**

Note. HAZ: height-for-age *z* score; OR: odds ratio; CI: confidence interval.

[a]Two baseline evaluations were conducted to control for the effect of season of food acquisition and consumption in this region. "Baseline 1" is the preintervention survey conducted in the dry season (2–4 months after harvest). "Baseline 2" is the preintervention survey conducted in the rainy season (8–10 months after harvest), also commonly referred to as the "hungry season" because of food and resource scarcity.

[b]β is the estimated difference in the mean frequency of egg consumption in the past 7 days, among those children consuming any eggs, between the two groups being compared in the row.

[c]β is the estimated difference in mean children's HAZ between the two groups being compared in the row.

[d]Although significant, these changes are unlikely to be as a result of the egg production centre (EPC) programme.

[e]Bolded values indicate that the OR or beta is statistically significant at $p<0.05$.

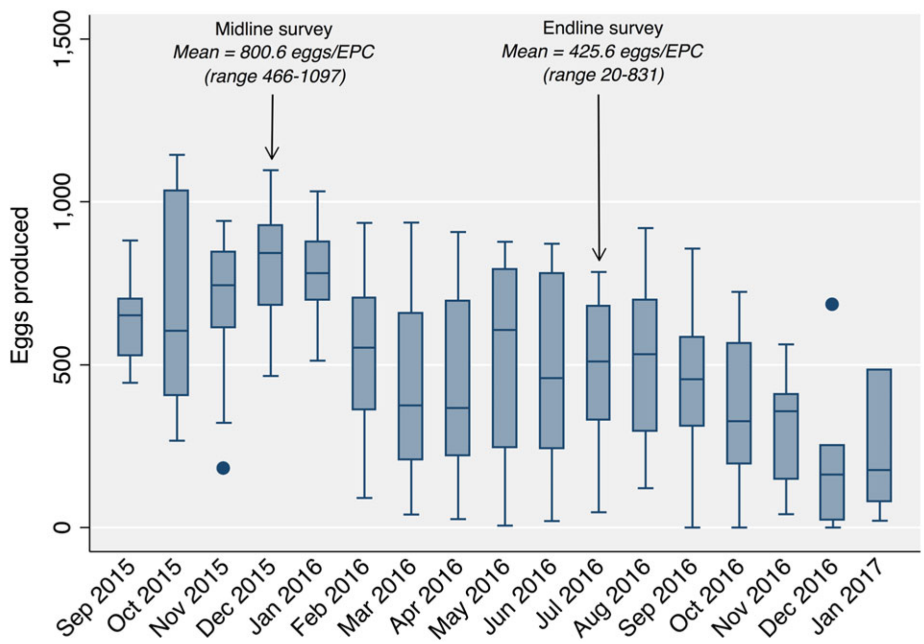

FIGURE 2 Total number of eggs produced per month in 16 egg production centres (EPCs). Production data excludes the four EPCs in Mwanya, for which insufficient records were available. Anecdotally, three of these four EPCs had very low production throughout the year. Arrows indicate the months that midline and endline surveys were conducted

proximity of the household to the EPC. Among children consuming any eggs, the *frequency* of egg consumption in the past 7 days increased from Baseline 2 to midline in both project and control communities (Figure 3b and Table 2), before returning to approximately baseline levels at endline, as egg production declined.

3.4 | Outcome 3: Did the programme affect children's HAZ?

Mean children's HAZ did not differ between those living in project and control communities at any of the four time points (Table 2), and there

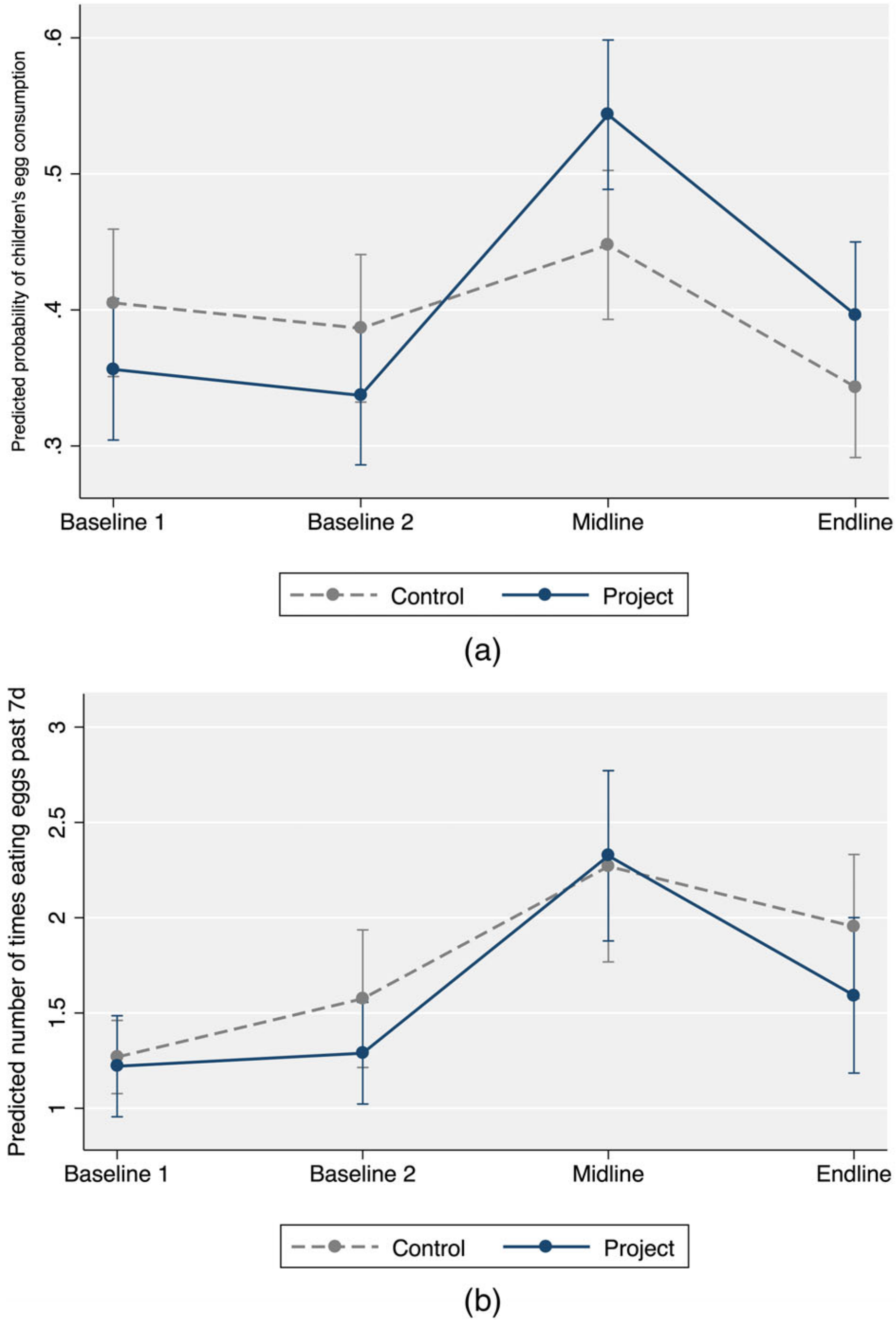

FIGURE 3 (a) Predicted probability and 95% confidence intervals of any child egg consumption in the 7 days prior to the survey in project (solid navy) and control (dashed grey) communities. (b) Among those consuming any eggs, predicted number of times children consumed eggs in the 7 days prior to the survey, in project and control communities

was no significant change in HAZ over time that could be attributed to the project.

4 | DISCUSSION

In summary, the EPC pilot programme in rural Zambia successfully increased household acquisition of eggs and their consumption by young children in participating communities. However, programme impact was significantly attenuated by endline due to declining egg production in EPCs. The greatest impact on household egg acquisition was among households located within 250 m of an EPC, but distance did not modify the impact of the programme on children's egg consumption. Interestingly, although the programme successfully increased the *odds* of egg consumption among children living in project versus control communities, there was no difference in their *frequency* of egg consumption. There was no evidence for programme impact on child HAZ.

Existing research on the use of small-scale egg production to improve diets in rural, low-income communities has focused entirely on village chickens (Iannotti et al., 2014). Unfortunately, village chickens are unlikely to effectively and sustainably deliver eggs to children in rural, low-income households because of a combination of factors. First, village chickens experience high flock mortality because of disease, poor management, or predation (Gueye, 2000a). Second, among those that survive to maturity, indigenous chickens have limited genetic potential for egg production, with hens laying 20 to 80 eggs per year compared with over 300 eggs per year for layer hens (Gueye, 2000a; Wong et al., 2017).

Third—perhaps most importantly—as a means of offsetting high flock mortality, smallholders have repeatedly demonstrated a preference for allowing eggs from village chickens to hatch rather than consuming them at home (de Bruyn et al., 2017; Dumas et al., 2016; Dumas et al., 2017; Gueye, 2000a; Olney et al., 2013). The multipurpose utility of poultry (as a source of food, income, and resilience in the face of shocks) requires a daily cost–benefit analysis on the part of the smallholder, who must weight the many demands of their household in the face of limited resources (Pell & Kristjanson, 2017). Thus, although appropriate interventions in the village chicken system can increase productivity and profitability, there is limited evidence to date that they have successfully increased child ASF consumption, dietary quality, and/or growth and development (Appendix S1). At the other end of the production spectrum, commercial egg production is largely found in peri-urban areas to serve the larger (and wealthier) urban markets, with limited penetration of fresh, quality eggs to poorer, rural areas. The limitations of these two most common poultry systems therefore demand a novel approach for delivering eggs to the children most likely to benefit.

In response to this, the EPC model uniquely aims to improve the local food environment in rural, low-income communities. Additionally, previous research in similar settings has focused exclusively on the impact of poultry programmes on consumption of ASF *by the programme beneficiaries*. To our knowledge, the current study is the first to examine the effect of a poultry intervention on the diets and nutrition outcomes of the potential customers—families living in the surrounding community who were not direct beneficiaries of the programme. Because the intervention is market driven and the primary consumers are those living around the EPC, this model may be an economically sustainable approach to changing the local food environment to the benefit of the entire community while providing inputs (training, technology) to relatively few individuals.

Due to resource and time constraints, the follow-up time for the impact evaluation was just 1 year. This short time frame does not match the lengthy pathway from programme implementation to improved nutritional status and growth expected for nutrition sensitive programmes, which likely requires at least 1,000 days of programme exposure to achieve *full* impact (Leroy et al., 2016). Nonetheless, an egg feeding trial in Ecuador recorded significant effects on child length-for-age *z* scores after just 9 months of follow-up (Iannotti, Lutter, Stewart, et al., 2017a), suggesting that a larger "dose" of egg consumption (one egg per day, in the case of the Ecuador trial) is required to affect child growth and that the relatively modest increase in egg consumption as a result of the EPC programme was insufficient.

This may in part be because the evaluation was conducted in the first year of the pilot programme, during which time only 40 hens were placed in each EPC, and egg production was suboptimal, particularly at endline. Decreased egg production over time is expected as hens age, but in many EPCs, production was below expectations throughout the year because of production challenges (Dumas, 2017). These included difficulty in consistently accessing layer feed, suboptimal husbandry and management practices in some EPCs, excessive ambient temperatures, and an inability to increase egg prices in response to rising feed costs (Dumas, 2017). As a result, there were fewer eggs available in project communities than initially expected and demand often exceeded supply. Nonetheless, some EPCs met performance benchmarks (Dumas, 2017), indicating that the programme can be successful in this setting with appropriate management. Prior to replication, the lessons learned from this project, detailed at length elsewhere, need to be integrated into training and monitoring protocols to maximize productivity of the EPCs (Dumas, 2017). Additionally, market research is needed to analyse demand, market size, and buyer behaviours (e.g., distance people will travel to buy eggs at an EPC, frequency of egg consumption) such that EPCs can be built and stocked appropriately to meet market demand. A repeated evaluation after the programme has reached its highest level of quality or production that the system can support is warranted.

Although this study has many strengths in its design, including controlling for season and analysing intermediate outcomes, a cluster randomized controlled trial was not possible due to COMACO's internal programme goals and resource availability. Project areas were purposively selected, and matched control areas were selected based on a subjective assessment of their characteristics, a process that produced adequate but not ideal counterfactuals based on observed characteristics. We attempted to control for these differences in our models; however, there are also likely differences between the groups that were not observed or controlled, resulting in biased estimates.

These limitations notwithstanding, the EPC programme investigated here adds to the empirical evidence for a link between livestock development programmes and child nutrition outcomes. Although not measured in this paper, the model may also address some of the drawbacks and pitfalls of previous livestock interventions: (a) by distributing inputs to groups of farmers rather than households, it may avoid contributing to women's time poverty; (b) it can limit children's exposure to zoonotic pathogens by operating within a confined poultry system and training EPC members in proper hygiene practices; and (c) it was integrated with extension support that provided programme beneficiaries with access to feed, vaccination and veterinary services, and ongoing support to limit catastrophic losses. Improvements to the programme should consider the "lessons learned" in this pilot (Dumas, 2017) to optimize productivity of the EPCs and ensure the local market demand is met. Integration with a nutrition education programme should also be considered, an approach that the literature suggests may maximize the impact of livestock interventions on nutrition outcomes (Leroy & Frongillo, 2007; Randolph et al., 2007). Given the positive short-term impact of the programme on egg consumption among children when egg production was high, we encourage continued evaluation of the programme to investigate the model's long-term potential to improve dietary quality, micronutrient adequacy, women's empowerment, and child growth and development after the model has been optimized.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

S.E.D. was responsible for research design, project administration, research methodology, data collection, database management, data analysis and data visualization, funding acquisition, and initial drafting of the manuscript. D.L. contributed to project administration, study design, and critical reviewing and editing of the manuscript. A.J.T. contributed to research design, project administration, research methodology, funding acquisition, supervision of all research activities, and critical reviewing and editing of the manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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SUPPLEMENT ARTICLE

WILEY | Maternal & Child Nutrition

An agriculture–nutrition intervention improved children's diet and growth in a randomized trial in Ghana

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Abstract

Stunting in Ghana is associated with rural communities, poverty, and low education; integrated agricultural interventions can address the problem. This cluster randomized controlled trial tested the effect of a 12-month intervention (inputs and training for poultry farming and home gardening, and nutrition and health education) on child diet and nutritional status. Sixteen clusters were identified and randomly assigned to intervention or control; communities within clusters were randomly chosen, and all interested, eligible mother–child pairs were enrolled (intervention: 8 clusters, 19 communities, and 287 households; control: 8 clusters, 20 communities, and 213 households). Intention-to-treat analyses were used to estimate the effect of the intervention on endline minimum diet diversity (≥4 food groups), consumption of eggs, and length-for-age (LAZ)/height-for-age (HAZ), weight-for-age (WAZ), and weight-for-length (WLZ)/weight-for-height (WHZ) *z*-scores; standard errors were corrected for clustering. Children were 10.5 ± 5.2 months (range: 0–32) at baseline and 29.8 ± 5.4 months (range: 13–48) at endline. Compared with children in the control group, children in the intervention group met minimum diet diversity (adjusted odds ratio = 1.65, 95% CI [1.02, 2.69]) and a higher LAZ/HAZ (β = 0.22, 95% CI [0.09, 0.34]) and WAZ (β = 0.15, 95% CI [0.00, 0.30]). Sensitivity analyses with random-effects and mixed-effects models and *as-treated* analysis were consistent with the findings. There was no group difference in WLZ/WHZ. Integrated interventions that increase access to high-quality foods and nutrition education improve child nutrition.

KEYWORDS

agriculture, dietary diversity, length-for-age, nutrition education, poultry, weight-for-age

1 | INTRODUCTION

Nutrition indicators among Ghanaian children under 5 years of age have improved over the past decade at the national level; the prevalence of stunting declined by one third to reach 19% in 2014 (Ghana Statistical Service, Ghana Health Service, & ICF International, 2015; Ghana Statistical Service, Ghana Health Service, & ICF Macro, 2009). However, a large disparity in rates across subpopulations persists. The prevalence of stunting was 63% higher in rural compared with urban areas in the latest national survey (Ghana Statistical Service et al., 2015). There was about a threefold variation in rates across regions and wealth quintiles and a sevenfold difference between children of mothers with no education and those with secondary education. Child diet also showed variation. Whereas 28.1% of all 6–23 months met the criteria for minimum diet diversity (≥4 food groups), only 16.9% did in the Eastern Region (Ghana Statistical Service et al., 2015). Targeted efforts are needed to address these problems to diminish the physical, cognitive, and social consequences of poor child nutrition.

An agricultural-based intervention has the potential to diminish nutrition disparities as it typically targets a rural population affected by poverty and low educational opportunities. There are several pathways by which such interventions may work. Meeker and Haddad (2013) suggested that agricultural practices influence nutrition via (a) food availability, (b) income for food purchases, (c) food prices, (d) women's social status and empowerment, (e) women's time, and (f) women's health. Surprisingly, there is limited evidence that agricultural interventions lead to improved child nutritional status. Over the past 14 years, a series of reviews of published research on agriculture interventions (e.g., Berti, Krasevec, & Fitzgerald, 2004; Girard, Self, McAuliffe, & Olude, 2012; Masset, Haddad, Cornelius, & Isaza-Castro, 2011; Pandey, Dev, & Jayachandran, 2016; Ruel, Quisumbing, & Balagamala, 2018) have reported mixed results for nutrition outcomes, often reflecting weak study designs. The wide range of agriculture interventions and diverse indicators of nutritional status add to the challenge of linking agriculture and nutrition (Webb & Kennedy, 2014). The greatest effect has been noted with agricultural interventions that directly addressed specific nutritional deficiencies (e.g., orange-fleshed sweet potatoes improved vitamin A status; Hotz et al., 2012; Low et al., 2007).

The multiple pathways by which agriculture may affect nutrition suggest that an integrated approach is necessary. Educational activities can complement agricultural initiatives by helping participants (a) use agricultural outputs to improve their dietary practices, (b) mitigate health risks associated with agricultural activities, and (c) manage agriculture-related time demands that compete with child caregiving. Two recently published studies demonstrated the value of an integrated approach. Olney, Pedehombga, Ruel, and Dillon (2015) reported on a 2-year cluster randomized trial in Burkina Faso that integrated home garden production and education on child feeding. Anaemia in young infants (difference-in-difference = −14.6 percentage points; $P = 0.03$) and wasting in infants (difference-in-difference = −8.8 percentage points; $P = 0.08$) improved. A 16-month quasiexperimental project in Ghana integrated microcredit, entrepreneurial training for small businesses, and nutrition education, with an emphasis on animal source foods (Marquis et al., 2015). Participation was associated with an increase in preschool children's height-for-age (HAZ; +0.19 z; $P < 0.05$) and weight-for-age (WAZ; +0.28 z; $P = 0.01$).

Recent studies support a focus on animal source foods for agriculture interventions. Semba et al. (2016) found that essential amino acids were lower in the diets of stunted compared with nonstunted Malawian children, suggesting that the lack of high-quality protein in the diet may be limiting linear growth. Iannotti et al. (2017) reported that a randomized controlled trial in Ecuador, which provided children with one egg per day for 6 months, reduced the prevalence of stunting by 47% and underweight by 74%. These results demonstrate that agriculture interventions need to assure a pathway that leads to high-quality diets for young children.

Interventions that include poultry farming have several advantages for child nutrition. First, healthy poultry produce a large number of eggs that are low-cost, small packages of high-quality macronutrient and micronutrient that can be kept without refrigeration for an extended duration (Brown, 2003). Second, poultry farming and the money gained from egg sales are often under women's control and can be used to make market purchases to diversify and enrich the home diet (Homiah, Sakyi-Dawson, Mensah Bonsu, & Marquis, 2012). Finally, as eggs are fragile and often break, they are likely to be used regularly in home meals.

Given the evidence that (a) children's diets were poor and stunting was prevalent in rural Ghana and (b) integrated and targeted interventions work, we proposed an integrated agriculture–nutrition intervention to improve children's diets through increased home production of nutrient-rich foods and improved child-feeding knowledge, income, and empowerment that would encourage purchases of nutrient-rich food from markets. This analysis tests whether the integrated intervention improved indicators of young Ghanaian children's diet and growth.

Key messages

- Stunting remains an issue in rural Ghana, and most young children in rural Upper Manya Krobo District, Ghana, did not meet the recommendation for minimal dietary diversity.
- Integrated support for agricultural production of nutrient-dense foods and poultry, combined with nutrition and health training, improves diet and growth of young children in rural Ghana.
- Intersector collaborations to implement and sustain integrated agriculture–nutrition programmes that reach vulnerable rural populations are warranted.

2 | METHODS

2.1 | Study design and site

This study was a cluster randomized controlled community trial carried out within the context of a 5-year capacity-building and research programme (*Nutrition Links* [*NL*]) in the Upper Manya Krobo District (UMKD) of the Eastern Region of Ghana.

The *NL* programme provided training on nutrition, gender and diversity, data management and analysis, and evidence-based decision making to government and private sector service providers in the health, education, agriculture, governance, and finance sectors of the district. The *NL* team stratified the six UMKD subdistricts by population size and randomly selected three subdistricts to serve as the study site for this trial.

In the three selected subdistricts, we completed a census of communities ($n = 86$) with GPS location of all households. Three additional communities were included in the study site (total $n = 89$) because they received services from the Ghana Health Service subdistrict personnel even though they were slightly outside the subdistricts' political boundaries. Based on census data generated, the 89 communities were then organized geographically into 16 clusters. Our aim was to have at least 14 households with infants/young children in each cluster, that is, the minimum target for group activities for the intervention. The clusters consisted of either one distinct community or multiple adjacent small communities (range of 2–10). Within each cluster, we randomly chose communities until we reached a minimum of our target number of eligible households per cluster. A total of 39 communities were selected (range: 1–6 communities/cluster) as the study area.

2.2 | Randomization and allocation

The 16 clusters were randomly assigned to treatment group (sequential, using random numbers). The eight intervention clusters had 19 communities (range: 1–6), and the eight control clusters had 20 communities (range: 1–4; Figure 1). Given the nature of the intervention, it was not possible to mask the treatment assignment; therefore, the project maintained separate field staff for the implementation of the intervention and survey data collection. The clusters were geographically distant enough from each other to avoid direct contamination—that is, no control community participants received inputs or took part in educational activities planned for intervention participants.

2.3 | Participant selection and enrolment

Given limited human and financial resources, enrolment and intervention implementation were carried out in two phases. In Phase 1 (2014–2015), all women with infants (0–12 months) who lived in the selected communities and who planned to remain in the

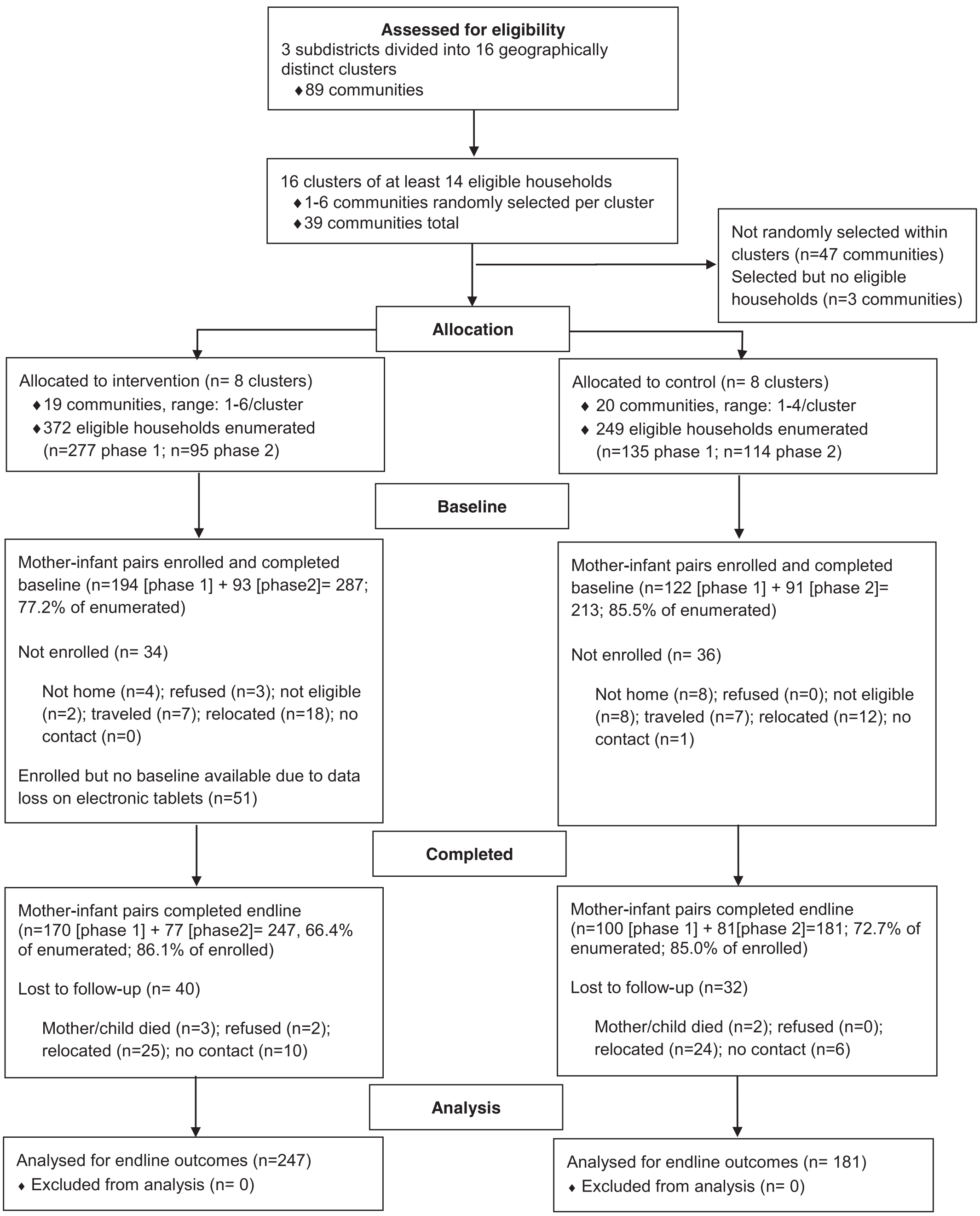

FIGURE 1 Flow of participants through the agriculture–nutrition cluster randomized controlled trial in Upper Manya Krobo District, Ghana

community for the duration of the project were invited to enrol in the trial. In Phase 2 (2016–2017), the age range was expanded to target young children <18 months to include the planned sample size. For both phases, additional eligibility criteria for the intervention participants included the timely preparation of (a) a chicken coop that met project specifications and (b) a fenced home garden plot. Although the trial was directed to women, the project staff encouraged the woman's household and community to support the activities.

All eligible households (n = 277) in the selected communities of the eight intervention clusters were invited to enrol in Phase 1 in 2014 (Figure 1). After the end of the first phase and the completion of the 12 months of trial activities, we identified newly eligible households (n = 95) from the same communities and invited them to enrol in Phase 2 in 2016. Two of the intervention clusters had no newly eligible households, so only six intervention clusters were active in Phase 2. A total of 34 eligible households were not enrolled, and 51 were enrolled, but baseline data were lost due to a malfunction of the electronic tablets. We considered it untenable to enrol participants a second time from control cluster communities that had received no benefit. Thus, the order of including the control clusters was randomly assigned. To mimic the intervention enrolment, five control clusters were used in Phase 1 (135 eligible households) and three control clusters (114 eligible households) in Phase 2. Among the control clusters, 36 households were not enrolled.

Ethics approval for the trial was obtained from the institutional review boards of McGill University (# 822-0514) and the Noguchi Memorial Institute for Medical Research at the University of Ghana (#060/13-14). All participants provided written informed consent for themselves and their children. The trial was registered at Clinicaltrials.gov (NCT01985243).

2.4 | Intervention

The 12-month intervention was an integrated package of agricultural inputs and training as well as education in nutrition, health care, and child stimulation for participants. Beekeeping was introduced for interested households only in Phase 1 for honey harvesting after the end of the trial. The relevant intervention components are described below in more detail.

1. Poultry for egg production. Participants received 4 days of intensive training from livestock extension and veterinary officers on a wide variety of topics to build their knowledge and skills in poultry farming. These included 2 days on coop construction using local materials and 2 days on feeding and caring of poultry, use of poultry manure, and handling and marketing of eggs. The intervention used Heifer's *Passing on the Gift®* (POG) community development approach where repayment of the cost of inputs provides funds for inputs for new participants. During Phase 1, each participant received 40 Swiss Brown chickens at point of lay. The POG funds supported the purchase of 30 chickens for each Phase 2 participant. To compensate for the lower number of chickens provided so that women in Phase 2 would have similar income to Phase 1, the POG repayment requirement was reduced by 50%. Initial feed for 1 month and vaccinations were provided to all participants at no cost; access to purchase feed after the first month was facilitated because there was no feed distributor in the district at the time of the trial. Weekly technical assistance on poultry production and poultry health management was available in the community throughout the year, provided by the project staff, sometimes accompanied by district agricultural extension officers. To assist women with their poultry-based small business, the project facilitated egg sales for women who could not access markets.
2. Home gardens. Project agricultural staff trained participants at the University of Ghana's Nutrition Research and Training Centre and in the communities on vegetable gardening, providing information on site selection, fencing, seedbed preparation, compost preparation and use, and organic weed, insect, and pest control. Households with limited space were encouraged to prepare their garden in available household receptacles (container gardening). Participants received planting materials (e.g., one sachet of seeds and 5–10 kg of vines) for nutrient-rich vegetables such as *kontomire* (Cocoyam leaves, *Colocasia esculenta*), tomatoes, and orange-fleshed sweet potato. Weekly technical assistance was available in the community throughout the year.
3. Group education. Weekly group education sessions were carried out using a curriculum of 12 lessons that was repeated during the year. The lessons emphasized young child diet and health, with special emphasis on diet diversity and consumption of eggs, green leafy vegetables, and orange-fleshed sweet potatoes. The preparation of the nutrition education activity was delayed and therefore was provided only during the final 5 months of Phase 1; Phase 2 participants received lessons during all 12 months. Eight lessons on psychosocial stimulation of young children were added during Phase 2. These additional lessons focused on child play and parent–child communication.
4. Community-wide education. The intervention communities received training that was accessible to all residents. The training included (a) food demonstration sessions that emphasized the consumption of vegetables promoted for home gardens and eggs, (b) mother-to-mother support groups that encouraged optimal child-feeding practices, (c) enhanced community-based growth monitoring and promotion, and (d) community-wide discussions on gender and diversity. Training in the community was provided by the project as well as through collaborations with district government staff.

2.5 | Data collection

Household and maternal sociodemographic data (e.g., maternal ethnicity and education) had been collected through the *NL* district-wide baseline survey (November 2013–June 2014) and were incorporated into the data set for this analysis. The intervention-specific data were collected using electronic tablets through baseline and endline surveys completed during the months before and after each phase of the trial.

Household data included characteristics such as family composition and demographics, household assets, water and sanitation facilities, agricultural practices including raising of poultry, use of district services, and food insecurity. Household food insecurity was measured with the 15-item Latin American and Caribbean Food Security Scale (Food and Agriculture Organization, 2012). Maternal- and child-specific information included diet, anthropometric measurements, haemoglobin concentration, health behaviours, and symptoms of physical and mental (mother only) health. Weight was measured to the nearest 100 g with a digital scale (Tanita Corporation of America, Inc., Arlington Heights, IL, USA) and length/height to the nearest 0.1 cm with a stadiometer (Shorr Productions, Olney, MD, USA). All measurements were done using standard procedures, and weight and length/height measurements were taken in duplicate. A third measurement was taken if the discrepancy was above the World Health Organization (WHO) cut-off for acceptable difference in repeated measurements (WHO Multicentre Growth Reference Study Group, 2006).

2.6 | Statistical analysis

The sample size was calculated with an $\alpha = 0.05$, power = 0.80, effect size $d = 0.35$, and variance inflation factor = 1.79, resulting in 227 households/group. Assuming a loss-to-follow-up of 10%, the sample size estimate was 250 per treatment group or a total of 500 mother–child pairs. The data were analysed with STATA version 13 (StataCorp, 2013).

The primary outcome measures of interest were endline diet quality (minimum dietary diversity [≥4 out of 7 food groups] and consumption of eggs during the previous day) and endline nutritional status (WAZ, length-for-age [LAZ]/height-for-age [HAZ], and weight-for-length [WLZ]/weight-for-height [WHZ]). A nonquantitative list of foods consumed yesterday was used to identify children's intake of seven food groups: grains, roots, and tubers; legumes and nuts; dairy products (milk, yogurt, and cheese); flesh foods (meat, fish, poultry, and organ meats); eggs; vitamin A-rich fruits and vegetables; and other fruits and vegetables (WHO, 2008). The minimum diet diversity score of children was coded as a dichotomous variable (<4 food groups [not minimally diverse] or ≥4 food groups [minimally diverse]). Weight and length/height data were transformed into standardized deviation scores using the WHO age and sex growth references (WHO Multicentre Growth Reference Study Group, 2006).

The wealth variable was derived from a principal components analysis of 13 household asset variables (floor material, wall material, cooking fuel, electricity, and ownership of a telephone, radio, television, video player, DVD/CD player, refrigerator, sewing machine, motorcycle, and car). Wealth scores were extracted from the first component and categorized by tertiles (low, medium, and high). A food security score was constructed with the 15 questionnaire items (Food and Agriculture Organization, 2012). Households were categorized by the number of affirmative answers: food secure (0), mildly food insecure (1–5), moderately food insecure (6–10), and severely food insecure (11–15).

Unadjusted bivariate analyses were performed to test the relationship between outcomes and possible covariates using independent Student's *t* test for continuous variables and Pearson's goodness-of-fit chi-square for categorical variables. Factors were included initially in the multivariable models if baseline group comparisons had a P value < 0.20 or if factors were considered to be important to child diet or growth based on previous research.

We completed an intention-to-treat (ITT) analysis first. We estimated the size of the effect of the intervention on continuous outcomes (WAZ, LAZ/HAZ, and WLZ/WHZ) and dichotomous outcomes (minimum diet diversity and consumed eggs) using linear regression models with cluster-robust standard errors based on the Eicker–Huber–White robust approach as implemented in the "cluster()" option to the "regress" and "logit" commands in STATA (Cameron & Miller, 2011). For all outcomes, we conducted an initial model without covariates and then a second model that included phase of enrolment and covariates for the child (baseline age, sex, baseline value of the outcome, and time elapsed between measurements), mother (education, marital status, and ethnicity), and household (food security, wealth, and raised poultry previously). Endline diet diversity was also included initially in the models for anthropometric outcomes. Backward elimination stepwise covariate selection procedure was used to select covariates with a P value of <0.10 (testing across categories) to adjust for the final models. No interaction terms with intervention were significant and therefore were not included in the final models. Adjusted odds ratios (aOR) or beta coefficients from the models are reported. Statistical significance was set at $P < 0.05$ unless otherwise indicated.

To assess the robustness of the findings, we used different statistical models and indicators of the outcomes of interest in sensitivity analyses (Thabane et al., 2013). We have included two additional statistical approaches run for each of the final ITT models: (a) a random-effects model (using "xtreg" and "xtlogit") and (b) a mixed-effects model (using "mixed" and "melogit"). In addition, we ran an *as-treated* analysis that replaced "intervention" with "received inputs" as an indicator of level of participation in the trial. Among the 287 participants who were enrolled in intervention clusters, 233 received the poultry and garden inputs (144 in Phase 1, 89 in Phase 2). The primary reason for not receiving the inputs was because participants had not prepared the coop and garden. The three models (linear regression with cluster-robust standard errors, random effects, and mixed effects) were used for the as-treated analyses.

3 | RESULTS

A total of 500 women and their infants were enrolled in the trial and completed the baseline; 287 lived in the eight intervention clusters, and 213 lived in the eight control clusters (Figure 1). The rate for enrolment with baseline completion was lower among the intervention compared with the control clusters, partly due to a malfunction of the electronic data collection system (77.2% vs. 83.5%; $P < 0.01$). The first phase of the trial enrolled 316 mother–infant pairs, and the second phase enrolled 184 women with their infants. There were no enrolment phase differences in baseline values for the infant anthropometric indices (data not shown). Baseline dietary outcome values (egg consumed and minimum diet diversity) were not compared, as phase was associated with child age and diet changed with age. In Phase 2, children were about 3 months older (12.4 ± 6.3 vs. 9.4 ± 3.9 months; $P < 0.01$); mothers were more educated (46.7% vs. 28.9% had completed secondary education or above; $P < 0.001$)

and were in a marriage/union (86.7% vs. 74.7%; $P < 0.01$), and more households reported being food secure (50.5% vs. 40.3%; $P < 0.04$) compared with Phase 1. Phase was tested in all models and retained if significant.

There were no baseline treatment group differences in child, maternal, or household characteristics (Table 1). There tended to be a group difference in the time interval between baseline and endline anthropometric measurements (intervention: 19.7 ± 3.2 months vs. control: 19.1 ± 4.1 months; $P = 0.07$). Over half of the households (56%, $n = 276$) reported experiencing some level of food insecurity at baseline. Among the children who were over 6 months of age at baseline, only about one quarter (23.7%, $n = 91$) consumed eggs on the previous day and one third (32.1%, $n = 121$) had a minimally diverse diet. The mean baseline values for LAZ (−0.84 ± 1.28 *z*) WAZ (−0.74 ± 1.18 *z*), and WLZ (−0.34 ± 1.15 *z*) demonstrated poor growth status during infancy.

The rate of study attrition was 14.4%. Total loss-to-follow-up cases were due to refusal ($n = 2$), participant moved outside study area ($n = 49$), and maternal or child death ($n = 5$). The remaining cases could not be found ($n = 16$). There were no significant differences in child, maternal, or household characteristics (see list of variables in Table 1) between those participants who were lost to follow up and those who completed the study (data not shown). There was no difference in attrition rate by treatment group (13.9% intervention vs. 15.0% control; $P = 0.73$).

3.1 | Dietary outcomes

The availability of eggs during the project implementation was high among the intervention households, with a production of 110.7 ± 50.6 eggs per week (sold, given as a gift, consumed, or lost to breakage). At endline, the unadjusted prevalence of consuming eggs in the previous 24 hr was higher in the intervention than control group (31.5% vs. 22.6%, respectively; $P < 0.05$). Children who consumed eggs at baseline were more than twice as likely to consume them at endline (aOR = 2.25, 95% CI [1.38, 3.66]; Table 2). The aOR for consuming an egg over the previous 24 hr did not differ by treatment group (aOR = 1.35, 95% CI [0.83, 2.20]). The effect of the intervention on consuming eggs was almost identical in the sensitivity analyses that used random-effects and mixed-effects models (data not shown). The as-treated analysis, however, demonstrated a tendency for a higher odds of consuming eggs among those who "received inputs" compared with those who did not (aOR = 1.59, 95% CI [0.98, 2.59]).

The endline prevalence of having minimum diet diversity was higher in the intervention than control group (80.2% vs. 69.5%; $P = 0.02$); the unadjusted odds ratio for intervention (but accounting for clusters), however, was not significant (Table 2). Adjusting for covariates, children in the intervention group had a 65% higher odds of having minimum diet diversity at endline compared with children in the control group (OR = 1.65, 95% CI [1.02, 2.69]). The sensitivity analyses that used the random-effects and mixed-effects models demonstrated a similar estimate for the odds ratio but a slightly weaker relationship (aOR = 1.65, 95% CI [0.93, 2.94] for both models). The as-treated model gave a slightly lower odds ratio that also tended to be significant (aOR = 1.51, 95% CI [0.94, 2.42]).

TABLE 1 Baseline characteristics of participants of an agriculture–nutrition intervention in rural Ghana, by treatment group[a]

Characteristic	Intervention $n = 287$[a]	Control $n = 213$[a]	P value[b]
Child			
Age, months	10.52 ± 5.17	10.43 ± 5.07	0.85
Length-for-age, *z*-score	−0.88 ± 1.27	−0.78 ± 1.30	0.39
Weight-for-age, *z*-score	−0.78 ± 1.12	−0.68 ± 1.27	0.34
Weight-for-length, *z*-score	−0.37 ± 1.08	−0.31 ± 1.24	0.61
Female	143 (49.8)	97 (45.5)	0.34
Consumed eggs in previous 24 hr[c]	56 (25.3)	35 (21.5)	0.38
Minimal diverse diet[d]	67 (30.9)	54 (33.8)	0.55
Maternal			
Marital status			0.94
Not married/cohabitation	48 (21.8)	46 (22.1)	
Married/cohabiting	172 (78.2)	162 (77.9)	
Education level completed			0.17
None	54 (24.5)	40 (19.2)	
Primary	100 (45.5)	89 (42.8)	
Secondary or higher	66 (30.0)	79 (38.0)	
Ethnicity[e]			0.80
Krobo	217 (76.4)	161 (77.4)	
Others	67 (23.6)	47 (22.6)	
Household			
Wealth tertile[f]			0.93
Low	92 (33.0)	70 (33.8)	
Middle	95 (34.0)	67 (32.4)	
High	92 (33.0)	70 (33.8)	
Food security[g]			0.87
Food secure	123 (43.3)	95 (45.2)	
Mild food insecurity	79 (27.8)	54 (25.7)	
Moderate food insecurity	48 (16.9)	39 (18.6)	
Severe food insecurity	34 (12.0)	22 (10.5)	
Raised poultry in past 12 months	140 (48.8)	114 (53.5)	0.29

Note. Data shown are mean ± standard deviation or *n* (%).

[a]Total $n = 428–500$ for all but "egg consumed" and "minimal diverse diet" (intervention $n = 220–287$; control $n = 207–213$). Includes all participants with baseline data for these variables. [b]Independent Student's *t* test for continuous variables and Pearson's goodness-of-fit chi-square test for categorical variables. [c]Includes only children ≥6 months ($n = 384$). [d]Minimal diet diversity: includes only children ≥6 months ($n = 377$); ≥4 of the following food groups: grains, roots, and tubers; legumes and nuts; dairy products; flesh foods; eggs; vitamin A-rich fruits and vegetables; and other fruits and vegetables (World Health Organization, 2008). [e]Krobo: the local ethnic group; others: Akan, Ewe, Ga, among others. [f]Wealth: tertiles for the first component of a principal components analysis using 13 household assets: floor material, wall material, cooking fuel, electricity, and ownership of a telephone, radio, television, video player, DVD/CD player, refrigerator, sewing machine, motorcycle, and car. [g]Food security: classification based on the 15-item Food Insecurity Experience Scale (Food and Agriculture Organization, 2012).

3.2 | Nutritional status outcomes

During the project period, overall stunting increased (14.0% to 24.3%; $P < 0.001$) and wasting decreased (6.3% to 2.9%; $P < 0.05$); underweight did not change (11.9% to 12.2%; $P = 0.89$). The intervention had a positive direct effect on linear growth. The intervention group LAZ/HAZ

TABLE 2 Logistic regression models for the effect of an agriculture–nutrition intervention on the diet of Ghanaian rural children, unadjusted and adjusted for covariates[a]

	Minimal diet diversity[a,b]		Egg consumption in last 24 hr	
	Model 1	Model 2	Model 1	Model 2[c]
Group assignment				
Control (reference)				
Intervention	1.78 (0.70)	1.65 (0.41)*	1.57 (0.43)†	1.35 (0.33)
Baseline value of outcome				2.25 (0.66)**
Second phase of enrolment		0.21 (0.03)***		
Maternal education				
None (reference)				
Primary		1.53 (0.63)		
Secondary or above		2.68 (0.99)**		
Marriage status				
Married (reference)				
Not married/cohabitation		0.31 (0.09)***		
Wealth[d]				
Low (reference)				
Middle		1.02 (0.28)		
High		1.53 (0.39)		
Constant	2.28 (0.64)**	3.09 (0.09)**	0.29 (0.06)***	0.26 (0.04)***
Pseudo R^2	0.01	0.13	0.008	0.03
Sample *n*	425	354	425	327

Note. Values are odds ratios (standard errors).

[a]This is an intention-to-treat analysis with logistic regression models with standard errors adjusted, accounting for clustering. For Model 2, models initially included phase of enrolment and covariates for child (baseline age, sex, baseline value of the outcome, and time elapsed between measurements), mother (education, marital status, and ethnicity), and household (food security, wealth, and raised poultry prior to project). Backward elimination stepwise covariate selection procedure was used; the models retained covariates with a *P* value of <0.10 for the overall significance for the variable (not individual categories). No interaction terms with intervention were significant. [b]Minimal diet diversity: includes only children ≥6 months (*n* = 377); ≥4 of the following food groups: grains, roots, and tubers; legumes and nuts; dairy products; flesh foods; eggs; vitamin A-rich fruits and vegetables; and other fruits and vegetables (WHO, 2008). [c]Includes only children who were at least 6 months of age at baseline as the baseline value was retained in the model. [d]Wealth: tertiles for the first component of a principal components analysis using 13 household assets: floor material, wall material, cooking fuel, electricity, and ownership of a telephone, radio, television, video player, DVD/CD player, refrigerator, sewing machine, motorcycle, and car.

†$P < 0.10$. *$P < 0.05$. **$P < 0.01$. ***$P < 0.001$.

declined less than that of the control group over the trial period (unadjusted change: −0.38 ± 1.0 *z*-score vs. −0.64 ± 0.86 *z*-score; *P* = 0 < 0.01). In the unadjusted LAZ/HAZ model, the intervention beta coefficient was not significant (Table 3). After adjusting for baseline anthropometric status and other covariates, children in the intervention group at endline had a higher LAZ/HAZ (β = 0.22, 95% CI [0.09, 0.34]) than children in the control group. The sensitivity analyses showed similar results for LAZ/HAZ (random-effects model β = 0.21, 95% CI [0.09, 0.34]; mixed-effects model β = 0.22, 95% CI [0.07, 0.36]; as-treated model β = 0.25, 95% CI [0.10, 0.41]).

The intervention estimate from the unadjusted model WAZ was not significant; however, the adjusted model estimate reflected a higher WAZ for the intervention group compared with the control group (β = 0.15, 95% CI [0.00, 0.30]; Table 3). The effect of the intervention on WAZ was identical in the sensitivity analyses that used random-effects and mixed-effects models (data not shown). The as-treated analysis gave a similar result (β = 0.17, 95% CI [0.03, 0.31]).

There was no treatment group difference in WLZ/WHZ in the ITT analysis (Table 3) or in any of the sensitivity analyses. Similarly, the ITT and sensitivity analyses did not reveal any treatment group differences for stunting, underweight, and wasting outcomes (models not shown).

4 | DISCUSSION

Agricultural interventions have the potential to improve child growth; however, the scarcity of well-designed studies has limited researchers' ability to examine causal relationships (Pandey et al., 2016). To the best of our knowledge, our study is the first randomized controlled community trial of an integrated agriculture–nutrition intervention to demonstrate a measureable effect on both LAZ/HAZ and WAZ in young children.

The intervention mitigated the decline in linear growth that occurs in late infancy and toddlerhood in Ghanaian communities. The 2014 mean national LAZ *z*-score was −0.5 for 9–11 months and −1.3 for 24–35 months (for HAZ), a −0.8 *z*-score difference across about the same age range as our participants (Ghana Statistical Service et al., 2015). The LAZ/HAZ decline in our intervention group (Δ = −0.38 *z*-scores) was <50% of the national cross-sectional difference. Our adjusted 1-year difference in LAZ/HAZ would be considered a small intervention effect (see Cohen, 1977); for a 20-month-old girl, for example, 0.22 *z* would represent about 0.75 cm. The results are consistent with the findings (+0.19 HAZ) from our previous agricultural intervention work carried out in three different regions of Ghana (Marquis et al., 2015). In both studies, opportunities existed for rural women to engage in income generation activities and improve child caregiving practices without providing any food or supplements directly. The consistency of results suggests that future comparable interventions may expect about a 0.20 *z*-score improvement in LAZ/HAZ in young children over 1 year. If the intervention had continued longer, the results may have mirrored the 2.45-cm difference associated with intake of a high protein energy supplement in the Guatemala 3-year trial (Habicht, Martorell, & Rivera, 1995). Given the reported long-term benefits of that intervention (e.g., cognitive development, Stein et al., 2008; and economic productivity, Hoddinott, Maluccio, Behrman, Flores, & Martorell, 2008), the small length gains seen here may reflect future benefits for these Ghanaian children.

The treatment difference in LAZ/HAZ as well as WAZ in this project was smaller than that reported by the Lulun project (Iannotti

TABLE 3 Regression models for the effect of an agriculture–nutrition intervention on anthropometric indices (z-scores) of Ghanaian rural children, unadjusted and adjusted for covariates[a]

	Length-for-age/Height-for-age z-score		Weight-for-age		Weight-for-length/Weight-for-height	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Group assignment						
Control (reference)						
Intervention	0.14 (0.11)	0.22 (0.06)**	0.09 (0.12)	0.15 (0.07)*	0.04 (0.13)	0.07 (0.08)
Baseline value of outcome		0.59 (0.03)***		0.61 (0.03)***		0.55 (0.04)***
Baseline age, month		0.02 (0.01)*		0.03 (0.01)*		0.05 (0.01)**
Sex						
Male (reference)						
Female				−0.19 (0.04)**		−0.21 (0.06)**
Maternal ethnicity[b]						
Krobo (reference)						
Non-Krobo		−0.18 (0.05)**		−0.15 (0.06)*		
Household food security[c]						
Food secure (reference)						
Mild insecurity		−0.02 (0.09)				
Moderate insecurity		−0.01 (0.09)				
Severe insecurity		0.12 (0.14)				
Reared chickens at baseline						0.14 (0.08)†
Constant	−1.41 (0.06)***	−1.16 (0.11)***	−0.99 (0.08)***	−0.83 (0.15) ***	−0.36 (0.10)**	−0.64 (0.15)**
R^2	0.005	0.48	0.002	0.51	0.0005	0.44
Sample *n*	415	408	416	411	415	408

Note. Values are beta coefficients (standard errors).

[a]This is an intention-to-treat analysis with logistic regression models with standard errors adjusted, accounting for clustering. For Model 2, models initially included phase of enrolment and covariates for child (baseline age, sex, baseline value of the outcome, and time elapsed between measurements), mother (education, marital status, and ethnicity), and household (food security, wealth, and raised poultry prior to project). Backward elimination stepwise covariate selection procedure was used; the models retained covariates with a *P* value of <0.10 for the overall significance for the variable (not individual categories). No interaction terms with intervention were significant. [b]Krobo: the local ethnic group; others: Akan, Ewe, Ga, among others. [c]Food security: classification based on the 15-item Food Insecurity Experience Scale (Food and Agriculture Organization, 2012).

†$P < 0.10$. *$P < 0.05$. **$P < 0.01$. ***$P < 0.001$.

et al., 2017). The randomized controlled trial in Ecuador saw a large increase in LAZ (0.63, 95% CI [0.38, 0.88]) and WAZ (0.61, 95% CI [0.45, 0.77]). In contrast to the Lulun project where eggs were given to participants at no cost, the women in our study made the decision about how to use their eggs each day (sell, give away, or consume). Egg income was used to meet many of their needs—from purchasing market foods to paying for health and educational expenses. Thus, our children did not have the same level of dietary exposure to eggs as the Lulun intervention children, which may explain part of the difference in results.

The path by which the intervention affected growth indicators is likely to be multidimensional. The present analysis gives support to improved diet diversity as one path. This may have happened because of (a) increased home production, (b) increased income for purchasing market foods, and (c) increased child-feeding knowledge. We did not see a group difference in egg consumption in our ITT analysis. However, the as-treated analysis suggested that those who received the intervention inputs tended to be more likely to consume eggs. In addition, the outcome data reflected the egg intake after the end of the project; group differences may have existed during the trial. Further examination of the dietary data will provide a more in-depth picture of how change in specific parts of the diet may be one of the agriculture–nutrition pathways.

Another pathway that is likely to have contributed to improving LAZ/HAZ is women's empowerment. Weekly meetings with educators and technical staff would be expected to increase women's knowledge and skills in their income generation activities and caregiving behaviours. Nutrition education alone can improve child nutrition if access to food is not limiting. Improved nutrition education in Peruvian health services resulted in a 0.272 (0.099 to 0.445) LAZ difference at 18 months of age ($P = 0.002$; Penny et al., 2006). Peruvian households were poor, but they had the capacity to act on the nutrition messages and purchase foods in local markets. Our smaller effect on LAZ/HAZ may be, in part, due to the limitations that households faced in carrying out our recommendations. Low wealth ranking and moderate-to-severe food insecurity were reported by about one third of households, and access to markets was limited for some. Thus, our results are relevant for communities similar to the UMKD; larger effects might be expected where poverty is less acute.

The strengths of the study included the implementation of a cluster randomized controlled trial design, the selection of clusters sufficiently separated to prevent treatment contamination, and the use of two unique teams of field staff for data collection and for the implementation of the trial. There were a number of weaknesses. First, there may have been some selection bias due to enrolment procedures. At enrolment, all eligible women were informed of the project requirements including preparation of a chicken coop and a garden plot. Not all participants completed the requirement in time; those who did not received no project inputs. This additional requirement may have led to a group bias in willingness to participate. However, we did not detect any baseline differences by treatment group, and the sensitivity analysis results were consistent with the ITT analysis, suggesting that selection bias was not large enough to affect the results.

Second, due to financial limitations, the project was carried out in two phases with slightly different inputs available and cluster inclusion. The baseline anthropometric characteristics were not different by phase, and diet diversity was the only model that retained phase as a covariate. As the second phase children were slightly older, the indicator may be reflecting child age more than differences between the clusters or the years of enrolment.

In summary, this study demonstrated that integrated agricultural interventions that increase access to high-quality foods, women's income-generating activities, and women's nutrition knowledge can improve child dietary diversity, LAZ/HAZ, and WAZ. All of the project activities can be integrated into the mainstream activities of local district institutions. Financial support for small businesses can be addressed with microcredit programmes by the rural banks. Departments of agriculture and health can meet the educational and extension service needs of the population. Local governments can facilitate women's access to markets. Support is needed for implementation research to develop the methods for successfully expanding integrated agriculture–nutrition activities into sustainable programmes for vulnerable populations throughout rural Ghana.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

GSM was responsible for the data analysis and wrote the manuscript. GSM, EKC, RK, BA, and RA were involved in the study design and implementation and interpretation of results. CP and AA-Y were involved in implementation of the intervention and analysis interpretation. All authors contributed to and approved the final manuscript.

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SUPPLEMENT ARTICLE

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Implementing small-scale poultry-for-nutrition projects: Successes and lessons learned

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Abstract

This paper examines Helen Keller International's model for nutrition-sensitive poultry production using a programme implemented in four diverse African contexts—three rural and one urban. Consecutive cross-sectional surveys conducted every 5 months among ~15% of participating households show that despite project-provided training and inputs, there was only limited uptake of many "best practices." Few households constructed improved henhouses; vaccination rates varied and were highest when support was provided. Poultry mortality was high. Egg productivity remained average for village poultry systems, and egg consumption remained low (two to six eggs consumed per household per fortnight). However, children whose mothers were exposed to project messages on nutrition were more likely to eat eggs, and consumption was consistently higher among households with chickens. Women's involvement in chicken rearing was widespread, but their control over revenues from the sale of poultry products was limited. Key lessons learned from implementation were as follows: (a) strong behaviour change communication is needed to encourage egg consumption, (b) nutrition-sensitive village poultry programmes should often focus more on improved practices than improved breeds, (c) supporting women's chicken production is not a route to empowerment without complementary activities that directly support women's ownership and decision making. There is also a need for rigorous research on the role of village poultry in livelihoods, food systems, and consumption as well as the structure of poultry and egg markets in low-resource areas.

KEYWORDS

animal source foods, eggs, gender, nutrition, nutrition-sensitive agriculture, small-scale poultry production

1 | INTRODUCTION

There is renewed interest in poultry production as a means of improving nutrition among young children and women and increasing income. Though poultry meat is also a nutritious animal-source food (ASF), eggs are considered particularly promising from a nutrition standpoint (Iannotti, Lutter, Bunn, & Stewart, 2014). Eggs are a source of critical nutrients (including essential fatty acids, proteins, choline, vitamins A and B12, and selenium) at levels above or comparable with those of other ASFs but are more affordable. Described as having a "nearly perfect balance of nutrients" (Applegate, 2000), daily consumption of eggs by young children has been shown to improve linear growth (Iannotti et al., 2017), and poultry ownership has been found to be positively associated with poultry meat consumption (Azzarri, Zezza, Haile, & Cross, 2015) and nutrition outcomes in children (Headey & Hirvonen, 2016).

There are many practical advantages to poultry as an ASF. Eggs are easily prepared in numerous ways. Chickens can be raised on short cycles, laying eggs at 6 months of age or sooner, and produce regularly. They can be raised in a range of environments with limited inputs and are more efficient at converting feed to high-quality food and have a smaller environmental footprint than most other livestock (Steinfeld et al., 2006; Upton, 2004; Xin et al., 2011). Income from egg or poultry meat sales can be more regular and steady than that from crops or large-animal meat, as village chickens lay multiple times a year (Mapiye et al., 2008); an egg can be sold without slaughtering an animal; and birds' small size and rapid production cycles make households more likely to slaughter or sell them than larger livestock (Kariuki, Njuki, Mburu, & Waithanji, 2013). Finally, as chickens are smaller, lower value livestock, it can be more culturally feasible for women to own chickens than large animals such as cattle (Guèye, 2000; Iannotti et al., 2014; Mapiye et al., 2008).

Despite these benefits, proven models for boosting egg and chicken production among poor households and encouraging consumption by young children (e.g., Murty, Rao, & Bamji, 2016) are few. More evidence on what works, what does not, and why is needed. Lessons and experiences from Helen Keller International's (HKI's) "Enhanced Homestead Food Production" (EHFP) programme, one of the pioneering approaches to nutrition-sensitive agriculture (Haselow, Stormer, & Pries, 2016), may help fill this gap. Over the past 30 years, HKI has been using this integrated approach to address undernutrition in women and young children, especially among poor households. EHFP began with homestead gardening for improved consumption of vitamin A-rich fruits and vegetables and added a poultry-raising component in 2001 to provide animal protein via meat and eggs. Programme design also recognized that chickens could help raise household incomes and offer an income stream to complement that from crop production, potentially filling gaps during emergencies or the agricultural "lean season" (Leroy & Frongillo, 2007; Murphy & Allen, 2003).

This paper describes HKI's approach to nutrition-sensitive poultry production within EHFP. It draws on an EHFP programme implemented by HKI in four countries in Africa from 2013 to 2016 to describe the poultry-for-nutrition intervention, summarize implementation lessons, and suggest improvements in future programming. Data from a series of monitoring surveys implemented in each country are used to present indicators of poultry production and consumption during the programme.

Key messages

- Productivity, egg consumption, and uptake of best poultry-rearing practices are challenging to increase.
- Egg consumption was higher among those exposed to project messages on nutrition and in households with chickens.
- Women were widely involved with poultry but had limited control over revenues from the sale of products.
- Poultry-for-nutrition projects should emphasize strong behaviour change communication to encourage egg consumption.
- Empowering women through chicken production requires improving their ownership and decision-making power.

2 | DESCRIPTION OF INTERVENTION

2.1 | Overview of EHFP

A detailed description of HKI's EHFP approach is available elsewhere (Haselow et al., 2016). Briefly, HKI uses a community-based approach to provide participants with extension services and start-up inputs in collaboration with local non-governmental organizations and government agencies. Local staff train a group of farmers, approximately 75–100% of whom are women, via community-based platforms. Group leaders are identified through participatory processes: Those interested nominate themselves, and their nominations must be supported by fellow community members. They then act as resource farmers and provide technical assistance to others in their communities. The same women (and sometimes men) who participate in agricultural and poultry-rearing activities receive nutrition social behaviour change communication (SBCC) promoting the consumption of home-produced micronutrient-rich foods, particularly by young children and pregnant and lactating women. Over time, it is hoped that these women will serve as agents of change, using their new knowledge and skills to help improve nutrition in their communities. Programmes also include activities to encourage women's empowerment and emphasize the inclusion of marginalized families (e.g., low income or caste).

2.2 | Poultry component of EHFP

With respect to the poultry-raising component of EHFP, HKI adapts its strategy to the specific context. In most cases, HKI implements EHFP projects in areas where many households already raise poultry, but often as a secondary endeavour to their main livelihood, with minimal resource input; this aligns to typical village poultry systems (Wong et al., 2017). Birds are mainly indigenous, sometimes mixed with improved breeds, and kept in small flocks (five to 10 birds per household). Chickens scavenge and are rarely provided with high-quality feed; if additional food is given, it is usually kitchen leftovers or cheap grains. Henhouses are rare; when used, they are often poorly constructed. Farmers thus lose many birds to disease and predators (Guèye, 2000). Access to inputs such as vaccines, technical advice, and markets is often limited (Guèye, 2000). The productivity of village poultry, often only 10–12 eggs per hen during each of three cycles per year, is low as a result of the above characteristics (Ahuja & Sen, 2007).

In such contexts, HKI's poultry-raising component focuses on introducing improved production methods through hands-on community-based training (for an example curriculum used in Tanzania, see Muhairwa, Msoffe, Mtambo, & Ashimogo, 2015). Training content includes how to (a) prepare nutritious feed using local ingredients, (b) make a coop/henhouse from local materials, (c) take measures to prevent and control disease, (d) improve egg production, and (e) separate children from animals. Sometimes, projects provide chicks, help arrange for vaccinations, or provide inputs for coop building.

2.3 | Four-country case study programme

From 2013 to 2016, HKI implemented the Creating Homestead Agriculture for Nutrition and Gender Equity Project (CHANGE), in Burkina Faso, Tanzania, Senegal, and Cote d'Ivoire with funding from Global Affairs Canada. Its programme design was informed by the results of an earlier project in Burkina Faso (Olney et al., 2016; Olney, Pedehombga, Ruel, & Dillon, 2015). The goal was to improve the nutritional status of children and women of reproductive age by (a) increasing production, diversity, and consumption of nutritious foods; (b) improving women's access to and control over productive resources; (c) improving nutrition practices; and (d) increasing income through sales of surplus production.

Across all four countries, participants were encouraged to adopt home gardens to grow micronutrient-rich crops to feed their families (particularly young children). Nutrition SBCC was centred on a revised Essential Nutrition Actions and Essential Hygiene Actions (ENA/EHA) toolkit (Guyon, Quinn, Nielsen, & Stone-Jimenez, 2015), with close attention to building community agents' skills for facilitating interactive discussions and counselling. Messages were delivered by trained volunteers through once- or twice-monthly group discussions as well as home visits, radio programmes, and community events. In Cote d'Ivoire and Senegal, a gender-transformative curriculum was also used to shift local gender norms (HKI, 2015).

2.4 | Context-specific poultry component of the CHANGE programme

With respect to the poultry-related intervention, CHANGE sought to increase production through improved practices and/or improved breeds. Because a significant increase in meat consumption was unrealistic in these low-resource contexts, the goal was to increase egg production and consumption by pregnant and lactating women and young children. Thus, in each of the four countries, SBCC strategies promoted consuming eggs and feeding them to children 6–23 months, with minimal focus on the sale of surplus eggs or meat.

Despite these similarities, numerous adaptations were made for specific contexts. Table 1 summarizes the characteristics of the intervention areas, participants, and poultry production model across the four countries.

In Burkina Faso, CHANGE was implemented in 60 villages in the mainly agro-pastoral Eastern region, reaching about 2,400 participants, and targeting households with children < 12 months of age at baseline (March–May 2014). A baseline survey of the area revealed high levels of household food insecurity, child stunting, and anaemia (Becquey et al., 2014). Participants received two local-breed hens per household but had to pay a part (~USD 1.00) of the cost of each. They were also invited to two group trainings on improved practices. Communities were trained to construct village-level poultry facilities on their own; once constructed, these were provided with 10 local-breed hens and one local rooster.

In Tanzania, CHANGE was implemented in Sengerema and Ukerewe districts of Mwanza Region, bordering Lake Victoria. The region depends mainly on agriculture and fishing. At baseline, this area also had high levels of household food insecurity, stunting among children 6–12 months, and anaemia among children 6–12 months. Fifteen wards were covered by the project, including 1,232 participants (women with children 6–12 months of age at baseline; Abu-Jawdeh et al., 2015). In Tanzania, community-level henhouses were not established because of high population density and scare land. The project instead identified and trained “poultry resource farmers” (PRFs), selecting people (primarily women) with an affinity for poultry production to serve as models of best practices. These PRFs then provided training and support to about 30 other women. The project distributed chickens to households where the participating woman had none at baseline, around 30% of the total. Each of those households received two hens and one rooster, aged about ~5 months, so that the hens were old enough to be disease resilient and begin producing eggs. Participating households were then regularly supervised by agricultural extension agents and supported by the PRF. Both the Tanzania and Burkina Faso projects were implemented as cluster randomized controlled trials (RCTs), led by the International Food Policy Research Institute (IFPRI). Poultry activities did not vary across the EHFP intervention arms of either RCT.

In Cote d'Ivoire, the project was implemented in four departments in the north: Boundiali, Korhogo, Bondoukou, and Nassian. The areas

TABLE 1 Summary of CHANGE project intervention areas, participants, and poultry model used

Characteristics	Burkina Faso	Côte d'Ivoire	Senegal	Tanzania
Intervention zones	Eastern region, Fada District	North, north-east, Savanes and Zanzan regions	Dakar region, Guédiawaye District	Lake Victoria, Ukerewe and Sengerema districts
Average rainfall (mm/year)	700–800	900–1,200	400–500	1,000–1,200
Agro-ecology	Sahelian, one short rainy season	Guinea savanna, one long rainy season	Urban, Sahelian	Upland, humid zone, bimodal
Population density	Low	Low	Extremely high	High
No. of direct participants	2,400 in 60 villages	2,816 in 42 villages	1,300 in 2 zones	1,232 in 15 wards
Poultry model	*Village level:* (56/60 villages) local hens and 1 rooster provided *Individual level:* (some) local hens provided, training on improved practices	*Village level:* testing 3 systems (local, laying hens, broilers) *Individual level:* training on improved practices	*Individual level:* improved-breed laying hens, compact henhouse, training on improved practices	*Individual level:* (some) local hens, training on improved practices

Note. CHANGE: Creating Homestead Agriculture for Nutrition and Gender Equity Project.

are all primarily agricultural, with high household food insecurity (83.4% at baseline); stunting among children under 5 at baseline ranged from 27% to 46% across districts (Ouattara, 2014). There were 2,876 project participants (women with children < 5 years of age) from 42 villages. In Cote d'Ivoire, greater attention was given to income generation, and the project worked with pre-existing women's agricultural groups to promote more nutrition-sensitive crops, launch collective chicken raising, and encourage the women to use funds from selling their produce to buy the inputs needed for the future, thereby enhancing sustainability and autonomy. Village-level henhouses were constructed in each village and provided with chickens; women's groups were then given training in improved poultry-rearing practices. Across the villages, three different systems for poultry production were tested for performance and feasibility: (a) an intensive system with laying hens for egg production (in two villages), (b) an intensive system with broilers for meat production (in four villages), and (c) a semi-intensive system with local-breed hens and improved roosters in 36 villages. As the flocks grew, some chickens were distributed to individual participants, but there was no direct provision of chickens, as in other countries.

In Senegal, the EHFP model was adapted and pilot tested in an urban setting, encouraging women to produce eggs in their own homes using improved compact henhouses. The target area, Guédiawaye District, is characterized by high population density, low-rise concrete buildings mixed with small courtyards, a poor population, seasonal flooding, and pollution. A total of 1,300 women were reached in two waves. Each woman received a moveable, dual-level henhouse, one-on-one training on improved poultry-rearing practices, three improved-breed (Holland) laying hens, and one improved-breed rooster. In addition, each woman was expected to contribute a local hen to the flock, which could incubate certain eggs to produce chicks while allowing the more productive hens to continue laying.

3 | METHODS

As part of CHANGE, HKI designed and conducted a series of cross-sectional monitoring surveys among a sample of programme beneficiary households to assess implementation performance, intervention coverage, and uptake across the four countries. For each survey, a sample of ~15% of participating households in each village/neighbourhood was selected randomly from the beneficiary list maintained by HKI for that village/neighbourhood. “Beneficiaries” were defined as those targeted to receive services by the project. Surveys were implemented three times per country (except in Tanzania, where only two were done), starting about 1 year after programme implementation, and repeated every 4–5 months (Table 2).

3.1 | Data collection

Data were collected by teams of trained external enumerators in the local language using a tablet-based questionnaire. Primary respondents were the household's main project beneficiary, as identified on the HKI participant list. Information was obtained on project participation and agricultural, poultry-rearing, and nutrition practices. Observable practices, such as the use of a chicken coop or a feeding tray, were validated during the interview. All other data, including on mortality of chickens, vaccination rates, and egg use, were based on responses to interview questions. Recall periods varied depending on the frequency of the event in question: For frequent events, such as egg production, they referred to short intervals (2 weeks); for rare events, such as chicken death or sale, they referred to longer intervals (4 months). These periods were validated through internal piloting on the basis of feasibility of recall. The survey also included open-ended questions to ascertain participants' reasons for not applying certain project-promoted practices. Information on consumption of eggs in the past 7 days for young children and in the past 24 hr for women was collected via simple recall questions posed to the woman herself/the mother, using standard formats (e.g., Food and Agriculture Organization of the United Nations & FHI360, 2016). All questions about children's nutrition referred to the respondent's youngest child. Data collection instruments were nearly identical across countries and times.

Additionally, in Cote d'Ivoire, a secondary study by project staff (Traoré, 2016) collected data on cost of inputs, profit, and mortality associated with each of three poultry production models, over a year-long period, with the aim of determining the most cost-efficient model. These data are included only where specifically noted. Data from the IFPRI-led impact evaluations in Burkina Faso and Tanzania are not used here, as they are pending publication (Olney, Bilznashka, Becquey, Birba, & Ruel, 2017).

3.2 | Statistical analysis

Descriptive statistics were generated for key poultry-related variables for each consecutive monitoring survey per country. Open-ended responses were coded using Excel. Using the monitoring survey data, we examined associations between chicken ownership and egg consumption by women and children using Pearson's χ^2 test. Data were analysed using StataSE12.

4 | RESULTS

Analysis of the monitoring survey data taken in Jan–Feb 2015, midway through the project, shows 68–80% of project participants reporting participation in ENA/EHA SBCC sessions in the prior month, 71–90% in gardening training in the prior 4 months, and 50–56% in poultry-related training in the prior 4 months. Table 2 presents poultry production and consumption over the three consecutive monitoring surveys. There was no clear trend in flock size increasing during the project. Based on participant recall, mortality remained high throughout the project period: Approximately 45% of participants in each consecutive survey reported losing at least one chicken in the prior 4 months, and there was no clear decline over time.

Considering practices, the project encouraged the use of henhouses or coops for improved human hygiene and poultry productivity. However, monitoring data showed that (with the exception of Senegal) rates of fully enclosed chicken rearing never exceeded 6% and showed no clear upward trend during the project. Aside from the urban context of Senegal, where compact henhouses were

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TABLE 2 Trends in CHANGE poultry-related indicators, based on three monitoring surveys conducted over 1 year of implementation

	Burkina Faso			Cote d'Ivoire			Senegal			Tanzania		
Monitoring wave	1	2	3	1	2	3	1	2	3	1	2	3
Survey period	Feb 2015	Jul 2015	Dec 2015	Feb 2015	Jul 2015	Feb 2016	Feb 2015	Jul 2015	Jan 2016	NA	Sep 2015	Jan 2016
No. of households (HH)	378	378	377	401	399	395	73	153	195	NA	150	143
Production												
Percentage keeping chickens	92	88	89	56	77	65	59	100	96	NA	63.3	70.1
Median number of adult chickens (among those keeping)	12	12	14	5	4	4	4	5	4	NA	3	3
Percentage of chicken keepers with 10 or more adult chickens	63	59	67	27	24	28	4	19	14	NA	4	27
Use of improved practices										NA		
Henhouse/coop present (%)	67	78	66	62	66	77	100	98	98	NA	70	52
Henhouse is "improved" (among those with henhouse/coop; %)	37	66	34	45	40	71	–	–	100	NA	41	15
Chickens fed supplementary feed (%)	99	99	87	78	94	99	93	100	98	NA	63	71
Practising fully cooped rearing of chickens (%)	6	0	0	3	2	1	58	84	83	NA	2	0
Percentage losing chickens to illness in past 4 months	39	40	44	42	44	51	47	41	50	NA	39	48
Percentage (of those with chickens) producing at least one egg in past 2 weeks (Wave 1: past week)	63	75	62	49	75	58	70	95	83	NA	42	27
Median number of eggs produced (among those producing)	9	12	7	8	10	3	10	30	15	NA	6	12.7
Avg. number per adult hen (among those producing)	1.3	2.1	2.1	1.3	2.4	1.1	2.3	7.6	6.7	NA	2.5	4.9
Portion selling eggs in last 2 weeks (Wave 1: last week; %)	0	3	1	3	2	1	0	4	4	NA	3	3
Portion selling at least one chicken in last 4 months (Wave 1: last month; %)	35	37	32	32	30	38	5	0	7	NA	7	14
Median earnings from chicken sales in last 4 months (USD among earners; Wave 1: last month)	16.48	10.03	10.03	10.41	11.03	8.36	55.52	NA	8.36	NA	6.88	1.13
Reporting food was a main item purchased with garden/poultry revenue (%)	29	31	18	54	68	47	100	NA	35	NA	82	84
Reported purchasing eggs with revenue (%)	2	5	6	10	25	20	0	NA	0	NA	0	3
Gender and decision making												
Percentage of HH poultry owned by main project participant (woman)	40	40	27	74	65	79	46	43	53	NA	63	64
Of those earning revenue from chickens, percentage of HH in which woman has *full* decision-making power over its use	18	77	59	62	53	48	100	100	94	NA	71	21
Of those earning revenue from chickens, portion of HH in which woman has *full or partial* decision-making power over its use (%)	57	86	84	75	70	65	100	100	94	NA	86	49
Consumption												
Percentage of women consuming eggs (past 24 hr)	13	35	27	21	41	26.6	37	69	71	NA	8	9
Percentage of children 6 months to 5 years consuming eggs (past 7 days)	55	80	64	43	64	28[a]	65	87	73	NA	25	38
Avg. number of eggs consumed by HH in last 2 weeks	2.7	5.5	2.5	2.2	5.9	2.6	5.3	21.8	12.5	NA	2.1	2.0
Avg. number of eggs consumed by youngest child in last 2 weeks (Wave 1: last week)	1.9	3.2	2.1	1.0	2.1	1.3	2.5	7.2	5.4	NA	0.5	1.2
Portion consuming a chicken in last 2 weeks (Wave 1: last week; %)	64	51	52	44	36	38	7	15	31	NA	22	33

Note. CHANGE: Creating Homestead Agriculture for Nutrition and Gender Equity Project; NA: Not applicable.

[a]Data refer to the past 24 hr.

provided and scavenging was constrained by geography, fully enclosed chicken rearing proved untenable. Considering uptake of partially enclosed chicken rearing, about two thirds of participants (52–78%) in rural areas had coops and enclosed chickens at night, allowing them to range during the day to find their own feed. However, most of these coops/henhouses were not considered "improved" (defined as having a door, a roof, and ventilation) and thus likely did not convey as great of benefits in terms of chicken health, productivity, and environmental sanitation. The original objectives of encouraging coop use were thus largely unmet.

There were several reasons that improved coop/henhouse use was limited. In open-ended survey questions about reasons for not using coops, about 20% participants cited a lack of resources for construction; few viable options existed for coops that were both high quality (including able to withstand the rainy season) and affordable. However, 15–40% of participants did not feel that such henhouses were useful. Their survey responses cited reluctance to house chickens outside of the family compound amid fears they would be stolen or eaten by animals. Non-coop-using participants also cited the economics of providing feed: Scavenging chickens found most of their food themselves, with little effort or investment by the owner, whereas a fully enclosed chicken needed to be fed. Although it was common to give additional feed, this was often just leftover grains (i.e., leaving out a dirty cooking pot for chickens to find).

Most countries also saw challenges in achieving high vaccination rates. These were initially high in Burkina Faso and Senegal, with between 73% and 95% of households reporting in the first two monitoring surveys that all their chickens had been vaccinated in the prior 6 months. However, these rates fell to around 50%, level with rates in the other two countries, at the end of the project, when less support was provided. The project model had generally been to link participants with existing suppliers (e.g., village vaccinators) through free or subsidized services commissioned by the project, with the expectation that participants would return to them independently later on. However, this did not always occur once services were not subsidized. Additionally, there was some confusion about vaccinators' scheduled visits to villages, and the project suffered from a nationwide counterfeit vaccine problem in Tanzania. Improving vaccination coverage thus likely would require deliberate interventions to stabilize quality supply while also supporting demand (i.e., farmers' motivation to seek such services).

The main objective of chicken rearing within this nutrition project was to produce eggs for home consumption. However, likely due to the limited uptake of improved practices, productivity remained about average for village poultry systems, with only about 60% of chicken owners (range 27–95%) reporting any egg production in the past 2 weeks in the monitoring surveys and no obvious trend during the project. Among those producing, the median number of eggs produced (seven to 10 per fortnight) and produced per adult hen (one to four per fortnight) in the rural areas were about average or slightly above for village poultry systems (Fotsa, Sørensen, & Pym, 2014; Mapiye et al., 2008), well below that of more intensive systems. However, this must be interpreted in the context of households' cost–benefit calculus: With few production inputs, even low output can be a sufficient return on investment. This was even more the case here, as some initial investments (e.g., chickens and, in Senegal, coops) were provided by the project. The exception to the low productivity was Senegal, where intensive production using laying hens was practised and median productivity reached as high as 30 eggs per household per fortnight. For three of four countries, egg production was highest at the beginning of the final year of the project (July 2015) but declined by its end.

Egg consumption remained low in the three rural settings, with two to six eggs reported consumed by the household in the prior fortnight, far less than the number produced. Typically only 13–35% of women reported eating egg in the 24 hr prior to the survey, with this never exceeding 50% of women and being notably lower (8–9%) in Tanzania. Again, the intensive system used in Senegal saw much higher levels of consumption, reaching over an egg a day (for the household) at its peak. Encouragingly, in each country, about half of the eggs eaten in the household were reportedly fed to the youngest child. Household consumption of self-produced chickens was also fairly high, ranging from 31% to 52% of households in the prior 2 weeks at project end. Consumption among young children in the prior 7 days ranged from 25% to 80%, which compares favourably with overall practices in Africa (consumption in the past 24 hr averaging 12% of 6–24 months old; Iannotti et al., 2014).

Eating eggs and feeding them to children are typically uncommon in most of these settings (Iannotti et al., 2014)—particularly in rural areas, where there are often taboos related to egg consumption. In Burkina Faso, for example, formative research conducted as part of the project revealed the belief that if a young child ate eggs, he or she would become a thief as an adult (Keith, 2014). However, project SBCC regularly reinforced the importance of eating eggs and, particularly, feeding them to children. This seemed to influence egg consumption: Knowledge among participants that eggs were a healthy addition to a young child's porridge (a key SBCC message) increased over the project, from 12–41% in Year 2 to 23–77% at project end. Moreover, as shown in Table 3, there was a widespread association between a woman's participation in nutrition SBCC and egg consumption by herself and her young child: The reported prevalence of egg consumption is notably higher, in some cases twice as common, among those participating in nutrition SBCC in the prior month. This difference is significant for 16 of 22 comparisons examined. Table 3 also confirms another expected result: Egg consumption is consistently higher among those with chickens, with the difference being significant in 12 of 18 comparisons examined.

Among households producing eggs, sales remained very rare: Fewer than 4% of producing households reported selling eggs, with self-reported median revenues of USD 0.22–3.60 in the past 2 weeks, even in Senegal where production was high. Eggs that were not eaten were generally kept in the hopes of hatching. This was likely the result of several factors. First, the emphasis of SBCC on consuming eggs may have "stigmatized" their sale. Second, weak market infrastructure and higher prices than other foods in rural areas limited egg demand. Third, in urban Senegal, the market was saturated by eggs supplied by large-scale producers. Low levels of production also made it difficult to efficiently market eggs. Finally, there was a strong desire to hatch more chickens from the eggs. Selling chickens was more common, done by about one third (30–38%) of participating households in Burkina Faso

TABLE 3 Associations between SBCC, chicken ownership, and egg consumption

			SBCC association with		Chicken ownership association with	
Country	Survey round	Group / Significance	Women's egg consumption	Children's egg consumption	Women's egg consumption	Children's egg consumption
Burkina Faso	1	With	15%	60%	14%	57%
		Without	7%	40%	7%	27%
		P (χ^2)	**0.059**	**0.001**	0.28	**0.001**
	2	With	60%	86%	37%	81%
		Without	40%	66%	25%	66%
		P (χ^2)	**0.001**	**0.000**	0.123	**0.02**
	3	With	31%	69%	29%	65%
		Without	16%	50%	10%	5%
		P (χ^2)	**0.004**	**0.001**	**0.009**	**0.079**
Cote d'Ivoire	1	With	25%	45%	27%	54%
		Without	6%	32%	13%	27%
		P (χ^2)	**0.000**	**0.057**	**0.001**	**0.000**
	2	With	45%	60%	46%	60%
		Without	21%	27%	23%	34%
		P (χ^2)	**0.000**	**0.000**	**0.000**	**0.000**
	3	With	30%	31%	30%	35%
		Without	19%	21%	19%	16%
		P (χ^2)	**0.023**	0.175	**0.018**	**0.006**
Senegal	1	With	42%	71%	42%	72%
		Without	28%	46%	30%	50%
		P (χ^2)	0.251	0.104	0.302	0.135
	2	With	75%	83%		
		Without	56%	71%		
		P (χ^2)	**0.024**	0.122		
	3	With	74%	77%		
		Without	52%	43%		
		P (χ^2)	**0.031**	**0.003**		
Tanzania	2	With	10%	32%	11%	26%
		Without	4%	7%	4%	22%
		P (χ^2)	0.293	**0.001**	0.134	0.538
	3	With	14%	42%	12%	45%
		Without	0%	32%	2%	24%
		P (χ^2)	**0.006**	0.244	**0.072**	**0.02**

Note. Table compares rates among those with chickens/those participating in SBCC with rates among those without chickens/not participating; probabilities associated with χ^2 tests are reported in bold for $P < 0.1$. All data come from the monitoring surveys described in the methods section. No data reported for Senegal, Waves 2 and 3, as nearly all households owned chickens. SBCC: social behaviour change communication.

and Cote d'Ivoire in the prior 4 months, with median earnings of about USD 10, a meaningful amount in such resource-poor areas. Such revenues may have indirectly impacted nutrition: 18–68% of households earning revenues from poultry or garden products in these two countries (and over 80% in Tanzania) reported using that money to buy food (primarily fish but also salt, oil, and vegetables). Interestingly, about 20% of households in Cote d'Ivoire reported using the money earned from poultry raising and gardening to purchase eggs to eat, whereas this was very rare (0–6%) in the other countries.

Considering breed choice, egg productivity and consumption were, as expected, much higher for the improved-breed laying hens used intensively in Senegal. This suggests a role for improved breeds in poultry-for-nutrition projects, but the trade-offs against indigenous breeds must be weighed carefully, especially in contexts with weak poultry extension services. Improved-breed chickens tend to be more susceptible to disease than their indigenous equivalents and do not fit well within most household systems. Indeed, an earlier HKI project in Tanzania suffered considerable losses due to high mortality of improved chicken breeds; experience has also shown that village production systems can be ill equipped to provide the improved feed and care required for high productivity in improved breeds. As captured in a recent review (Wong et al., 2017), local-breed chickens are often an integral part of low-resource village production systems, resilient to local diseases, adapted to the climate, and offering a high return relative to the low investment required.

In CHANGE Cote d'Ivoire's comparative evaluation of three different village-level production systems (Traoré, 2016), the improved-breed laying hens were a clear underperformer: Mortality levels were higher, and the hens slower to mature, more complex to raise, and less efficient at converting feed. Although the laying hens produced considerably more eggs than did local breeds, it was insufficient to outweigh these costs. Local chickens were thus identified as the best option for egg production in low-resource homestead-based systems. In contrast, a village-level system aimed at generating revenue was found to be better served by a focus on meat production using broilers, which were quick to reach maturity and by far the most lucrative. A village-level operation could earn over USD 1,000 in profit in a year, more than twice that earned by a laying hen operation. Smaller scale broiler production also proved profitable in Senegal, where participants independently began adding broiler chicks to their flocks. The direct impact of such production on children's nutrition is likely limited, as such birds are typically sold, not consumed, but there could be an indirect income effect.

Gender equity was a key concern for CHANGE, which aimed at empowering women. Poultry rearing, widely practised by African women (Guèye, 2000), can offer women the chance to earn additional income. However, poultry rearing demands time and labour, which are often overwhelmingly supplied by women and children—who may have little control over the resulting revenues (Dumas, Maranga, Mbullo, Onono, & Young, 2018). In CHANGE, there were fairly high levels of women's involvement in chicken rearing: Women owned two thirds of birds in Cote d'Ivoire and Tanzania and about 40% in Burkina Faso and Senegal. However, women's share of household poultry holdings did not generally increase over the course of the project. Moreover, women's involvement in decision making on the use of any resulting revenues proved hard to increase in Cote d'Ivoire and Tanzania. In Tanzania, the final monitoring survey showed that in only 21% and 49% of surveyed households did women have full or partial control over the revenues resulting from chicken sales, respectively. Additionally, a negative trend in women's decision-making ability over time in two of four countries suggests that "capture" of poultry rearing's benefits by men may have played a role. Such results have implications for not only women's empowerment but also nutrition, as evidence suggests closer links between female livestock holdings and children's nutrition than male holdings (Jin & Iannotti, 2014). Nutrition-sensitive poultry projects thus likely need to place more explicit focus on gender equity to affect change.

5 | LESSONS LEARNED AND NEXT STEPS

The CHANGE project and HKI's prior 15 years of experience in this area have shown that poultry rearing for egg production can be integrated into nutrition-sensitive agriculture projects but that taking some key points into account when designing such projects may help improve nutrition outcomes.

First, the focus cannot be placed on production alone: There needs to be a strong SBCC component to encourage consumption. As noted above (Table 3), attendance at such sessions was positively associated with consumption throughout the CHANGE countries. Strong, focused SBCC is necessary to overcome both taboos against egg consumption by young children and an understandable motivation for poor households to save, rather than eat, eggs: After all, consuming an egg represents a chicken that cannot be raised and sold and is thus an economic loss. Useful approaches in this area include positive deviance (i.e., providing examples of children who have eaten eggs and turned out healthy), aspirational messaging using economic motivations (i.e., emphasizing the economic benefits of a healthy, well-nourished child), approaches that connect a chicken to a child in the caregiver's mind (i.e., officially providing the chicken to the child, not the parents, or describing it as "the child's chicken"), and SBCC that does not discourage egg or chicken sales but still stresses the importance of using income to buy ASFs for children.

Second, the most efficient area of focus in most cases is improved practices, not improved breeds. Delivering chickens is logistically challenging, mortality of young birds can be high, and outsider providers of chickens can be blamed for not only these birds' deaths but also subsequent mortality of other pre-existing chickens—CHANGE Tanzania experienced this. Moreover, improved breeds can suffer from high mortality and poor adaptation to local practices. Where there is a desire to increase ownership levels, an approach using vouchers for local purchase or postpurchase reimbursement may be a better option. Improved breeds are a more viable option in urban settings, such as CHANGE Senegal, where they are easier to source, are raised intensively and enclosed, and there is access to inputs, support, and markets for sale. On the other hand, training may be preferable to any kind of distribution: Improvements in poultry husbandry, such as how to enrich feed or improve housing, can significantly improve productivity (Mapiye et al., 2008). Although these approaches offer less risk and lower costs, they are not easy, and there is a need to develop more easily adopted "best practices" for low-resource areas.

Third, supporting chicken production by women is not an automatic route to their empowerment without complementary activities that directly support women's ongoing ownership and decision making around the use of their production and any resulting income. Such activities will likely need to involve both women *and* men and go deeper than chickens and eggs alone to tackle underlying gender norms that constrain women's decision-making power in many developing-country settings.

There are a number of promising directions for future work on this topic. There is a need for more rigorous research that quantifies the effects of small-scale poultry on income, food security, access, and consumption of poultry products by households, women, and young children across varying rural and urban contexts. In addition, there is a need to better understand which households are likely to sustain and expand on poultry inputs they receive when direct support ends and how to better support that transition. It would also be helpful to address the methodological problems associated with measuring the impact of small-scale poultry interventions on nutrition outcomes when they are part of a larger package of interventions, as was the case with the CHANGE project. Programmatically, it would be useful to devise novel ways to improve the separation between humans and chickens: Past research (e.g., George et al., 2015; Headey & Hirvonen, 2016) has found negative associations of close-quarters chicken rearing with nutritional outcomes, likely due to exposure to faeces, but poor households (as in CHANGE) often find enclosed chicken rearing to be infeasible.

Finally, poultry-for-nutrition projects have rarely succeeded at building in a marketing component. Indeed, as shown in this project, participants rarely sell chickens and even less frequently sell eggs, even when production levels would allow this. However, market-connected approaches are likely to be important for long-term sustainability and greater impact. Although there are opportunities for marketing poultry meat in urban areas, it is unclear that sufficient demand for eggs or meat exists in many rural areas to support widespread marketing; as noted by Headey, Hirvonen, and Hoddinott (2017), eggs in Africa are a relatively expensive source of nutrients, nine to 10 times as expensive as staples. In urban areas, there is growing competition because of increasing efficiency in broiler-meat production. Meat from indigenous chickens often commands a price premium (Guèye, 2000), but farmers in most rural areas face severe constraints in taking advantage of such opportunities. They also face high transaction costs due to market imperfections stemming from poor physical and institutional infrastructure as well as asymmetric information. There is thus a need to understand the structure of poultry meat and egg markets in low-resource areas and to identify potential opportunities for helping small-scale producers market their poultry. In this context, family poultry systems must be viewed as part of the wider food system in which households participate as both producers and consumers.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

SN analysed the data and prepared the manuscript. RK contributed to and reviewed the manuscript. SN and RK approved the final manuscript for submission.

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SUPPLEMENT ARTICLE

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Use of chicken eggshell to improve dietary calcium intake in rural sub-Saharan Africa

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Abstract

Undernutrition resulting from inadequate access to high-quality, nutritious food is a widespread issue in sub-Saharan Africa impacting the health and survival of mothers and their children. Inadequate dietary intake leads to a deficiency in nutrients including calcium, required for growth and physiological functioning. This study investigated the potential of increasing dietary calcium intake by the addition of heat-treated ground eggshell to locally prepared food. A mixed methods approach of literature review, Delphi expert survey and focus group discussions with women of childbearing age in rural Tanzania, were used to assess the practicality, safety, and acceptability of consumption of ground eggshell. Chicken eggshell has high calcium content (380 mg of calcium/gram) and bioavailability comparable to calcium carbonate (~39%) with 1 g sufficient to provide one half of a sub-Saharan African adult female's dietary calcium needs. *Salmonella* was indicated as the most likely threat to human health through eggshell consumption. Experts agreed that eggshells boiled for 10 min when preparing hard-boiled eggs with a further 20 min cooking of crushed eggshell in staple foods would eliminate identified egg-associated pathogens. Five focus groups (n = 46) indicated eggshells were perceived as waste. However, there was an indication of general acceptance of the approach and a willingness to consider the incorporation of ground eggshells into their diets. Development of suitable communication methods are required to convey benefits and safe preparation methods. Ground eggshell could be a highly equitable method of increasing calcium intakes across rural sub-Saharan Africa where calcium intake is low and village poultry ownership common.

KEYWORDS

calcium deficiency, diet, egg, food and nutrition security, nutritional adequacy, resource-limited settings

1 | INTRODUCTION

Undernutrition continues to be a widespread issue in low-income countries globally, impacting infant and child survival (Black et al., 2013). Maternal undernutrition restricts foetal growth increasing the risk of neonatal death or stunting in infants who survive. Combined with wasting, micronutrient deficiencies and suboptimal breastfeeding, undernutrition as a whole is estimated to be the cause of 3.1 million child deaths annually (45% deaths in 2011; Liu et al., 2015). Undernutrition is a significant problem in Tanzania, one of the world's poorest countries (The World Bank, 2016) where the

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prevalence of stunting among children under 5 years of age was 37% in 2013 with children in rural areas most affected (National Bureau of Statistics Ministry of Finance Dar es Salaam and Office of Chief Government Statistician President's Office, Ministry of State, President Office, State House and Good Governance, 2014). In Tanzania, 68% of the population live in rural areas (The World Bank, 2015), and 80% of rural households are subsistence farmers (United Nations, 2017) who are often food insecure and rely on government subsidised food rations (United Nations, 2013). Around 40% of the rural population continues to fall below the basic needs poverty line and 20% below the food poverty line (National Bureau of Statistics (NBS) [Tanzania], 2013).

Nationally, dietary diversity is poor and evidence shows that rural-dwelling women and infants' diets are low in energy, protein, fat and micronutrients including iron, zinc, and calcium (Food and Agriculture Organization of the United Nations [FAO]; National Bureau of Statistics [NBS] [Tanzania], 2010; Kulwa, Mamiro, Kimanya, Mziray, & Kolsteren, 2015). Calcium is an important micronutrient required for growth and maintenance of teeth and bone and has an essential role in muscle contraction, blood clotting, and nerve conductivity (Mann & Truswell, 2012). Furthermore, calcium is an important factor in regulating the cardiovascular system and an adequate intake is recommended to prevent hypertension (van Mierlo et al., 2006) and preeclampsia. A recent meta-analysis of 13 randomised controlled trials showed that calcium supplementation during pregnancy in populations at risk of low calcium intake reduces the incidence of preeclampsia by 55% and is associated with a reduced risk of preterm birth and increased birthweight (Hofmeyr, Lawrie, Atallah, Duley, & Torloni, 2014). Daily calcium supplementation (1.5–2.0 g oral elemental calcium) of pregnant women in populations with a low dietary intake is a current recommendation of the World Health Organization (WHO), to reduce the risk of preeclampsia (World Health Organization (WHO), 2016). However, a number of issues have been noted in calcium supplementation to prevent preeclampsia in low-income countries including effective dose, timing of initiation, and mode of administration (Omotayo et al., 2016). Prenatal supplements in Australia contain about 125 mg of calcium per dose.

Micronutrient supplementation and food fortification have been successful in addressing stunting in several contexts (Bhutta et al., 2013; Zerfu & Ayele, 2013), but the sustainability is often challenged by funding, supply and access issues, low acceptability, and/or poor compliance, especially by the rural poor (Darnton-Hill & Mkparu, 2015). Chicken eggshell is a potential source of calcium that is readily available and accessible to rural communities; over 85% of rural households in sub-Saharan Africa (SSA) keep poultry (Guèye, 2000). In general, these communities use all edible parts of the animal for food consumption (Alao, Falowo, Chulayo, & Muchenje, 2017). The potential use of ground eggshell is consistent with these practices. In Nigeria, limestone and ground fish were both showed to heal calcium deficiency rickets in the majority of children in a 6-month period (Thacher, Bommersbach, Pettifor, Isichei, & Fischer, 2015).

Chicken eggshells are used in the manufacture of some food products, as a calcium additive, for example, in rice crackers and confectionery, in Japan (Kewpie, 2014; Mine, 2008) and in Slovakia, a calcium supplement, that contains calcium carbonate from eggshell powder is available (Rovenský, Stancíková, Masaryk, Svík, & Istok, 2003). Ground

Key messages

- Chicken eggshell contains approximately 380 mg calcium per gram and 1 g could provide 50% of an adult female's daily requirement.
- Experts involved in an e-Delphi survey agreed that eggshells boiled for a total of 30 min would pose no risk to human consumption.
- Equipment and skills needed are present in rural areas and the concept of incorporating eggshell into foods was generally accepted.

eggshell as a dietary calcium source has not been reported in SSA. Furthermore, no studies have been found that evaluate the practicality and acceptability of this method of dietary supplementation.

This study investigated the potential of increasing dietary calcium intake by adding ground, chicken eggshell to food in SSA. Preparation methods and associated food safety risks were evaluated. Practicality and acceptability of the proposed methods for preparing ground eggshell and including it in food as a dietary supplement were investigated in rural Tanzania.

This study contributes to an ongoing project in Tanzania and Zambia, which seeks to test opportunities to enhance the key role that women play in strengthening household nutrition in an ecologically sustainable manner (Alders et al., 2014).

2 | METHODS

2.1 | Development of an eggshell preparation method

A literature review was conducted to determine the following:

(1) calcium content and bioavailability of ground eggshells of different bird species;
(2) food and nutrients that improve or impair eggshell calcium absorption; and
(3) ways to make ground eggshell safe and palatable for human consumption.

Three databases, PubMed, Web of Knowledge, and Medline, were searched in March 2016 for qualitative and quantitative research published between 1976 and 2016. Subject and keyword (multipurpose) search terms related to eggshell, food safety, and nutrition were combined using Boolean operators. Search terms were eggshell* AND chicken OR poultry AND *availability OR digestibility OR *nutrient* OR safety OR calcium OR limitations OR vitamin* OR sanit* OR foodborne OR health OR salmonella OR diet* OR dietary supplement OR composition AND human nutrition OR sub-Saharan Africa OR Africa OR children OR adult* OR women OR food insecurity OR human* OR eating. Reference lists of relevant articles were hand searched for additional references. Citation searches were also conducted on relevant articles. The recommended daily allowance of calcium set by the WHO for women (including the maternal life stages of preconception, pregnancy and lactation) and children were compared against calcium content per mean gram of ground chicken eggshell from the literature review. A method of preparing ground eggshell and adding it to food was then proposed.

2.2 | e-Delphi survey to evaluate food safety risks

A two-round modified e-Delphi survey containing both qualitative and quantitative questions was conducted to ascertain expert opinions on microbial food safety risks regarding human consumption of chicken eggshell (Appendix S1). The Delphi method is a structured communication process consisting of at least two rounds of questionnaires peppered with opinion feedback to evoke and refine group judgement of experts (Boulkedid, Abdoul, Loustau, Sibony, & Alberti, 2011; Rowe & Wright, 1999). Both rounds of the survey were pretested for ease of completion, readability, and clarity by independent reviewers from the University of Sydney. A panel of individuals from existing personal networks of researchers with expertise in egg-associated pathogens was selected. Nineteen experts (16 experts from personal contacts and three from snowball sampling) were contacted; six participated in the initial round; five completed the second-round survey. The five were internationally recognised experts from Australia, Belgium, Canada, Scotland, and USA with experience in resource-limiting settings. Four were university professors, and one was an international research centre programme leader. Their self-reported expertise was related to egg microbiology, egg production systems, poultry microbiology, poultry medicine, poultry health, and food safety.

The survey assessed microbial risks associated with the type of egg production systems (large-scale commercial, small-scale commercial, and village). The survey evaluated the following aspects: level of microbial contamination risk; possible source (s) of contamination; likelihood and mode of contamination ("vertical", "mechanical" or "both"); ranking of eight common eggshell-associated pathogens; likely existence of pathogens that could cause food safety problems in humans in general and specifically in a SSA village; the microbial risks of the inclusion of ground chicken eggshells in commonly eaten foods in central Tanzania; and the likelihood that the proposed preparation method for eggshell powder would be a risk. Experts were also asked to comment on the proposed method for preparing eggshell powder in relation to food safety risks.

The two-round survey was conducted on the online platform SurveyMonkey, over 5 months. Each round was open for 2 weeks. A summary of initial round responses was sent to panellists by email to consider before they participated in the second round. Consensus measurement began in the second round with 80% agreement required for consensus. The responses "Do not know" and "Uncertain" were combined for analysis.

Qualitative data from the e-Delphi survey were organised into themes with similar statements. Quantitative data were collated using Microsoft Excel 2013 (Microsoft Corp., USA) and analysed using SPSS Statistics version 22 (IBM Corporation, USA). In the initial round, 4-point Likert-scale questions were described as median, 25th and 75th percentiles and range. The ranking of pathogens was expressed as count.

2.3 | Focus group discussions on acceptability and practicality of ground eggshell

Five focus group discussions (FGDs) to investigate the concept, acceptability, and practicality of ground eggshell for human consumption were conducted in January 2017 in five villages in Iwondo Ward, Mpwapwa District, Dodoma Region, Tanzania. These wards were selected for the overall study by the larger projects's Country Coordinating Committee based on: the level of child undernutrition; an absence of existing nutrition-oriented interventions; and a willingness by leaders at the regional, district, and ward level to be involved. Recruitment to the groups was undertaken by community leaders in each village who invited available women at random. The purpose and nature of the study was explained to the participants and written consent obtained. Participants were provided with a complimentary meal after the discussion group.

Each discussion group was held in a neutral location in the village. Discussions were facilitated by an investigator in a semi-structured format in English with simultaneous Swahili translation. All of the FGDs were audio-recorded and later transcribed and translated. The investigator made fieldnotes on the non-verbal interactions of the participants during the discussions. Questions were related to normal practice of food preparations, egg consumption and uses, acceptability, and practicality of preparing and using ground eggshell (Appendix S1).

Analysis of the transcripts was carried out by manual coding and thematic analysis (Braun & Clarke, 2006). Codes were drawn out from the transcripts in an inductive manner. From these initial codes, the data were then grouped into broad themes to provide a basis for further subtheme analysis using Microsoft Excel 2013 (Microsoft Corp., USA). The investigator's field notes on non-verbal communication and behaviour during the discussion groups were used to supplement the transcript data across the major themes.

2.4 | Ethical approval

Ethical approval for the e-Delphi survey was provided by the Human Research Ethics Committee (HREC) as an amendment to the broader project to which this study contributes, "Strengthening food and nutrition security through family poultry and crop integration in Tanzania and Zambia" (National Institute of Medical Research in Tanzania, NIMR/HQ/R.8a/Vol.IX/1690; University of Sydney, HREC #2014/209). The focus group research was approved by the Clinical Research and Ethical Review Board at the Royal Veterinary College (#2016/1612).

3 | RESULTS

3.1 | Framework development

Eight published articles were found (dating from 1998 to 2015), reporting calcium content and bioavailability of eggshells, mostly from chickens. Eggshell is predominantly calcium carbonate (94%; Vaclavik & Christian, 2014), containing 360–400 mg (average 378 mg) of calcium per gram of eggshell (Table 1; Brun, Lupo, Delorenzi, Di Loreto,

TABLE 1 Calcium requirements by age and reproductive status and contribution of 1 g of chicken eggshell as a percentage of the recommended intake (RI)

Human life stage	Calcium RI (mg)	Percentage of RI (%)
Infants and children		
0–6 months	300	126
7–12 months	450	84
1–3 years	500	76
4–6 years	550	69
7–9 years	700	54
10–18 years	1,000	38
Adult—females		
19 years—menopause	750	50
Postmenopause	800	47
Pregnant (last trimester)	800	47
Lactating	750	50

Note. "WHO/FAO theoretical calcium allowance for animal protein intake 20–40 g" recommended intake (RI) (World Health Organization, 2003) by 1 gram of chicken eggshell. Calcium for chicken eggshell was calculated by taking the mean of the three journal articles measuring content, of approximately 378 mg (*SD* = 14.8) (Brun et al., 2013; Milbradt et al., 2015; A. Schaafsma et al., 2002).

& Rigalli, 2013; Milbradt et al., 2015; A. Schaafsma et al., 2002), that is equivalent to approximately 1.5 g of calcium per eggshell, based on 42 g sized egg. One gram of ground chicken eggshell provides 69% (on average) of a four-to-six year old's recommended daily intake for dietary calcium (Table 1). Trials suggested that the bioavailability of eggshell calcium is similar to that of calcium carbonate (Brun et al., 2013; Anne Schaafsma & Beelen, 1999; A. Schaafsma et al., 2002), estimated to be 39% from a 500-mg calcium carbonate supplement (Sheikh, Santa Ana, Nicar, Schiller, & Fordtran, 1987).

Calcium requirements are affected by protein and sodium intakes, and generally, the diets of populations in developing countries are lower in sodium and animal protein compared with developed countries (World Health Organization, 2003). Therefore, the WHO calcium recommendations for diets with animal protein intakes of 20–40 g per day were selected for this study (Table 2). Based on the estimated average calcium content of eggshells of 378 mg (Brun et al., 2013; Milbradt et al., 2015; A. Schaafsma et al., 2002) and the WHO recommended intakes of calcium for adult females aged 17 to menopause consuming diets with a low animal protein intake (World Health Organization, 2003), approximately half the eggshell from a 42g egg would provide the WHO recommended intake of 750 mg of calcium daily. Additionally, this would provide six times the amount of calcium that is currently contained in Australian prenatal supplements.

Five articles were found on eggshell preparation for human consumption and included a number of preparation methods, including sterilisation, disinfection and mechanical processing. Sterilisation is a process by which all microorganisms are either destroyed or removed, whereas disinfection is the killing, inhibition, or removal of microorganisms that may cause disease (Willey, Sherwood, Woolverton, & Prescott, 2008). Sterilisation of eggshells has been achieved through the use of laboratory equipment such as an automatic steriliser autoclave (Brun et al., 2013). Chemical agents such as sodium hypochlorite (bleach) oxidise cellular materials and destroy vegetative bacteria and fungi however not all the spores will be destroyed (Willey et al., 2008). Temperatures above 100°C or saturated steam under pressure are required to ensure sterilisation of bacterial endospores (Willey et al., 2008). Almost all microorganisms die within 30 min at 0.1–0.5% sodium hypochlorite concentrations (Willey et al., 2008). Disinfection methods incorporate the use of 1–2% sodium hypochlorite and/or boiling water (Milbradt et al., 2015; Willey et al., 2008).

A typical household kitchen in SSA does not have the chemical agents or equipment to sterilise eggshell; however, the equipment to disinfect, for example, by boiling, is likely to be available and was selected as the most practical method. Placing eggshell in boiling water disinfects, with time required varying on the organism for removal.

Key components for preparation after disinfection included crushing eggshell into a powder form with the finer grinding of powder particles, reducing the impact on overall meal texture (Brun et al., 2013). The majority of mechanical processing preparation methods used commercial equipment (e.g., Retsch GmbH MM2001, mixer mill) although some used rolling pins, ovens, and other household items for the mechanical processing of eggshell.

Pastoral de Criança, a charity organisation helping Brazil's undernourished communities, teaches families how to create a nutritive powder to help meet nutrient requirements. One of the ingredients in this powder is eggshell. The original technique used to ensure eggshell is safe for consumption uses household methods, that is, placing the eggshell in a bleach solution for 20 min followed by boiling water for 20 min (Pastoral da Criança, 2000). Naves, Prado, Fernandes, and Serafini (2007) tested the method using reduced times for both boiling and bleaching and two eggshell drying processes, that is, sun drying for 2 hr and oven drying at 60°C for one and a half hours. Both methods provided adequate protection; however, the sun-dried sample had some microbial contamination (Naves et al., 2007). Milbradt et al. (2015) also compared two preparation methods of 1% sodium hypochlorite solution for 5 min followed by 10 min in boiling water or boiling water for only 10 min. Both treatments showed satisfactory sanitation according to the Brazilian microbiological standard and *Salmonella* was not detected in either sample (Milbradt et al., 2015).

From these studies, we proposed a preparation method incorporating the WHO "Five keys to safer food" (a programme designed to stop microorganisms causing illness):

- Wash hands before handling eggshell;
- Wash and sanitise all surface and equipment used for food preparation;
- Wash broken eggshell (contents removed/used) under water;
- Roughly crush the eggshell and remove (peel off) the eggshell membrane;
- Boil eggshell for 10 min;
- Dry eggshell in a low oven or sun dry on a clean tray;
- Crush eggshell in mortar and pestle until a powder consistency; and
- Store in an airtight container.

TABLE 2 Calcium intake recommendations required to ensure calcium adequacy for the majority of women and children

Human life stage	WHO/FAO (animal protein intake 20–40 g)[a] 2004 Recommended intake (RI) (mg/day)	Canada and United States[b] 2010 Recommended dietary allowance (RDA) (mg/day)	Australia[c] 2006 Recommended dietary intake (RDI) (mg/day)	WHO/FAO (developed countries)[d] 2004 Recommended intake (RI) (mg/day)
Infants and children				
0–6 months	300	200[e]	210[f]	300
7–12 months	450	260[e]	270[f]	400
1–3 years	500	700	500	500
4–5 years	550	1,000	700	600
6 years	550	1,000	700	600
7–8 years	700	1,000	700	700
9 years	700	1,300	1,000	700
10 years	1,000	1,300	1,000	1,300
11 years	1,000	1,300	1,000	1,300
12 years	1,000	1,300	1,300	1,300
13–14 years	1,000	1,300	1,300	1,300
15–18 years	1,000	1,300	1,300	1,300
Adult-females				
19 years—menopause	750	1,000	1,000	1,000
Postmenopause	800	1,200	1,300	1,300
70+ years	800	1,200	1,300	1,300
Pregnancy (<18 years)	-	1,300	1,300	-
Pregnancy (>18 years)	800	1,000	1,000	1,200
Lactating	750	1,000	1,000	1,000
Adult - males				
19–50 years	750	1,000	1,000	1,000
51–65 years	750	1,000	1,000	1,000
66–70 years	800	1,000	1,000	1,300
70+ years	800	1,200	1,300	1,300

[a]Theoretical calcium allowance. Values based on lower calcium excretion. (World Health Organization, 2003).

[b](Health Canada, 2010).

[c](National Health and Medical Research Council, 2006).

[d]Based on Western European, American & Canadian data (World Health Organization, 2003).

[e]Acceptable intake.

[f]Adequate intake.

3.2 | E-Delphi survey

The panel reached consensus on the microbial contamination risk related to four out of nine pathogens to human eggshell consumption (Table 3). They agreed 100% that the Enterobacteriaceae family, in particular, *Salmonella*, would be a threat to ground eggshell consumption, whereas *Mycoplasma* and Newcastle disease virus would not. Eighty percent of experts agreed that all organisms, except *Bacillus cereus* which is a soil rather than a poultry pathogen, would become innocuous to human consumption after eggshells were subjected to 10 min in boiling water and 20 min while preparing a maize flour dish being cooked in boiling water (Table 4).

3.3 | Focus group discussions

A total of 46 women of childbearing age participated in the FGDs, which lasted between 48 and 72 min. The authors stopped after five FGDs due to data saturation becoming evident (Fusch & Ness, 2015). Practicality of preparing and using ground eggshell, eggshell and equipment availability, skills and human resources, and batch preparation methods were themes common to all FGDs.

The majority of participants reported that they do not regularly eat eggs due to low poultry ownership associated with chickens dying, low productivity of laying poultry, eggs being kept for reproduction and income, and eggs being an expensive food item to purchase. Most participants discussed the importance of selling chickens (and occasionally eggs) to provide income; however, most expressed a desire to eat more eggs. The response to "What is currently done with eggshells?" was "They are disposed of" with only one participant adding the eggshell to her chicken feed. Therefore, shells from any accessible eggs are available.

Participants in all groups agreed they have all the equipment required for eggshell preparation including a clay pan, local stove, firewood, metal pan, plate, wooden spoon, water, and local grinder (*kinu*

TABLE 3 Likelihood of contamination and possible mode (s) of transmission of common egg-associated pathogens

Risk of contamination and mode of transmission of individual pathogens	Risk of contamination (1 = high; 2 = medium; 3 = low; 4 = negligible)	Mode of transmission
Common egg-associated pathogens	Risk Median (IQR) Min-max	Vertical/ mechanical/ both (n)
Avian influenza (HP)	Low 3 (3–3.5) 3–4	V(1), M(3), B(1)
Avian influenza (LP)	Low 3 (2–3.5) 2–4	V(1), M(3), B(1)
Bacillus cereus	Low 3[a] 2–3	M(3)
Campylobacter	Medium 2 (1–4) 1–4	V(1), M(3)
Mycoplasma	Low 3 (1–3) 1–3	V(3), B(2)
Newcastle disease	Low 3 (3–3) 3–3	V(1), M(4)
Salmonella	High 1 (1–2) 1–2	V(2), B(3)
Staphylococcus aureus	Low 3 (2.5–3.5) 2–4	M(3), B(1)

Note. B: both mechanical and vertical; LP: low pathogenic; M: mechanical (microbial transmission to an egg via fomites); HP: high pathogenic; V, vertical (microbial transmission from hen to her chick via the egg).

[a]IQR is not available as two out of five experts chose "Do not know" option.

nan mchi). When discussing the eggshell preparation method, participants from all FGDs concluded that they have enough time to try the idea within their normal routine. Overall, the average amount of time the participants spend preparing food is 3 hr per day.

Opinion was divided as to whether preparing a large batch or one eggshell at a time would be most suitable. Many participants felt that preparing a batch would be simpler so the task would not have to be carried out so regularly. However, the problem recognised by many was the availability of eggs to be able to make a large batch. Others questioned the method of grinding the eggshell with the local grinder, preferring the idea of grinding the eggshell at the same time as flour by machine.

All groups cited *ugali* and *mlenda* as their staple diet. *Ugali* is a stiff porridge made from maize or sorghum and prepared by boiling in water. *Mlenda* is made from green leaves, commonly cowpea leaves or young baobab leaves, also boiled. The regular use of boiling and grinding techniques in everyday cooking suggests people have the relevant skills to prepare ground eggshell, and that the methods are acceptable.

In addition, the concept of adding powders to food is familiar. Powdered spices were mentioned frequently, although most participants associated spices with adding flavour to food. Adding nutritional supplements to food was an unfamiliar concept with no participants reporting having ever used them.

Eggshell is generally perceived as a waste product and nearly all participants dispose of eggshells. When the idea of eating eggshell was introduced to each group, it elicited a surprised reaction, with participants laughing or talking privately. Some described the idea as "like what chickens do," suggesting they had not previously associated eggshell with human nutrition nor perceived it as a human food. Nevertheless, once the concept was explained and understood by participants, the idea of eating something normally discarded appeared acceptable.

In general, understanding of why eggshell might be good for health was low and participants had no prior knowledge of calcium. Some participants did not want to comment on potential health benefits without having tried eating ground eggshell themselves. This suggests that participants relate nutrition and health to taste, experiential feelings of health, and if something is accepted as common practice. When identifying who in their family would benefit the most, none of the participants mentioned pregnant women or breastfeeding

TABLE 4 Expert agreement on risk of individual pathogens to human eggshell consumption in SSA village context

	Expert agreement (number of experts chose this option out of all members of the panel [*n* = 5])					
	This pathogen would be a risk to human consumption of eggshell in SSA villages			With 10-min boiling and 20-min cooking time, this pathogen would remain a risk		
Pathogens	Yes	No	Uncertain/ Do not know	Yes	No	Uncertain/ Do not know
Avian influenza (HP)	3	1	1	0	5	0
Avian influenza (LP)	2	2	1	0	5	0
Bacillus cereus	2	1	2	1	3	1
Campylobacter	3	2	0	0	5	0
Enterobacteriaceae	5	0	0	0	5	0
Mycoplasma	0	4	1	0	5	0
Newcastle disease	0	4	1	0	5	0
Salmonella	5	0	0	0	5	0
Staphylococcus aureus	2	1	2	0	5	0

Note. HP: high pathogenic; LP: low pathogenic.

mothers. Children were frequently cited, with the reasoning that they need a lot of nutrients to grow.

The three main concerns about consumption of eggshell raised during the FGDs were the flavour of the ground eggshell, potential overdosing, and digestion problems. Responses to try eggshell were mixed but overall most participants thought that it was a good idea, very useful, and would like to try it out. Other concerns related to being able to follow the method accurately.

4 | DISCUSSION

This study found that ground eggshell appears to be a safe, practical, and acceptable method to improve dietary calcium intakes in SSA. Eggshell has a bioavailability of about 39%, similar to calcium carbonate supplements and 1 g could provide one half of an SSA adult female's calcium daily requirement. Boiling eggshell for a total of 30 min was found by the e-Delphi expert panel to be adequate to disinfect and be safe for human consumption. Equipment and skills needed are present; however, the concept of nutritional supplements added to food is novel and requires extension materials that increase nutritional understanding to promote its uptake.

Eggshell, like all food, is a possible vehicle for pathogen transfer, able to transmit a variety of diseases to humans. Rough treatment of eggs that results in the cracking or removal of the cuticle, a protein layer on the surface of the shell, and poor personal hygiene by egg handlers increases the risk of microbial contamination and growth (Mayes & Takeballi, 1983). *Salmonella* contamination of eggshell has been noted globally (Whiley, Clarke, & Ross, 2017), and *Salmonella* is a major cause of bacterial infection in SSA (Feasey, Dougan, Kingsley, Heyderman, & Gordon, 2012; Marks et al., 2017). Multiple studies suggested contaminated faeces as probable transmission route of *Salmonella* on eggshells (Gantois et al., 2009; Messens, Grijspeerdt, & Herman, 2007).

The expert e-Delphi panel reached agreement that most pathogens identified would not remain a threat to humans when eggshells are subjected to the preparation method proposed. There was uncertainty on *Bacillus cereus*, as two experts considered the possible survival of thermal-stable spores of *Bacillus cereus*; however, the panel suggested there was a low–medium risk of *Bacillus cereus* contaminating eggshell. This pathogen is soil-associated rather than egg-associated and ubiquitous and opportunistic in nature (Helgason et al., 2000; Humphries & Linscott, 2015); therefore, the threat it may pose remains constant among all food sources in our study population setting. Moreover, covering the cooking vessels with a lid during boiling has been shown to be effective in inactivating spores of this pathogen, further reducing risk (Rice et al., 2004).

FGDs explored the practicality and acceptability of the proposed eggshell preparation method. On understanding their nutritional importance, women were positive about potential uses of eggshells and displayed a sense of empowerment. The idea of adding eggshell to grain before being taken to the milling machine, raised by FGD participants, could be practical and would reduce time and labour involved but needs to be trialled in situ to determine whether it is technically and commercially viable. There could be problems with how effectively the eggshell is ground and its distribution in the flour. Furthermore, if portion sizes of local porridge fluctuate with individual serving sizes, season, and harvest/availability of grain, it would be more challenging to control calcium intake (Bagnol et al., 2016). Each household mills varying quantities of grain at varying frequencies (usually once per week), so a clear recommendation would be needed for the number of eggshells to be added per kilogram of grain if this method of grinding is practical.

Palatability and texture need to be assessed in local foods among all family members, with men typically the “head” of the household as they are influential as to whether a new idea is accepted (Richards et al., 2013). No changes in food flavour, but some changes in food texture were observed in a trial using various foods (Brun et al., 2013) likely due to inadequate crushing and/or sieving, supporting the need for testing in rural conditions. Sieves were proposed to ensure the smoothness of the ground eggshell before adding to food, and this additional step may increase acceptability. Sieves are used in a laboratory setting in the preparation of ground eggshell by Brun et al. (2013) and Naves et al. (2007) and are a commonly available item in rural households. An investigation into alternative preparation methods using village machinery, palatability in local foods, and food safety hazards would help increase practicality and acceptability.

The development of a set of comprehensive extension materials, as well as training, would be necessary to communicate persuasively this novel concept. Some form of extension training, ideally involving a physical demonstration and active learning, would be a more appropriate way of communicating the concept and method in this environment.

Although current availability of eggs for consumption appears low, work being done by projects such as “Strengthening food and nutrition security through family poultry and crop integration in Tanzania and Zambia” is expected to increase flock sizes of village chickens through the control of Newcastle disease (Alders et al., 2014). Increased availability of eggs combined with extension messages encouraging consumption of eggs for their nutritional health benefits, rather than for income (Bagnol et al., 2016), could increase egg consumption in these rural areas.

Generally considered a waste product, eggshell has large potential as a low-cost alternative to commercial supplements recommended by the WHO. These supplements are estimated to cost $11.50 per person for 6 months (World Health Organization (WHO), 2016) or $1914 million annually ($ denotes international dollars) for 90% coverage in 34 countries with 90% of the burden of malnutrition (Bhutta et al., 2013). The production of ground eggshell is cost-free, other than time involved, for people who have the necessary equipment and available eggshells—potentially up to 85% of rural households in SSA, who keep poultry (Guèye, 2000).

4.1 | Strengths and limitations

There are several advantages of using an e-Delphi survey as a decision-making tool for subject matters with limited explicit knowledge or historical data (Wentholt, Fischer, Rowe, Marvin, & Frewer, 2010); however, the e-Delphi small panel size (n = 5) used is a limitation. Advantageously, the panel members were internationally renowned experts in their fields. There are no established standards for e-Delphi panel sizes (Akins, Tolson, & Cole, 2005), nor evidence on the impact of small panel size on their effectiveness (Rowe & Wright, 1999) and the inclusion of experts of mixed speciality is believed to improve decision-making (Boulkedid et al., 2011). The e-Delphi provided expert consensus of risk but no microbiological assays for potential pathogens on eggshells in the SSA environment were undertaken. The panel did not reach consensus on the possible mode (s) of transmission of seven common egg-associated pathogens, that is, only three out of five experts agreed; however, consensus was reached on the possible mode (s) of transmission of Newcastle disease.

The advantages of using FGDs as a methodology are that this format allowed participants to contribute questions and enabled the investigator to be responsive to the nature of the discussion. Emerging themes were followed up instantly, gathering more pertinent data. Although Tanzanian translators were used, language barriers may have affected the investigator's full comprehension of the participant's responses. Discussions were in Swahili; therefore, participants who usually converse in local languages may have had difficulty expressing themselves fully in Swahili and may have felt less willing to contribute. Participants may have provided responses they anticipated the investigator wanted or expected, rather than an honest report due to an "asymmetrical relationship" (Dowling, 2010). Moreover, group dynamics may have affected how representative responses were.

5 | CONCLUSIONS

This study found that adding ground eggshell to traditional foods could be considered a safe, practical and acceptable method of increasing dietary calcium intakes in SSA. Equipment and skills needed are present. However, the concept of nutritional supplements added to food is novel and requires extension materials that increase nutritional understanding to promote its uptake. Expert group consensus indicated that *Salmonella* is the most prominent threat to human eggshell consumption but *Salmonella* and other potential pathogens: Avian Influenza virus, *Campylobacter*, *Staphylococcus Aureus*, and Enterobacteriaceae would not remain a risk after boiling.

Because it is possible to eliminate potential pathogens on eggshells, we believe that eggshell consumption as a calcium supplement can be considered safe and could play a role in relieving maternal and childhood calcium deficiency. However, further applied research to assess women of reproductive age's ability to use eggshell and identify any safety issues will be required.

The proposed preparation method could be utilised across rural SSA where calcium intake is low and village poultry ownership common. With increasing village poultry productivity due to Newcastle disease control, we predict that eggshell will be more available and accessible to all, particularly the rural poor who are most at risk of low calcium intakes. Using ground eggshell to increase dietary calcium could be a highly equitable nutritional recommendation.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

RA conceived the research idea, with contributions from FO and BH. JB, YHY, and HD completed one primary research component each and wrote the draft paper. JB and HD wrote subsequent drafts of the paper. WM facilitated fieldwork by HD. FO, BH, WM, and RA contributed to critical revision of the paper. All authors contributed to and approved the final manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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SUPPLEMENT ARTICLE

WILEY | Maternal & Child Nutrition

Increasing egg availability through smallholder business models in East Africa and India

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Abstract

Availability and consumption of eggs, especially in Sub-Saharan Africa and Asia, is low despite their apparent benefits. We investigated constraints in egg production in four countries; Kenya, Ethiopia, Malawi, and India and identified five business models that are viable and sustainable. They are (a) micro-franchising, (b) microfinancing, (c) co-operative farming, (d) enterprise development, and (e) out-grower model. All of them involve smallholder farmers to increase egg production. These farmers have access to soft loans and use improved inputs and extension services to varying degrees. Inputs include resilient breeds of day-old chicks or point-of-lay hens, feed, vaccines, medicines, and housing. Outgrower and enterprise development models have a significant potential of rapidly increasing egg yields, achieve self-sufficiency, operate at or near scale, and provide a high income for the farmers. This study shows how a range of actors in commercial, not-for-profit and microfinance sectors with specialized skills, can facilitate the transformation of the egg production sector. Specific skills include brooding (hatchery operations), feed milling, aggregation, and training of smallholder farmers or large-scale rearing. The five archetypes we describe here are promising ways to increase egg availability in rural areas.

KEYWORDS

business models, East Africa, eggs, India, rural, smallholders

1 | INTRODUCTION

Eaten since the beginning of time, eaten almost everywhere in the world, relatively easy to obtain, adaptable to many different types of cooking techniques and an affordable source of highly digestible protein, the egg offers a high potential to improve maternal and child nutrition. In a recent study, all nine essential amino acids were significantly lower in stunted children compared with non-stunted Malawian children (Semba et al., 2016). This finding is important because it suggests that stunted children are not receiving sufficient quality protein from their diets. Studies promoting egg consumption for women and children as part of broader dietary improvements in low- and middle-income countries (LMICs) show that child growth indicators are significantly improved in the intervention group compared with control (Iannotti et al., 2017; Iannotti, Lutter, Bunn, & Stewart, 2014). Despite the apparent benefits of eggs, their availability and consumption in these countries, especially in Sub-Saharan Africa and Asia, is low (Iannotti et al., 2014).

In LMICs, extensively raised chicken or village poultry (flock size of less than 50) contribute to most of the poultry population and are owned by most rural households (Alders & Pym, 2009; Gilbert et al., 2015). Despite low productivity levels (30 to 80 eggs per bird per year), such backyard production systems have been beneficial as they provide supplemental income and insurance to vulnerable groups of society through the sale of eggs and birds using almost negligible inputs (Wong et al., 2017). However, several critical barriers to production need to be addressed to improve and maximize their contribution to food and nutrition security. These include high losses due to disease and predation, high and volatile feed prices, inadequate nutrition, housing, access to affordable vaccines and medicines, veterinary services, and flock management practices (Wong et al., 2017)—all of which are elements of an intensive production system. Intensive poultry systems have a minimum flock size of 100 birds, operate as commercial farms with much higher productivity levels ranging from 200 to 340 eggs per bird per year (Chatterjee & Rajkumar, 2015; Pym, Guerne Bleich, & Hoffmann, 2006). In rural areas, intensifying production through aggregation of smallholders as contract farmers or through cooperatives are known to improve productivity for several foods such as cereals, dairy, fruits, vegetables, and chicken meat (Prowse, 2012). However, published literature for egg production models is sparse. We, therefore, conducted a value chain assessment in three countries in East Africa and India to explore organizations that address the constraints in egg production and analysed their approaches that resulted in identifying five business models that are viable and sustainable. In this paper, we describe these five archetypes all of which involve smallholder farmers in Kenya, Ethiopia, Malawi, and India.

Key messages

- There are five archetypes of business models involving smallholder farmers that can increase egg availability in rural areas.
- Those with larger flock sizes can rapidly achieve high egg yields while ensuring the smallholder farmers have a good income.
- All of the models have access to soft loans and use improved inputs to varying degrees.
- Favourable policies are needed for diverse actors: commercial, not-for-profit, and microfinance institutions, to transform the egg production sector in rural areas.

2 | METHODS

We followed an empirical approach to profile business models with a comprehensive literature review and discussion with experts in the poultry sector, donors, and impact investors in agriculture in Kenya, Ethiopia, Malawi, and India. We selected these four countries based on the priority geographies of the funding institution and our prior experience in India. Through 160 key informant interviews with farmers, input suppliers, integrators, women self-help groups, and poultry social enterprises, we mapped the poultry ecosystem and documented the initiatives of nongovernmental organizations (NGOs), small and medium enterprises, large corporations, and government entities. After an extensive due diligence of 21 initiatives involved in rural egg production, we applied four criteria, (a) impact, (b) relevance, (c) sustainability, (d) scale, and shortlisted six organizations for an in-depth assessment. **Impact**: interventions that aim to solve deep-rooted challenges and empower rural communities to make a lasting positive change in their lives have a high impact. **Relevance**: an initiative's offering is relevant if it increases the smallholder farmer's ability to adapt quickly. **Sustainability**: sustainable programs rely less on donor funds and create revenue streams for the organization to be self-sufficient. **Scale**: an initiative can continue to scale up if it can increase profits by adding additional farmers, or an initiative can scale up rapidly if the cost of reaching a new farmer decreases as the number of farmers increase. We then developed case studies of these six organizations including qualitative and quantitative indicators of operational and financial performance, their approaches to scale, and sustainability. We conducted a comparative analysis of their performance, practices, and critical success factors for sustainability. Based on this assessment, we clustered their approaches into five archetypes or business models (Table 1). All local currencies were converted to US Dollars (USD), using the currency's 12-month average conversion rate (January 2017 to December 2017).

We now define key terms commonly used in the poultry sector and in subsequent sections. "Integrators" are commercial entities who have operations across the value chain. They distribute input packages, operate layer farms and sell eggs through their own shops. An "input package" comprises of young chicks, feed for chickens, medicines and vaccines, and housing for the hens. Young chicks are procured either as "day-old chicks" (DOCs) or "point of lay" chicken (17 to 20 weeks old). Eggs are hatched into DOCs in "hatchery" units. These chicks are then raised in "brooding units" with high quality of care, nutritious diets, and additional warmth to raise them into point of lay chicken. At this stage, they are ready to lay eggs. "Para-veterinarians" supervise birds for disease outbreaks and administer vaccines and medicines through "extension services."

3 | RESULTS

3.1 | Model 1: Micro-franchising

In this business model, a hatchery sells DOCs, together with vaccines and feed to agents (micro-franchisees). Agents breed the chicks till they are 4 to 6 weeks old, thus ensuring they are resilient when introduced to extensive or backyard rearing. They then sell these chicks to the backyard and smallholder farmers, sometimes together with feed. In Ethiopia and India, for example, two private companies created a vast agent network and a replicable distribution model to reach rural households (Figure 1). They developed a commercial breed that is agile and has high resistance to diseases when compared with the indigenous variety. The Ethiopian company, in a public–private partnership with the government, operates state-owned poultry breeding farms at higher efficiency and profitability. The Indian company has a hatchery, and DOCs are transported to mother units located across the country where they are vaccinated and raised for 3 weeks. Micro-franchisees, who are independent entrepreneurs, buy the 3-week-old chicks and transport them to rural areas on their bicycles where they sell these chicks to backyard farmers (mainly village women). They are also called "brooding entrepreneurs" or "agents." They would need to invest on their own or use credit from the company. Each micro-franchisee can cover between 120 and 150 households and is responsible for brooding up to 3,000 chicks. Village women raise the chicks on low-cost household and agricultural waste. Not more than 20 birds can be raised at a time, beyond which the farmer sees diminishing returns. Backyard farmers make a net supplemental income between USD 72 and USD 144 per year because of improved productivity of 100 eggs per bird (vs. 40 eggs per bird) and reduced mortality. In an

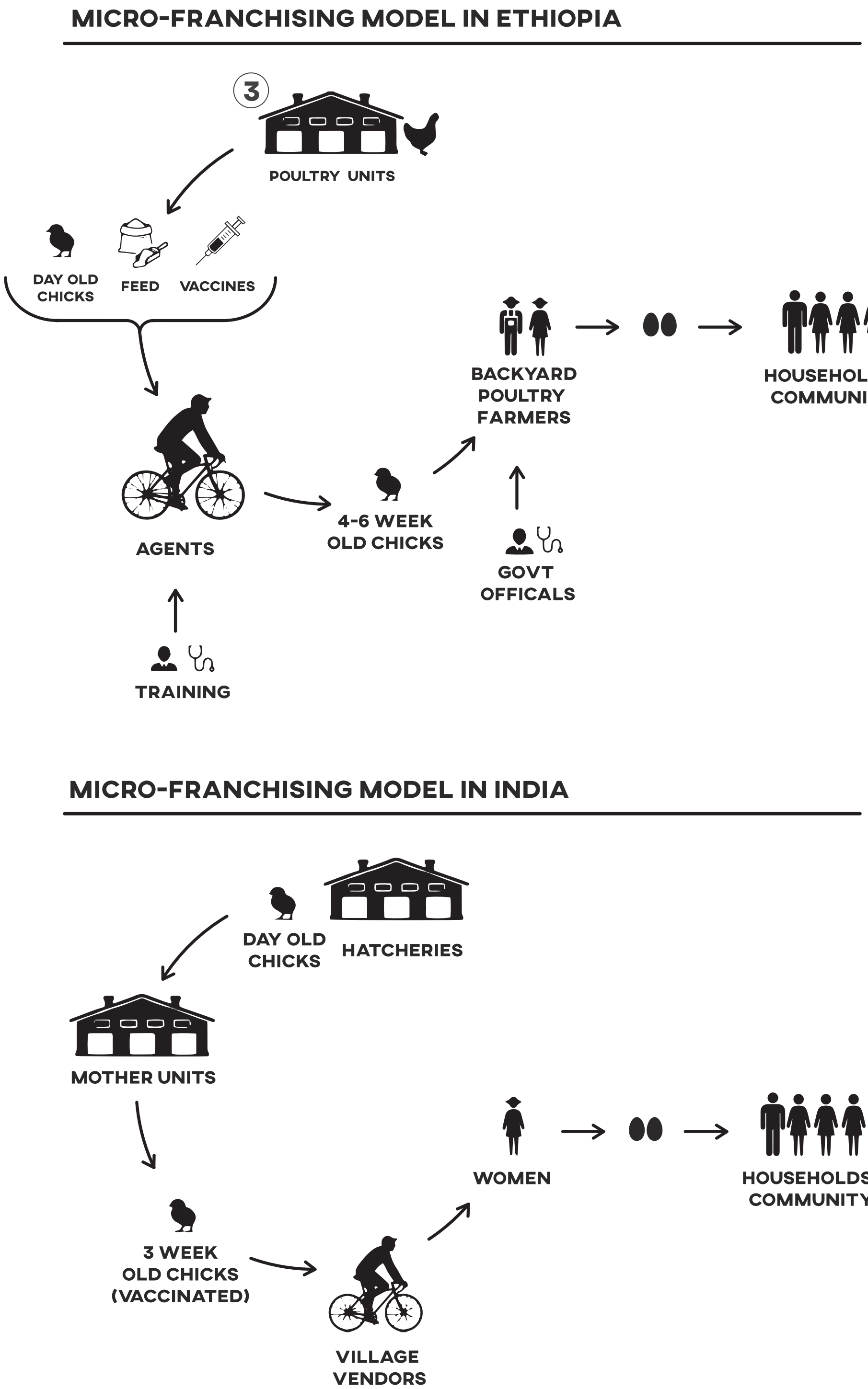

FIGURE 1 Micro-franchising model

optimistic scenario, where a farmer buys three batches of 20 birds each per year, the micro-franchisee or the brooding entrepreneur has a net annual income of USD 1,600 and can recover his capital investment in 2 to 3 years. Net margin for the micro-franchise is 20%. Nearly 40% of the costs is for DOC, 35% for feed, and the remaining for vaccines and other medicines. This model is laborious to set up as it requires hiring and training of several agents. A significant share of the revenue of eggs in the value chain is with the micro-franchisee and not the backyard farmer, and since the birds continue to grow in the suboptimal backyard environment, productivity is still low. As a result, the backyard farmers make less than a 10th of the income of farmers in the Models 4 and 5.

3.2 | Model 2: Microfinancing

In this model, a microfinancing institution (MFI) procures inputs from a supplier and distributes them to micro-entrepreneurs along with loans, training on backyard poultry, and extension services. Women rear hens and sell eggs within the community and to institutions while repaying the loan (Figure 2). Interest from the loans is income for

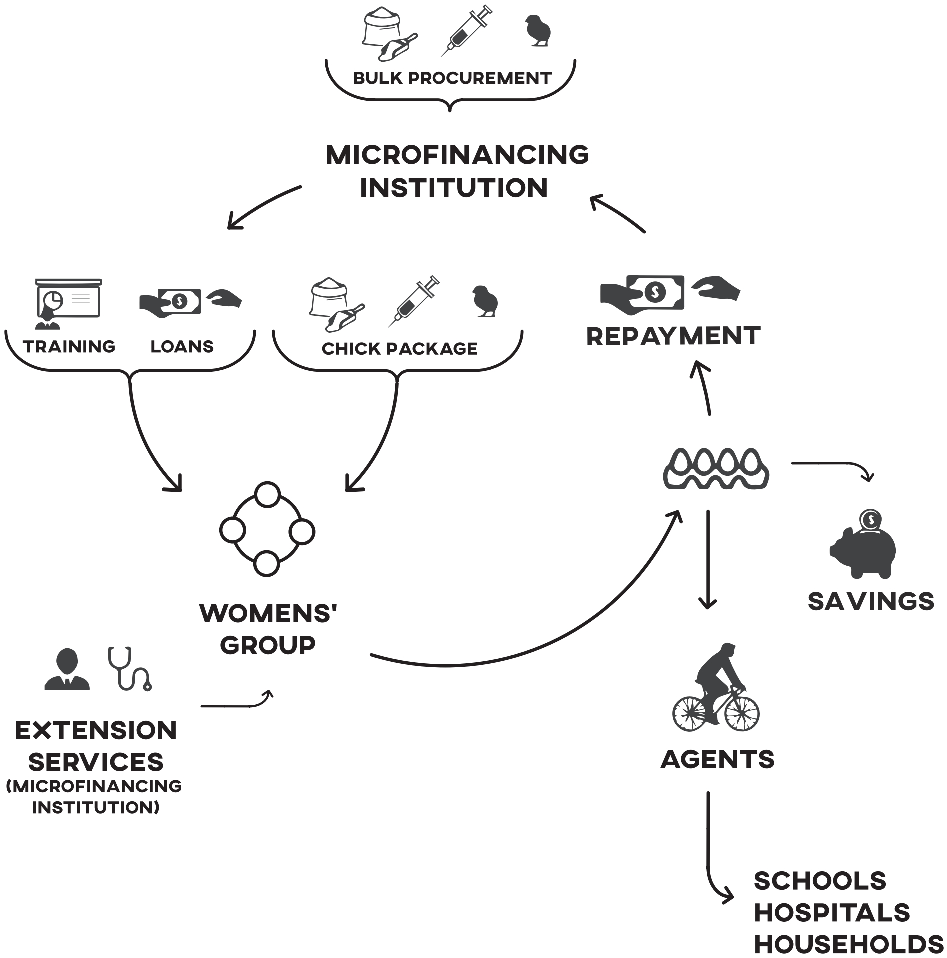

FIGURE 2 Microfinancing model

the MFI which, after covering its costs, is used to expand its coverage to other locations. We found two MFIs in Kenya and Malawi providing asset-backed loans for small-scale poultry farmers. Their group lending structure, working through self-help groups, minimizes risk for default. The MFI also advises the farmers on good suppliers of assets and inputs: brings technical partners to provide training to farmers while giving the farmers the flexibility to select where to sell or where to invest in the business process. Informal saving groups are common in Kenya, and hence this model is relatively more straightforward to set up compared with the previous models. For example, in Kenya, the MFI reaches more than 32,000 farmers across 14 counties whereas the one in Malawi covers 86,000 clients across 17 districts. Moreover, microfinance is a familiar concept among farmers. In the Kenya model, a farmer starts with a small loan of approximately USD 400. She earns USD 600 per year with 50 chickens. Through regular payments, she can graduate to a more substantial loan amount, which she invests to expand flock size. Farmers typically expand from 50 chickens to 100 and then to 200 chickens reaching productivity levels of 200 eggs per bird. They also expand their ownership in the value chain by setting up their own hotels or food kiosks in the village that buy the eggs produced by their own farms. Critical success factors in this model are encouraging farmers to diligently save earnings however small it may be; weekly meetings where farmers learn about new products, practices, share ideas, and support each other; and farmer groups organized to bargain for better deals with input suppliers and distributors to markets.

3.3 | Model 3: Co-operative farming

In a co-operative farming model, many farmers own and jointly run the enterprise and share the profits and benefits (Figure 3). A not-for-profit organization in central India has pioneered the co-operative model for poultry farming successfully with nearly 10,000 farmer-owners in two units. Most of the farmer-owners are women belonging to vulnerable communities who were engaged in manual labour and wood collection before the establishment of the co-operative. Interested women were organized into groups and provided training in poultry rearing and management practices. Once the training was over, farmers were provided with part loan and part grant amount for construction of sheds. Each entrepreneur started operations with 300 to 400 chicks and currently operate 600 to 1000 birds per batch with productivity levels of 220 eggs per bird per year. About 25 to 30 such sheds are located within a tight cluster, enabling the enterprise to achieve production and cost efficiencies usually seen in large-scale production. Each cluster is supported by a para-veterinary technician hired with a small fixed fee and performance-based variable pay and a village store for delivery of inputs at the doorstep. The co-operative is vertically integrated, owns and operates hatcheries, feed mills,

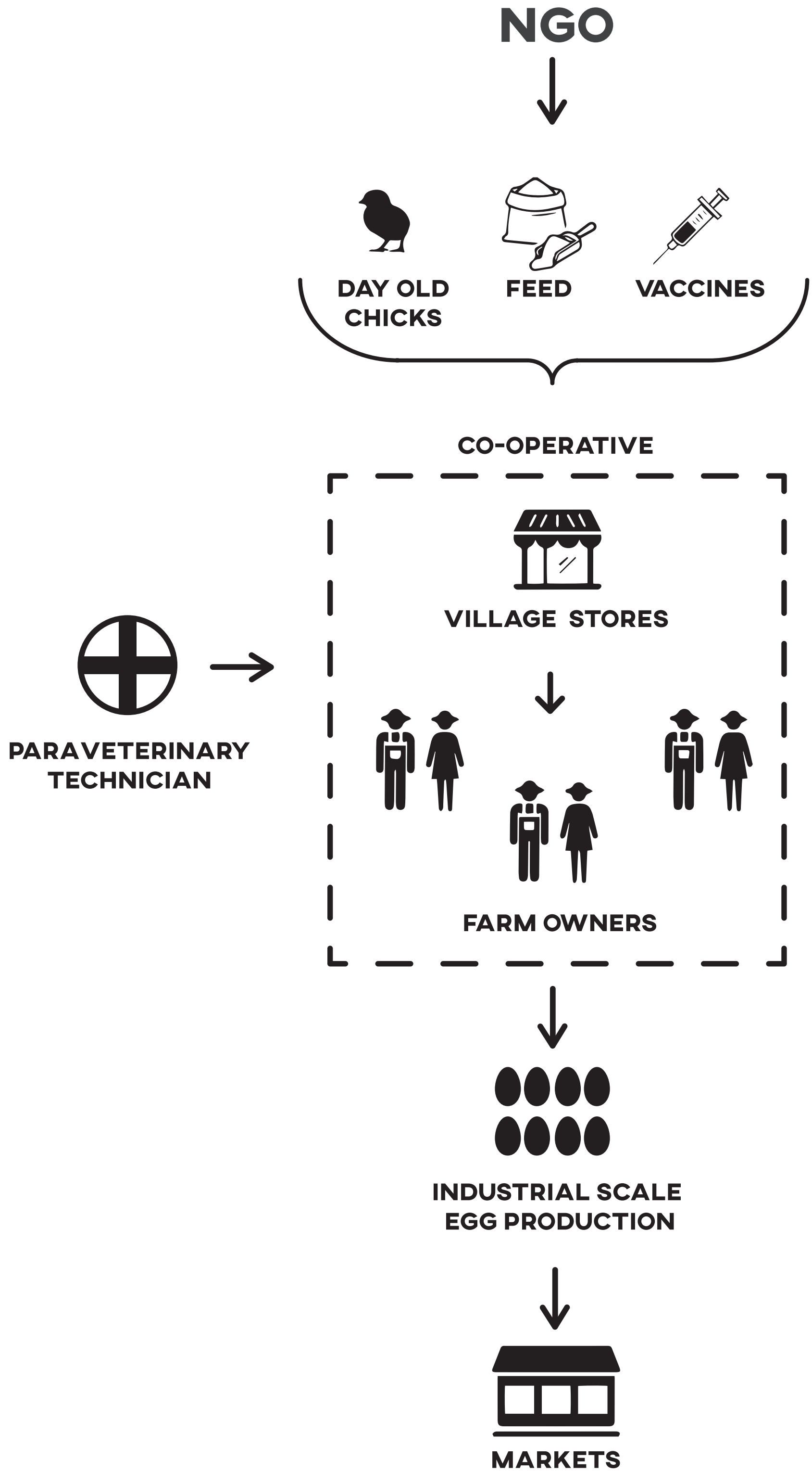

FIGURE 3 Co-operative farming model. NGO: nongovernmental organization

procurement, and retail outlets. The enterprise has a collective turnover of USD 58 million. Each farmer has a net income of USD 620 to USD 780 for 200 working days as a part-time engagement.

3.4 | Model 4: Enterprise development

At the core of this model is an input supplier who organizes the backyard farmers into small groups and supports them to set up and develop an enterprise. Such support includes the provision of input package with credit, training, and access to markets to sell eggs. Farmer groups are encouraged to buy improved feed and other inputs from the supplier at wholesale rates. Farmers sell eggs primarily in their communities. Any excess eggs are transported to urban markets through the trucks of the input supplier that are used to deliver feed to the farmers (Figure 4). An example of this model is an integrated poultry company in Malawi. A breeder of DOCs, the company has extended its business

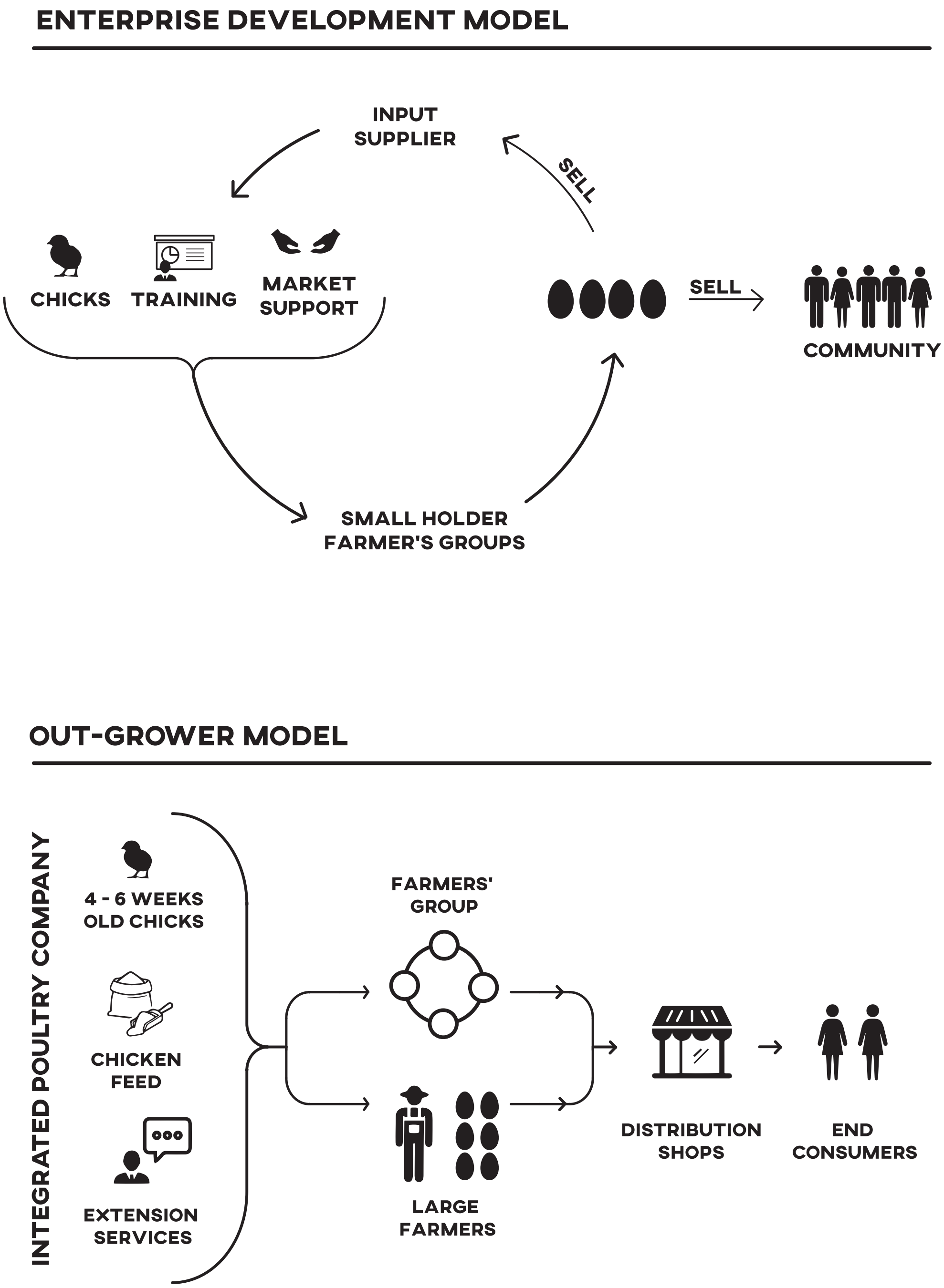

FIGURE 4 Enterprise development model and outgrower model

to include commercial broiler and layer hatcheries and farms, poultry vaccines, extension services, and feed mill. The company aggregates five backyard or smallholder farmers into one group to establish a medium-scale farm of 5,000 to 6,000 birds, that is, each farmer is supplied with 1,000 to 1,200 sixteen-week-old birds (near point-of-lay). Point-of-lay birds have lower mortality than DOCs. The risk for the farmer is lowered in this model as the company broods DOCs to point-of-lay birds in a high quality of care and temperature-controlled environment. The company provides cages, biosecurity clothing, and inputs on credit for the first production cycle. Farmers are trained in flock, enterprise and financial management, marketing of eggs, and learn to save through a revolving fund to be able to buy inputs regularly. Productivity level of the hens starts at 70% (255 eggs per bird per year) and reaches at least 80% by the end of the second year. Capital expenditure, spent on land, shed, cages, and other assets, of nearly USD 29,000 incurred by the group of farmers, is recovered in 3 years. Recurring capital required for subsequent laying cycles is much lower, which is usually available to the group from sales of spent birds from the first cycle. Though the capital needed is high in this model, ongoing program costs are quite low. Every farmer makes a net income of USD 144 per month, which is 2.3 times more than Malawi's minimum wage rates.

Two factors are critical to the success of this model. First, the model is feasible only when an integrator is committed to building robust technical capacity with farmer groups and sells inputs to them at wholesale prices. The integrator may not profit in the short-term but benefits from sustainable gains in the long term as overall market

TABLE 1 Comparison of business model elements in micro-franchising, microfinancing, co-operative farming, enterprise development, and outgrower models to backyard poultry

Model characteristics	Backyard poultry operations[a]	Model 1: Micro-franchising	Model 2: Microfinancing	Model 3: Co-operative farming	Model 4: Enterprise development	Model 5: Outgrower model
Description	A low-input and low-output system; birds are reared in household backyards where they scavenge on kitchen and farm waste.	Hatchery sells day-old-chicks to micro-franchisee agents who rear them until they are 4 to 6 weeks old; agents in turn sell them to backyard and smallholder farmers.	Microfinancing institution procures inputs and distributes them to its smallholder farmer clients with tailored loan packages.	Many farmers co-own and run a poultry enterprise and share profits and benefits. Each member operates a small farm on their own land. The co-operative buys inputs and services for its members.	An input supplier aggregates a group of five backyard farmers to set up and own the farm. Eggs produced are sold in communities; excess eggs are collected by the input supplier and sold to other markets.	Contract between a company and independent farms; the company sells inputs and services to the farms and guarantees buy-back of eggs.
Beneficiaries	Households rearing backyard vpoultry	Households rearing backyard poultry	Small-scale farmers	Small-scale farmers	Smallholder farmer groups	Medium-scale farmer or smallholder farmer groups
No. of farmers owning each farm	1	1	1	1	5	1
Flock size (No. of birds per farm)	20	20	50	800	5,000	5,000
Productivity (eggs per bird per year)	40	100	200	220	290	290
Mortality	60%	25%	20%	15%	7%	7%
Input and services adopted	None	Point of lay birds, improved feed	Input package, loans, training, extension services, and access to markets	Input package, infrastructure, training, loans, and access to markets	Input package, credit, training, and access to markets	Input package, technical and veterinary assistance, and regular farm visits
Frequency of use of inputs	Never	Rarely	Sometimes	Regular	Regular	Regular
Access to extension services	Never	Sometimes	Sometimes	Regular	Regular	Regular
Extent of biosecurity	Low	Low	Low	Medium	High	High
Access to markets	Households, communities, and village markets	Barter and sell within village community	Sold in village markets	Sold through own retail shops	Sold in village markets, communities; excess eggs bought by the integrator	Bought by the commercial entity

(Continues)

size in rural areas increases. Second, frequent and adequate training and availability of low cost credit is necessary to improve farmer's initial adoption and consistent use of inputs and services (high-quality feed, vaccine, and veterinary services) for subsequent laying cycles: a practice that is missing in small-scale farms.

3.5 | Model 5: Outgrower model

An outgrower model is a contract between independent farmer groups (five farmers managing 5,000 birds) or a single farmer with a minimum farm size of 5,000 birds and a commercial entity. The commercial entity provides chicks, input package, technical and veterinary assistance, and regularly visits the farmers, that is, two to three times a week to discourage from selling to others, assure quality, and ensure regular procurement of target quantity of eggs (Figure 4). The organizer buys back all eggs from the farmer groups and distributes them through its own retail channels. A medium size layer farmer in Kenya who also owns a feed mill is piloting this model to source eggs from contracted smallholder farmers for sale through its own branded retail stores in peri-urban areas. The smallholders have a low risk in this

TABLE 1 (Continued)

Model characteristics	Backyard poultry operations[a]	Model 1: Micro-franchising	Model 2: Microfinancing	Model 3: Co-operative farming	Model 4: Enterprise development	Model 5: Outgrower model
Economic characteristics						
Start-up capital[b] required per farm (USD)	10	~70	~600	2,500	~30,000	~30,000
Recurring capital[c] per laying cycle (USD)	10	60	150	~1000	~9,000	~9,000
Minimum no. of farms required to set up the model	n/a[d]	120	15	30	1	1
Minimum capital required to set up the model (USD excl. program management costs)	n/a	~8,000	~8,000	75,000	~30,000	~30,000
Number of eggs produced per farm per year	320	1500	8000	~0.15 million	~1.35 million	~1.35 million
Start-up capital[b] required per egg produced (USD)	0.031	0.044	0.069	0.017	0.022	0.022
Recurring capital[c] required per egg produced (USD)	0.0313	0.04	0.0188	0.0074	0.0065	0.0065
Program cost per egg produced (USD)	n/a	0.24	Data not available	0.02	0.03	0.03
Each farmer's net annual income (USD)	~40	~75 to 150	600	~600 to 800	~1,700	~2,200 to 5,000[e]

Note. USD: US Dollars.

[a]Akinola & Essien, 2011.

[b]Money required to start a poultry farm: includes infrastructure (building and cages) and starter pack. For Model 3 and backyard poultry, includes starter pack only.

[c]Money required to repopulate chickens after one laying cycle. Farmers typically use sales proceeds to buy next cycle of chickens.

[d]n/a: not applicable.

[e]USD 2,200 per farmer if it is a group of five farmers and USD 5,000 for a single farmer managing a flock size of 5,000 birds.

model due to guaranteed price and quantity agreements and performance incentives for excess eggs. Capital requirements for the farmer and program costs for the company are the same as the enterprise development model. Outgrower farming can help increase production capacity of commercial players without significant capital investment as the farmer groups use their own farm for production. However, this model requires the commercial entity to have a sophisticated network of own or shared dealers and distributors to be able to transport fresh eggs quickly. The farmer groups and integrator need to be in close vicinity. Remotely located villages cannot be chosen since aggregation of eggs will become costly. Due to poor road infrastructure, transportation of eggs is usually limited to an area of 5,000 km^2. To expand outgrower models to remote rural areas, a one-stop hub for distribution of inputs, extension services, and eggs would be needed. The company usually invests in marketing of its branded eggs through community events, radio advertisements, banners, posters, wall paintings, and billboards. Due to constant checks and rigorous quality control procedures deployed by the company, the productivity of hens is high at 80% or more that also translated into more value for the farmers. Identifying committed and diligent farmers is a crucial factor for this model to succeed.

4 | DISCUSSION

More than 80% of chickens in East Africa and 50% in India are extensively raised, that is, in the backyards (Gilbert et al., 2015). Despite economic growth and known health benefits, availability of eggs per capita per year is very low: nine in Ethiopia, 27 in Malawi, 46 in Kenya, and 60 in India (FAOSTAT, 2013). Our analysis describes business models that engage smallholders in improving egg availability in these four countries. We found that these models were successful in improving hen productivity from an average of 40 eggs per bird in the backyard setting to a minimum of 100 eggs per bird in the micro-franchising model (Model 1) and a maximum of 290 eggs per bird in the enterprise development and outgrower model. Models with flock size of more than 200 birds per farm could achieve self-sufficiency in 3 years and thus become independent from investors and donors. However, to scale, flexible funding or patient capital would still be required. All of them have access to soft loans, use improved inputs, and extension services, to varying degrees. These inputs include resilient breeds of DOCs or point-of-lay hens, feed, vaccines, medicines, and housing. Integrators in Models 4 and 5 and NGOs as aggregators in Models 2 and 3 organize the value chain for smallholder farmers, lowering cost of reach and improving access to markets.

Model 1, micro-franchising is an improved backyard situation. Despite light capital requirements, the micro-franchising model struggles to breakeven or operates with slim margins. This model has the lowest productivity and the highest program costs as it must create a vast agent network to reach rural households and train individual backyard farmers. Moreover, weak extension services and nonavailability of inputs for subsequent laying cycles for backyard farmers make it difficult to sustain improved productivity. Therefore, this model must also service larger farms to sustain investment in developing the distribution network for inputs and services.

Microfinancing and cooperative farming offer encouraging alternatives for the micro-franchising model where backyard farmers can instead be transitioned to own and rear up to 800 birds. This means hens would be more than an asset or insurance and be a primary source of income while also increasing egg production. In these two cases, farmers earn 5 times more than in Model 1. By aggregating farmers into small groups, recurring capital and program costs for each egg produced are significantly lower than the micro-franchising business model.

The vast presence of microfinance organizations in LMICs is a promising channel to leverage for increased egg production in rural areas. Since NGOs and MFIs would not have poultry farming expertise, they would need to engage a wide range of partnerships from parastatals who often have veterinary and other extension services or subsidies for smallholders to input suppliers as an anchor buyer and coordinate activities along the value chain. The co-operative model from India must be considered as a unique scenario and may not be feasible in Sub-Saharan Africa. This is because India has a thriving and rapidly growing input industry, thus making procurement at affordable prices possible for NGOs. India is the third largest producer of eggs in the world, mostly driven by medium- and large-scale farms (Mehta & Nambiar, 2007) leading to the development of a flourishing input industry around these larger farms.

Private companies developed Models 4 and 5. They are an input supplier of DOCs in Malawi and a large-scale layer farmer in Kenya. These two models have stringent biosecurity measures, large flock sizes, follow best practices in flock and farm management, and hence have a very high and steady productivity of 70% or more. Despite heavy capital requirements, with each farm producing more than a million eggs every year, they are best placed to increase egg availability in rural areas and minimize losses due to a disease outbreak. Neither commercial player had any immediate, short-term profit but would have long-term sustainable gains through increased market share. Smallholder farmers in these two models spend up to 10 hr a day and have high annual incomes of nearly USD 2,000, that is, 2 to 15 times more than the farmers in the other models. Further, capital and program costs per egg is the lowest, thereby eggs produced can be made affordable to the consumer.

Favourable policies in the form of soft loans or subsidies are needed for the private sector to establish outgrower model or the enterprise development model in rural areas to rapidly increase egg production. Catalysing investments across the value chain, especially in the layer input sector would encourage NGOs to establish co-operatives and MFIs to support the transition of backyard farmers to more economically viable, intensive production models.

There are a few limitations in our study. First, we rely on the information provided by the social enterprises themselves. Triangulating with a market study would make our analysis more robust. Further, an extensive due diligence is needed to assess their economic, social, and environmental impact in the communities they serve. Second, we have not explored whether increased productivity of the layer hens in these models leads to a steady supply of eggs at affordable prices throughout the year in the communities. Third and most importantly, future research should consider whether improving availability and affordability of eggs through such business models will increase consumption among the most vulnerable groups, women, and children. This is important because price is a significant predictor of consumption of eggs in children. Low supply of eggs in lower income countries due to low productivity of egg production and the perishable nature of shell eggs appears to contribute to high prices of eggs (Headey, Hirvonen, & Hoddinott, 2017).

In conclusion, this study contributes to the global literature on approaches and elements required for extensive or backyard poultry farmers to adopt semi-intensive or intensive farming in LMICs. Four of the models we investigated have invested in the aggregation of smallholders to become more economically savvy trading partners and capitalize on economies of scale. These models are advanced by diverse actors: private companies, NGOs, and microfinance institutions. They developed specialized skills in brooding, feed milling, aggregation, and training of farmers or large-scale rearing of hens to ensure that their business models are viable and profitable. The five archetypes we see are essential ways to increase egg availability in rural areas with the outgrower model showing remarkable promise for rapidly increasing egg production.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

KB and KK conceptualized the vision and the need to find viable models. KB designed the framework and participated in data collection, analysis, interpretation of findings, and drafting of the manuscript. SL assisted in data organization and drafting of the manuscript. KB, SL and KK contributed to the interpretation of findings and the critical revision of the manuscript for final submission. All authors approved the draft.

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SUPPLEMENT ARTICLE

WILEY Maternal & Child Nutrition

Family poultry: Multiple roles, systems, challenges, and options for sustainable contributions to household nutrition security through a planetary health lens

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Abstract

Achieving sustainable production of eggs by family poultry production systems that meet both environmental health and welfare standards is a complex endeavour. Humans have been raising different species of poultry for thousands of years across many different agroecological zones. The Food and Agriculture Organization of the United Nations has identified four different family poultry production systems: small extensive, extensive, semi-intensive, and intensive. Each of these systems varies in terms of inputs, outputs, gender dimensions, poultry health and welfare, and environmental impacts. This paper addresses key issues associated with the production of family poultry eggs in support of both improved maternal and child nutrition and sustainable, nutrition-sensitive agricultural practices. It provides an overview of the history of poultry raising; characteristics of the different family poultry production systems; challenges and solutions to poultry production in low- and middle-income countries; poultry husbandry (including breeds, nutrition, and shelter); infectious disease prevention and control in line with national and international animal health regulations; and food safety (microbial pathogens, toxins, and egg storage). To ensure that bird, human, and environmental health can flourish, it is essential for interdisciplinary research and development teams to work in collaboration with communities to ensure the long-term environmental and economic sustainability of family poultry production enterprises that are a good fit with local circumstances.

KEYWORDS

food security, maternal and child nutrition, nutrition-sensitive agriculture, smallholder poultry, sustainable food production

1 | INTRODUCTION

Humans have been raising poultry for thousands of years. Archaeological evidence suggests that domesticated chickens existed in China at least 8,000 years ago with subsequent spread to Western Europe and other parts of the world by land and by sea. Domestication of chickens from the Red Jungle Fowl may have occurred separately in South and Southeast Asia. Domestic chickens appeared in Africa many centuries ago; they are now an established part of African life (Alders, 2004).

Poultry are domesticated avian species that are raised for eggs, meat, and feathers. The term poultry includes chickens, turkeys, guinea fowls, ducks, geese, and other species often considered game such as quails, pigeons, and pheasants. Chickens constitute about 90% of the poultry population and are, by far, the most important poultry species in all parts of the world (Food and Agriculture Organization, FAO, 2014). Up until the 20th century, poultry were generally raised under "extensive systems," a term used to describe a practice where birds are largely free ranging and dependent on scavenging, with some supplementation of feed where birds were raised in larger numbers or on tracts of land where the scavenging feed resource base could not sustain them. Since the end of the Second World War, the production of poultry meat and eggs has increased dramatically due to the rapid growth of the intensive commercial poultry industry (Speedy, 2003). The selection of high yield meat and layer breeds has been shaped by agricultural value chains where commodities are priced on weight with little regard for nutrient profiles.

In relation to international development activities, a range of approaches has been employed to promote improved poultry production, including egg production, with varying degrees of success. Sustainability of small-scale layer chicken projects has met with mixed results in peri-urban areas and proved largely elusive beyond the end of external support in rural areas, frequently due to inadequate access to essential and affordable inputs (Alders & Pym, 2009). In unimproved extensive poultry systems, where mortality rates are high, eggs are rarely consumed by women and children, as they are preserved for hatching of replacement birds (Alders et al., 2003; de Bruyn, Bagnol, et al., 2017). Lessons learnt have been incorporated into the "Decision Tools for Family Poultry Development" manual (FAO, 2014). This FAO toolkit is designed to assist the development of feasible and appropriate family poultry projects via a stepwise decision-making process, as a considerable proportion of development projects and programs are implemented in ecologically fragile areas where vulnerable households have to overcome poverty while also protecting the lands and natural resources on which their livelihoods depend. In addition to this manual, key reference material relating to the sustainable production of family poultry for each specific production system is listed in Table 1.

In 2015, the United Nations launched the Sustainable Development Goals, a suite of goals that define key development indicators applicable to all member countries (U.N., 2015). Also in 2015, *The Lancet* and The Rockefeller Foundation launched the Planetary Health concept—the health of human civilization and the state of the natural systems on which it depends (Horton & Lo, 2015). These frameworks provide an opportunity for all development activities, including poultry development and human nutrition projects, to contribute to achieving long-lasting positive changes both locally and globally. In relation to poultry production, as poultry are monogastric omnivores, they can potentially compete with people for the same foodstuffs (FAO, 2014). Agriculture is estimated to be responsible for approximately 10% of anthropogenic greenhouse-gas emissions (Tubiello et al., 2015), and in relation to poultry, this includes not only the production of poultry products themselves but also all the inputs required to support this production. In terms of animal-source food (ASF), the production of poultry eggs has been found to contribute lower levels of greenhouse-gas emissions, with emission levels varying across production systems and opportunities for further reduction by using alternative feedstuffs (Taylor, Omed, & Edwards-Jones, 2014).

Key messages

- Family poultry have been raised for thousands of years and continue to be raised in expanding numbers under a range of production systems across many different agroecological zones.
- Achieving sustainable production of eggs that meets both environmental health and welfare standards is a complex endeavour.
- Family poultry production requires attention to husbandry practices, disease prevention and control in line with national and international animal health regulations, and food safety.
- Interdisciplinary research and development is required to ensure the long-term environmental and economic sustainability of family poultry production enterprises that are a good fit with local circumstances.

Smallholder poultry producers commonly operate in resource-limited situations, employing a range of activities to achieve sustainable livelihoods. Under these conditions, poultry fulfil a range of functions from income generation to strengthening social cohesion (Alders & Pym, 2009). This paper aims to highlight key issues associated with ecologically and financially sustainable smallholder poultry production and factors that must be taken into account to achieve increased egg consumption in support of both improved maternal and child nutrition and sustainable, nutrition-sensitive agricultural practices.

2 | METHODS

2.1 | Review of literature

To capture as many relevant references as possible, two approaches were adopted: (a) Co-authors involved with family poultry research and development from differing geographies and disciplines were identified, and (ii) scientific databases were searched to identify primary studies and reviews of family poultry health and production with internet search engines utilized to identify web pages that might provide references. Relevant studies, reviews, and manuals were then selected for review. Their potential relevance was examined, and nonrelevant citations were excluded. The full text of the remaining references was assessed to select publications with a primary focus on family poultry that directly related to the theme. To ensure the number of references cited was kept to a manageable number, preference was given to literature meeting the above criteria and that was also available via open access sites. References were drawn mainly from low- and middle-income countries (LMICs) where family poultry play a major role in household livelihoods and nutrition security.

TABLE 1 Key references for essential components and history of family poultry production

Component	References: Extensive	Semi-intensive	Intensive
History	Alders, 2003		FAO, 2004
Introduction to family poultry production systems	Alders & Spradbrow, 2001; FAO, 2014	FAO, 2014	FAO, 2004, 2014
Roles (food, financial, and sociocultural security) of poultry including gender and livelihood strategy dimensions	Alders, 2003; FAO, 2014	Alders, 2003; FAO, 2014	Alders, 2003; FAO, 2014
Challenges and solutions to poultry development in low- and middle-income countries over the past 50 years	FAO, 2010 FAO, 2014	FAO, 2010 FAO, 2014	FAO, 2010 FAO, 2014
Poultry husbandry Breeds Nutrition Shelter Sanitation and waste management	Ahlers et al., 2009; FAO, 2010; FAO, 2014	FAO, 2014	Czarick and Fairchild, 2008; FAO, 2004
Infectious disease prevention and control	Ahlers et al., 2009;	Damerow, 2015;	Damerow, 2015;
National animal health regulations in relation to importation and use of veterinary pharmaceuticals (vaccines, antibiotics and vitamins and minerals)	Alders et al., 2003; FAO, 2014	FAO, 2014	FAO, 2004
Food safety			
Microbial pathogens, environmental enteropathy disorder	Ahlers et al., 2009;	FAO, 2014;	FAO, 2014;
Toxins	FAO, 2014;	Zambrano et al., 2014	Zambrano et al., 2014
Egg storage under resource-poor conditions	Zambrano et al., 2014		
Physical testing for fitness for human consumption			

2.2 | Conceptual framework

A conceptual framework was developed and employed to guide the structure of this paper, providing a sound foundation in relation to achieving the desired outcomes of egg consumption, dietary diversity, child growth, and development in association with family poultry production. Figure 1 illustrates the alignment of sustainable family poultry production systems with prevailing agroecological and socio-economic conditions and appropriate management practices that include (a) selecting appropriate poultry species and breeds that can be sustainably managed under local conditions in terms of nutrition and shelter; (b) infectious and non-communicable disease prevention and control, especially of diseases causing high mortality; and (c) risk management in terms of food safety, sanitation, and nutrition security.

2.3 | Family poultry production systems

"Family poultry" is a term used to describe the full variety of small-scale poultry production systems that are found in rural, peri-urban, and urban areas of LMICs. Rather than defining the production systems per se, the term is used to describe poultry production practised by individual families as a means of obtaining food security, income, and gainful employment (FAO, 2014). The classification of poultry production systems developed by the FAO of the United Nations described in Table 2 was applied in the framing of this paper.

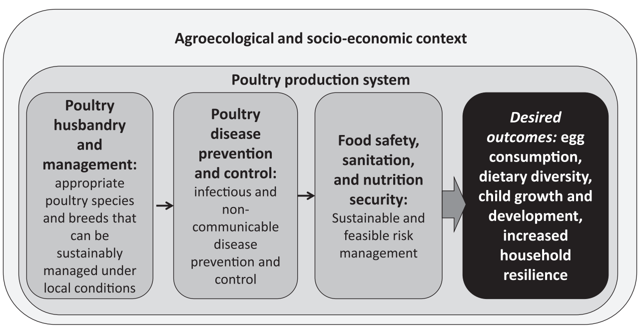

FIGURE 1 Key considerations to achieve sustainable egg production for improved maternal and child nutrition in resource-poor settings

3 | POULTRY PRODUCTION SYSTEMS

Family poultry can be found in all countries and play a vital role in many resource-limited rural and peri-urban households (Alders, 2004; Alexander, Bell, & Alders, 2004). In vulnerable households, they provide scarce ASF in the form of meat and eggs and can be sold or bartered to meet essential family needs such as medicine, clothes, and school fees. Free-ranging village poultry are active in pest insect control, provide manure, are required for special events, and are essential for many traditional ceremonies. The output of village poultry is lower than that of intensively raised birds, but it is obtained with minimum inputs of housing, disease control, management, and supplementary feeding (Table 2).

Different ways of characterizing family poultry production have been suggested based on criteria such as size of flock, management, and purpose of production including degree of commercialization and location (FAO, 2004). For the purpose of conducting a situation analysis and planning a development intervention, FAO (2014) identified four family poultry production systems:

- small extensive scavenging;
- extensive scavenging;
- semi-intensive;
- small-scale intensive.

TABLE 2 Characteristics of the four family poultry production systems

Criteria	Small-extensive scavenging	Extensive scavenging	Semi-intensive	Small-scale intensive
Production/farming system	Mixed, poultry and crops, often landless,	Mixed, livestock and crops	Usually poultry only	Poultry only
Other livestock raised	Rarely	Usually	Sometimes	No
Flock size	1–5 adult birds	5–50 adult birds	50–200 adult birds	>200 broilers >100 layers
Poultry breeds	Local	Local or cross-bred	Commercial, cross-bred or local	Commercial
Source of new chicks	Natural incubation	Natural incubation	Commercial day-old chicks or natural incubation	Commercial day-old chicks or pullets
Feed source	Scavenging; almost no supplementation	Scavenging; occasional supplementation	Scavenging; regular supplementation	Commercial balanced ration
Poultry housing	Seldom; usually made from local materials or kept in the house	Sometimes; usually made from local materials	Yes; conventional materials; houses of variable quality	Yes; conventional materials; good-quality houses
Access to veterinary services and veterinary pharmaceuticals	Rarely	Sometimes	Yes	Yes
Mortality	Very High, >70%	Very High >70%	Medium to High 20% to >50%	Low to Medium <20%
Access to reliable electricity supply	No	No	Yes	Yes
Existence of conventional cold chain	No	Rarely	Yes	Yes
Access to urban markets	Rarely	No, or indirect	Yes	Yes
Products	Live birds, meat	Live birds, meat, eggs	Live birds, meat, eggs	Live birds, meat, eggs
Time devoted each day to poultry management	<30 min	<1 hr	>1 hr	>1 hr

Note. Source: FAO, 2014.

Although this range of systems may be viewed as a continuum, family poultry farmers utilize the production system that best suits their situation and objectives (FAO, 2014). Small extensive, extensive, and semi-intensive poultry productions are common components of mixed agricultural farming systems involving crops and other livestock and permit vulnerable households to spread risks (FAO, 2014).

4 | THE MULTIPLE ROLES OF FAMILY POULTRY

It is important to remember that family poultry fulfil multiple roles within household livelihood strategies beyond improving maternal and child nutrition. Extensively and semi-intensively raised poultry are generally owned and managed by women and children and are often essential elements of female-headed households (Bagnol, 2001). In many regions of the world and unlike other livestock species, women have the possibility of making the decision to sell and/or consume poultry meat and eggs without need to formally negotiate with their husband/partner (Dumas et al., 2017). This happens often in a situation in which poultry, especially chickens, are one of the only assets over which women have some degree of relative control. For this reason, chickens play an important role in women's economy and women's capacity to carry out her responsibility of caring for home and family issues (Bagnol, 2001, 2009; de Bruyn, Wong, Bagnol, Pengelly, & Alders, 2015; Dumas et al., 2017). Chickens are often considered the petty cash, that is, the smallest financial reserve, of the household, as they are sold to solve regular needs such as buying school materials, uniforms, or paying fees; going to the hospital.; buying medicine or offering a chicken to a traditional healer; and buying sugar, salt, oil, or other household items. Chickens are also extremely important for exchanging against goods, services, or to consume when there is a guest, or for rituals and ceremonies. This is particularly true when chickens are kept in small quantities at village level (Bagnol, 2009) in scavenging flocks of indigenous breeds in communities throughout low-income, food-deficit countries. In these settings, chickens contribute to human nutrition, livelihood, and sociocultural activities (Sonaiya, 2007). Their contributions to food availability are both direct, through supplying nutrient-rich and culturally acceptable products for consumption, and indirect, through the sale of chickens and eggs to buy food staples, and through the provision of manure and pest insect control in association with vegetable and livestock production (Wong et al., 2017). It is common for livestock to fulfil multiple roles within households in resource-limited settings, and livestock ownership does not necessarily translate to increased utilization of ASFs (Turk, 2013), as they may be used for sale or exchanged to fulfill other needs. However, family poultry utilization across all of these roles is high (Azzarri, Cross, Haile, & Zezza, 2014). This is due to their small size, short production cycles, and availability in most rural households, a situation that makes them more likely to be consumed, exchanged, or sold in times of need, compared with larger livestock. Chickens are particularly important in times of hunger where they are the first livestock to be sold to buy cheaper food (Bagnol, 2001) or slaughtered before higher valued animals such as pigs, goat, or cattle (Dumas et al., 2017).

It has been reported that when an activity becomes lucrative, men who previously were not involved in the activity tend to take over from women (Mayoux, 2009). Such a situation highlights that poultry development interventions may not automatically result in an improvement of women's and household's situation if subsequent increased economic benefits incentivizes men to take over flock management. In larger chicken production systems, men have tended to be in control (Sambo et al., 2015), whereas women may continue to contribute a significant portion of the required labour. Given this potential, it is critical that poultry development projects include an explicit gendered lens to avoid eroding women's control over this important livelihood activity.

5 | SUSTAINABLE POULTRY HUSBANDRY AND MANAGEMENT

The production of poultry meat and eggs has risen dramatically over the past 50 years (Speedy, 2003), and most of this increase occurred due to the intensification of production. Although this increase has been hailed as a great success in economic terms, questions are now being asked of poultry production in terms of animal welfare (Nicol & Davies, n.d.); antimicrobial resistance (Goetting, Lee, & Tell, 2011); and the nutritional profile of poultry products (Wang, Lehane, Ghebremeskel, & Crawford, 2009).

5.1 | Breeding and reproduction

Genetically improved specialized meat or egg-type chickens are widely available and are used by the large majority of large-scale commercial poultry producers and companies. These birds have been bred exclusively for meat or egg production and require high-level nutritional and health management inputs to reach their genetic potential (FAO, 2014).

General-purpose indigenous breed birds are raised widely in the rural regions of nearly all LMICs (Alders & Pym, 2009). In contrast with the above specialized breeds, these birds have, for the most part, considerably lower genetic potential for meat and egg production but are able to survive, reproduce, and produce meat and eggs in the often harsh, semi-scavenging village environment. Nevertheless, there is significant variation in productivity between indigenous breeds and ecotypes across different regions, within and between countries, as well as in the climatic and nutritional environments experienced by the birds.

In addition to these two broad types, a number of dual-purpose breeds/crossbreds are available in certain regions. These have been bred exclusively to yield relatively good meat and egg production under moderate climatic and nutritional management conditions, rather than the optimal conditions required by specialized meat and egg types. Commercial layers developed from imported parent stock have the capacity to lay more than 300 eggs per year, whereas crossbred hens lay approximately 200 eggs per year, and indigenous hens often lay only 40 to 60 eggs per year (FAO, 2004; Pym & Alders, 2016). Even when these indigenous hens are placed in laying cages and given ad libitum access to good-quality layer diets, their laying performance is much lower than commercial layers ranging from 63 to 165 per year (FAO, 2010; Pym & Alders, 2016).

Genetic potential to produce eggs aside, a major cause of the five to eightfold difference in egg production is the time—about 13 weeks—that a broody indigenous hen spends laying and hatching a clutch of eggs and rearing the chicks to about 7 weeks of age (FAO, 2014; Pym & Alders, 2016). During the hatching and rearing time, the hen does not lay, which shortens the remaining egg production time. This means that the indigenous hen can produce about 3–4 clutches per year only. As the capacity for broodiness has been bred out of commercial-strain layer hens (i.e., they are incapable of natural reproduction), under the right levels of lighting and nutrition, they lay continuously rather than in clutches.

To achieve a laying rate corresponding to more than 300 eggs per year, under confinement housing, a commercial layer hen requires approximately 100–110 g of a high quality layer diet, containing 11.7 MJ metabolizable energy, 180 g crude protein, and 35 g calcium per kg of weight, per day. The typical scavengeable feed resource base would provide well under half of this, which means that if reasonable productivity is required, these birds are unsuitable for unsupplemented extensive production systems. Additionally, chickens are photoperiodic and respond to daylight by timing reproduction so that it takes place at a time when feed is more likely to be plentiful, which means that, in the absence of artificial lighting, hens will lay the majority of their eggs during the spring and summer months when daylight hours are increased.

Under intensive production systems, there is a very good argument for using genetically improved meat or egg genotypes, or at least intermediate performing crossbred birds. The low productivity of indigenous breed birds, even under high-level management and nutrition, does not warrant their use under intensive management, unless the premium paid for their eggs and meat compensates for their generally much lower performance (Pym & Alders, 2016). Due to the short duration of most development projects, the ability to influence the genetic potential of either the genetically improved egg or meat birds, or of the indigenous breed birds, is limited. Short-term gains may be made by crossbreeding with higher producing breeds providing that all husbandry requirements to support higher productivity can be met. Longer term approaches to selecting for improved egg production traits amongst locally adapted birds are likely to yield more sustainable improvements (FAO, 2010).

5.2 | Poultry nutrition

Proper nutrition is essential for flock health, survival, and productivity. Poultry are monogastric omnivore animals requiring at least 38 nutrients in proper balance, and this balance varies by poultry type, genetic strain, body size, and age, as well as the ambient temperature, level of physical activity, and presence of stressors (e.g., disease; Klasing, 2016). In addition, egg quality is influenced by certain nutrients and dietary feed formulation with insufficient or excessive nutrients in feed leading to poor-quality eggs (Wang, Yue, Wu, Zhang, & Qi, 2017). It is important to note here that the nutritional content of eggs listed in national food composition tables in LMICs is often imported from U.S. or U.K. databases and so may not accurately reflect the local situation (de Bruyn et al., 2016).

The National Research Council (United States) has published the minimal nutrient requirements for egg laying hens derived from the literature (Table S4; National Research Council, 1994; Leeson, 2011). Compared with other poultry, the calcium requirement for laying hens is particularly high to meet the demands of eggshell development. This is especially true for older or high-producing hens, who require additional dietary calcium to maintain eggshell strength (Klasing, 2016).

For extensively raised indigenous chickens, these nutritional requirements are primarily met by scavenging, coupled with occasional supplementary feeding of home-grown grains and household food waste. Feed is an important component in sustainable egg production enabling the supplemented chickens to produce more eggs than chickens surviving solely on the scavenging feed resource base (Goromela, Kwakkel, & Verstegen, 2008). Although nutritionists design complete rations to meet a laying hen's nutritional requirements determined by maintenance, body weight, and level of egg production (Leeson, 2011), in scavenging systems, the energy, protein, and micronutrient content of the feed is often critically deficient, especially during the dry season in tropical zones when feed resources are scarce. A study by Goromela et al. (2008) in Tanzania revealed that scavenged feed resources consumed daily by free-ranging chickens vary from 45 g in the dry season to 54 g in the rainy season, amounts considered insufficient to fulfill the protein requirements for high egg production.

In contrast, because poultry raised in intensive systems are necessarily housed, they need to be provided with balanced feed. Commercial feeds are formulated to meet the nutritional requirements of a particular type of bird at a particular stage of maturity (e.g., starter, grower, and layer feed) and are available with different contents of protein and micronutrients. Commercial feeds are therefore ideal for meeting the nutritional requirements of the flock, especially for a new poultry producer.

However, for small-scale producers in low-income countries, especially those in rural areas, feed access and cost can be a major constraint to productivity and economic sustainability of the enterprise (FAO, 2014). In a semi-intensive egg-production program in rural Zambia, for example, feed access was limited by erratic stocking of commercial layer mash by local shop owners, impassable roads during the rainy season, and lack of transportation (Dumas, Lungu, Mulambya, Lewis, & Travis, 2018). As a result, producers were at times forced to feed only maize bran, leading to dramatic drops in egg production (Dumas et al., 2018). Conditions for successful interventions involving feed provision are outlined in Table 3.

As an alternative, home-mixed feeds can be formulated using locally available grains, protein-rich feedstuffs, and a vitamin/mineral premix (Damerow, 2015; FAO, 2004; Table S5). Primary energy sources are grains, grain by-products, and vegetable and animal fats (Chiba, 2009). Amino acids, often the most challenging and costly nutrients to provide in smallholder systems, are primarily derived from soybean meal and fish/meat meal or their alternatives (Chiba, 2009). Along with the vitamin/mineral premix, added ground limestone oyster shells provide additional calcium, whereas bone meal or rock phosphate provide added phosphorus (Chiba, 2009), both critical for eggshell development.

Because many of the components of these feeds are also suitable for human consumption, efforts should be made to utilize alternatives to avoid competition between humans and poultry for feedstuffs, particularly in food-insecure communities (FAO, 2014). By-products from local crop processing (brans, oils, and meals) can partially fulfill the energy and protein requirements of poultry (FAO, 2014). For example, a by-product of starch production, 15% cassava pulp, can replace maize in layer diets with no detrimental effect on egg production or quality, with the exception of paler egg yolks (Iji, Bhuiyan, Chauynarong, Barekatain, & Widodo, 2011). Termites, maggots, or earthworms can be cultivated or collected using traps and used as suitable protein sources, whereas blood can be dried on a vegetable carrier to make blood meal (FAO, 2014). Eggshells, which are 98.2% calcium carbonate, can be boiled, dried, and crushed and provided as a microbially safe substitute for limestone (Gongruttananun, 2011).

Many of these alternatives are also suitable to provide to extensively raised, indigenous chickens to supplement their scavenging resources, thereby optimizing body weight and fat deposition necessary for maximal egg production (Ahlers et al., 2009; FAO, 2014).

Additionally, there are numerous lesser known crops and wild plants that are well adapted to particular agroecological conditions that may be appropriate livestock feed resources (Quansah & Makkar, 2012), but further research is needed to examine their suitability as poultry feed. The exact nutritional content of these alternatives are rarely known, and dietary fibre or antinutritive factors may inhibit nutrient bioavailability and negatively affect egg production (Martens, Tiemann, Bindelle, Peters, & Lascano, 2012).

5.3 | Shelter

Housing and other infrastructure requirements vary considerably depending on the production system concerned. For all poultry systems, the basic requirements for poultry housing are space, ventilation, light, and protection.

In an extensive system—which typically rely on scavenging as the primary feed resource—birds must remain free ranging during the day but can be housed at night. Predators are often a major challenge, especially in rural areas, and chicks are particularly vulnerable (Alders & Pym, 2009). Sturdy, elevated poultry houses built using locally available materials can reduce the risk of predation and additionally serve to concentrate faeces (to be used as fertilizer), protect the flock from adverse weather and theft, and facilitate health inspections and vaccinations (Ahlers et al., 2009). Care must be taken to use designs and materials that do not promote infestations of internal and external parasites; the design should allow for good ventilation and easy cleaning to prevent the transmission of infectious disease agents within the flock.

By definition, intensively and semi-intensively raised flocks require permanent housing. These must be designed with a ventilation system to maintain optimal temperature in hot climates (Czarick III &

TABLE 3 Examples of successful extensive and semi-intensive poultry management interventions in rural areas, including country, time period, nature of interventions, outcomes, and conditions for success

Country	Production system	Program start	Program end	Nature of interventions	Outcomes	Conditions for success	References
Mozambique and Tanzania	Extensive	July 2002	November 2005 (approach is ongoing with vaccination coverage increasing in both countries)	Project scale: Mozambique—45 villages across five provinces; Tanzania—10 villages across two regions Community vaccination against ND through trained community vaccinators Participatory implementation of vaccination program Training in general poultry husbandry for extensive systems In-country thermotolerant ND vaccine production	70–500% increased flock size across project sites, improved off-take* and reduced mortality Consumption and sale of chickens increased significantly Small increase in consumption and sale of eggs	Gender-sensitive approach Cost-sharing mechanism with farmers paying a fee-for-service to community vaccinators and community vaccinators purchasing vaccine Capacity building of and coordination with community members, NGO and government workers, community leaders, etc. Development of appropriate extension materials Timely availability of ND vaccine	Alders, 2009; Harun et al., 2009; Msami & Young, 2009
Malawi, Mozambique, Zambia, and Tanzania	Extensive	2009	2013	Project scale: Mozambique – 33 villages; Tanzania—27 wards Zambia: eight villages Malawi: 50 villages Thermotolerant ND vaccine production Community vaccination against ND through trained community vaccinators Participatory implementation of vaccination program Training in general poultry husbandry for extensive systems	More than 48.8% of households vaccinating regularly Chicken off-take 13.7% in Mozambique, 15.4% Malawi, and 33.9% in Tanzania Increase in flock size 10.1% in Mozambique, 9.9% Malawi, and 20.9% in Tanzania	As above.	Fisher, 2014
Tanzania	Extensive	April 2014	Ongoing	Project scale: 12 villages across two districts Community vaccination against ND through trained community vaccinators Participatory implementation of vaccination program Training in general poultry husbandry for extensive systems	Increased flock size Increased participation in vaccination campaigns, especially among households having larger flocks	Participatory and cost-sharing approaches to implementation of ND vaccination program Timely availability of ND vaccine Children significantly more likely to consume eggs if mother also consumed	de Bruyn, Bagnol, et al., 2017; de Bruyn, Thomson, et al., 2017

(Continues)

TABLE 3 (Continued)

Country	Production system	Program start	Program end	Nature of interventions	Outcomes	Conditions for success	References
Zambia	Extensive	July 2007	Ongoing (evaluation endline: November 2011)	Project scale: >5,271 farmers in one province Community vaccination against ND Training of "Poultry Lead Farmers" and formation of community poultry production groups Training and demos for an improved model of poultry housing Training in supplementary feeding and disease prevention	160% increase in average flock size in participating HHs compared with no change in controls 65% increase in poultry profitability in participating HHs No change in chicken meat or egg consumption in participating HHs	Requires a supporting organization with local relationships and capacity, including refrigeration for vaccine	Dumas et al., 2016
Zambia	Semi-intensive egg production	June 2010	June 2016	Project scale: 24 villages across two districts Trained and supported households or small groups in semi-intensive egg production practices and business management Provided 40 layers and materials for secure poultry housing	Pilot: >11,000 eggs were produced and locallysold in 10 months Nearby HHs reported a 75% increase in egg consumption Egg producers had a 45% increase in total HH income Extended pilot: >156,000 eggs were produced and locally sold in 12 months Young children 6–36 months were significantly more likely to eat eggs if they lived near an egg production centre March/April 2018: 8915 poultry owners (65% female), 34,196 chickens vaccinated across 4 districts	Requires a supporting organization to provide access to replacement layers, a viable local market for eggs, and local access to layer feed	Dumas et al., 2016; Dumas, 2017; Dumas et al., 2018

Note. ND: Newcastle disease; HH: Household.

*Off-take defined here as eaten by household, sold, exchanged, given to guests or eaten in association with ceremonies.

Fairchild, 2008); use good quality building materials (FAO, 2004); and consider biosecurity practices.

6 | DISEASE PREVENTION AND CONTROL

6.1 | Infectious diseases

Infectious diseases are recognized as one of the major constraints to improving family poultry production (Pym & Alders, 2016). Viral diseases have a major impact on the health and productivity of poultry. The major tools that poultry owners have to protect their flocks against these diseases are good biosecurity and vaccination. Although there is no specific treatment for viral diseases, broad-spectrum antibiotics may only be of some benefit to prevent or treat secondary bacterial infection. Numerous studies have identified Newcastle disease (ND) as the major killer disease of chickens globally.

ND is a highly contagious viral infection that affects many species of domestic and wild birds. Chickens, turkeys, pigeons, and parrots are most susceptible, whereas a mild form of the disease affects ducks, geese, pheasants, quail, and guinea fowl. ND is a member of the Paramyxoviridae family of viruses, which also includes the human measles virus. The pathogenesis and epidemiology of ND was reviewed by Alexander et al. (2004). The major source of infection of ND is the introduction of new birds to family poultry flocks. Markets also serve as a common source of ND infection, sometimes through the random sale of infected birds during outbreaks to salvage those not yet showing clinical signs (Ahlers et al., 2009). Models for the sustainable control of ND under resource-limiting conditions through the training of community vaccinators who work on a fee-for-service basis have proved sustainable in Sub-Saharan Africa since the early 2000s (Alders et al., 2003; Alders, Bagnol, & Young, 2010; Alexander et al., 2004; Dumas et al., 2016; Table 3). Vaccination of family poultry has received little attention from animal health services in Sub-Saharan Africa with most funding from national governments and donors continuing to focus on ruminants. The introduction of cost-sharing methodologies using community vaccinators has facilitated increased coverage of vaccinations against ND in family poultry in rural areas (Alders, 2009; Alders et al., 2003).

However, family poultry are exposed to a number of other viral pathogens such as avian influenza, fowlpox, infectious bronchitis, infectious bursal disease, and Marek's disease, all of which can cause significant mortality and morbidity (Ahlers et al., 2009).

Bacterial diseases may also have a significant impact on the health and productivity of family poultry. Poultry owners have a number of tools to protect their flocks against these diseases: good biosecurity, treatment with specific antibiotics, and vaccination. Chronic respiratory disease, colibacillosis, fowl cholera, fowl typhoid, infectious coryza, and pullorum disease have been recorded in extensively raised indigenous chickens. Salmonellosis (Ahlers et al., 2009), pasteurellosis, and mycoplasma infection occur across all production systems.

Concerns over growing antimicrobial resistance in association with the inappropriate use of antibiotics in food animals have led to increasing regulation of their use. Additionally, drug residue in eggs is of concern due to the protracted nature of egg development, and a review of the literature has found very large variation in the duration of persistent detectable residue of most antimicrobials in eggs (Goetting et al., 2011). As a result, few antibiotics are approved for laying hens in either the United States or the European Union (Marmulak et al., 2015), and any extra-label antimicrobial use should occur under the supervision of a veterinarian. Without the guidance of a veterinarian or livestock officer, few family poultry owners are likely to be aware of egg withholding time (the time after administration of the antimicrobial during which eggs should be discarded) appropriate for the drug, dose, route, and duration of treatment.

Parasitic diseases, mycotoxins, and nutritional deficiencies may also have an impact on productivity of family poultry. The impact of parasitic diseases including helminths, ectoparasites, and coccidia (Ahlers et al., 2009) has also been demonstrated.

Disease in hens, as well as poor husbandry or nutrition, may affect egg production. A hen in poor condition will produce fewer or even no eggs. The quality of eggs can also be affected by several diseases and disorders (Ahlers et al., 2009).

Where poultry disease surveillance and diagnosis are weak, participatory epidemiology (Alders & Spradbrow, 2001) can be employed to identify diseases or disease syndromes of importance, which can be confirmed by laboratory diagnosis.

6.2 | Biosecurity

The FAO and the World Organization for Animal Health (OIE) define biosecurity as the implementation of measures to reduce the risk of the introduction and spread of disease agents. Although ways of classifying these measures vary, the two basic principles are bioexclusion (i.e., preventing infectious agents from entering the farm by introducing healthy birds and providing clean supplies of feed, water, and litter) and biocontainment (i.e., preventing infectious agents from spreading) and involve segregation of the flock (confinement, controlling contacts with other birds and/or people, and introduction of healthy birds only); cleaning (shelters, equipment, clothes, and shoes); and disinfection (FAO, 2014). Specific recommendations for family poultry settings found in literature usually refer to highly pathogenic avian influenza-related risks and vary according to production system (FAO, 2014). It is important to note that investing in adequate biosecurity practices is commonly difficult for small-scale intensive poultry producers with low profit margins, which places them at risk, as the frequent movement of inputs and outputs increases the opportunity for disease introduction and spread.

6.3 | Diet-related diseases

In areas where the scavenging feed resource base is limiting, non-communicable diseases related to poor nutrition, for example, protein and/or vitamin deficiencies, may occur seasonally (FAO, 2004). In situations where commercial poultry rations are not routinely tested, deficiencies of key nutrients may also occur in these rations with their absence being detected only when birds fail to grow or produce as expected or become immunologically compromised and susceptible to an increased range of infectious diseases.

6.4 | Ethno-veterinary medicine

Rural and family poultry systems in LMICs typically lack access to organized poultry health inputs, and where they do exist, farmers are usually constrained by lack of finance and unavailability of consultancy advice from veterinary and extension officers. Small flock size, mixed-age and species flock composition, improper housing, scavenging, among other factors have made the use of conventional schedule-oriented health inputs like medication and vaccination difficult. Conventional poultry health packages are designed for the commercial sector and therefore feature large dose-packages usually for hundreds or thousands of birds. Hence, in the villages, farmers usually rely on traditional medicine for meeting health care needs (Alders & Spradbrow, 2001). The application of indigenous knowledge to treat animal diseases is known as ethno-veterinary medicine and is defined as an indigenous animal health care system that includes the traditional beliefs, knowledge, skills, methods, and practices of a given society. The active ingredients of some traditionally used treating plants may contain many compounds effective against different clinical signs or may just alleviate signs found across illnesses such as pain and are therefore not specific treatments to any one particular disease.

Making time to document ethno-veterinary practices provides an opportunity to increase understanding of community perceptions regarding the origins of disease and how it may be controlled.

6.5 | Toxins

Aflatoxin, the most potent and widespread mycotoxin, has been associated with increased incidences of liver cancer in adult humans and reduced growth rates and stunting in infants and children in LMICs from consumption of contaminated dietary staples, particularly maize and groundnuts (Strosnider et al., 2006). Equally, poultry exposure to aflatoxin-contaminated feed will lead to poor feathering, listlessness, anorexia with lowered growth rate, poor feed utilization, decreased weight gain, decreased egg weight and production, increased susceptibility to environmental and microbial stresses, and increased mortality (Ortatatli, Oguz, Hatipoglu, & Karaman, 2005), causing severe economic losses in the poultry industry. Hence, strategies that aim at reducing grain mycotoxin contamination such as proper harvesting, drying, and storage may help mitigate significant health problems and production losses in poultry and potential exposure of humans to the toxin (more likely via the consumption of contaminated poultry liver than eggs; Sineque, Macuamule, & dos Anjos, 2017).

6.6 | National and international animal health regulations

Animal health practices are governed by national and international regulations. The purchase and use of veterinary pharmaceutical agents, such as antibiotics and vaccines, are proscribed by law to ensure the appropriate use of these products. For example, veterinary pharmaceutical should be appropriately registered in the country where they are to be administered, and the administration of antibiotics and vaccines, especially where needles are used, should be done by authorized technicians.

7 | FOOD SAFETY, SANITATION, AND NUTRITION SECURITY

7.1 | Zoonotic pathogens and risks to human health

Poultry production has received increasing attention from the public health community in recent years due to its links to direct transmission of zoonotic diseases to humans through contact with poultry, or indirect transmission through poultry food products or waste. Zoonotic diseases of major interest include salmonellosis, campylobacteriosis, colibacilosis, and highly pathogenic avian influenza. These diseases have been more problematic in intensive production systems; however, their prevention (e.g., by purchasing birds from flocks certified free of key diseases, training on appropriate biosecurity, and hygiene practices) should be included in any new family poultry project, irrespective of the production system (FAO, 2014). For example, *Salmonella* is of particular public health concern, and contamination of eggs can be limited through good management, such as routine disinfection of poultry housing between flocks and pest eradication (Whiley & Ross, 2015).

In addition to the risk of clinical disease, family poultry ownership has been negatively linked with child nutrition outcomes because of its potential to contribute to an unsanitary household environment (Gelli et al., 2017), leading to increased exposure of household members to chicken faeces and feather dust. In extensive systems, although the waste produced is minimal, there is high human–chicken interaction, and infants may consume chicken faeces or contaminated dirt during exploratory play (Ngure et al., 2013). Exposure to livestock (Zambrano, Levy, Menezes, & Freeman, 2014); geophagy (George et al., 2015); animal faeces in the compound (Headey et al., 2017); and corralling livestock inside (Headey & Hirvonen, 2016) has been statistically associated with environmental enteric dysfunction (EED)—a disorder associated with reduced intestinal absorptive capacity and undernutrition—diarrhoea, and stunting in some but not all countries studied. In rural Ethiopia, poultry ownership was positively associated with linear growth, but corralling poultry indoors was negatively associated with linear growth, completely off-setting the benefit of poultry ownership on child nutrition in those households (Headey & Hirvonen, 2016). However, in a longitudinal study conducted in central Tanzania over 2 years, no significant association was observed between keeping indigenous chickens within human dwellings overnight and linear growth performance or diarrhoeal incidences in 503 children under 5 years (de Bruyn, 2017). Research continues in this same study site with an analysis of findings over 4 years to become available by the end of 2018. The complexity of potential linkages between EED pathways and child stunting was emphasized in a recent systematic review (Harper, Mutasa, Prendergast, Humphrey, & Manges, 2018). Key findings by Harper et al. (2018) were that it is possible that EED is not a single entity, but instead a set of phenotypes dependent on unique environmental exposures that vary geographically;

that it is not firmly established that EED is always consequential to linear growth, or indeed that it is definitively associated with stunting; and that some support existed for the link between intestinal inflammation and stunting.

Given these potential risks, appropriate housing and waste management practices are vital to ensure that poultry can contribute to improved nutrition outcomes. Birds must be provided appropriate shelter as described above, to minimize their negative impact on household hygiene and the local environment. For chickens raised in extensive systems, a lack of durable poultry housing to resist predators, adverse weather, and theft incentivizes owners to shelter birds inside the family home at night (Msami, 2008). Emphasis should be placed on educating farmers about the potential health risks of this practice and how to instead build sturdy, elevated poultry houses for nighttime sheltering of birds (Ahlers et al., 2009).

In semi-intensive or intensive poultry systems, where larger numbers of birds are sheltered in permanent housing, strict biosecurity practices (e.g., designated footwear, exclusion of children from the poultry house, and hand-washing with soap before and after entering the poultry house) can prevent contamination of the household environment. These systems additionally require a waste management plan, particularly during the rainy season when microbial count in surface water increases due to run-off from areas contaminated by livestock faeces (Chouhan, 2015). Application of poultry litter to agricultural lands as an organic fertilizer is a safe, sustainable disposal method suitable for mixed crop-livestock systems, particularly if it is first composted to inactivate potentially harmful pathogens and produce more stable organic matter (Kelleher et al., 2002).

7.2 | Egg storage and quality assessment in resource-limiting conditions

Between 8% and 24% of raw eggs in Africa have been reported to be contaminated with *Salmonella*, and proper storage, handling, and preparation are therefore critical to their safe consumption (Ejo, Garedew, Alebachew, & Worku, 2016). With fertile eggs, the embryo will start to grow even at ambient temperature (above 20°C). Eggs should therefore be kept in a cool, shady place. Where refrigeration is not available, a basket or box containing sawdust or bran placed in a hole in the floor in the coolest part of the dwelling makes a good system for storing eggs. Eggs for incubation should not be stored for longer than 2 weeks (Ahlers et al., 2009). Egg storage conditions are important, especially if a more consistent supply of eggs is to be achieved via seasonal production of eggs by indigenous or dual-purpose hens.

The quality of albumen declines very rapidly when eggs are stored at room temperature, especially in hot climates. Refrigeration is effective in maintaining quality for several months. Oiling eggs on the day of lay will preserve their quality for several weeks, and the oil film also prevents germs from entering (Ahlers et al., 2009). Fresh eggs can be distinguished from old ones by the height of the albumen (the white or clear part of the egg) once an unboiled egg is opened and put on a dish (Ahlers et al., 2009).

Hard-boiled eggs can be stored for several weeks. These eggs might also be oiled to preserve their quality for even longer periods. Another possibility is to store raw eggs in waterglass (sodium silicate) solution. Eggs will keep for several months in waterglass if covered and stored in a cool place. The waterglass solution is made by mixing one part of waterglass (sodium silicate) to five parts of previously boiled but cooled water (Ahlers et al., 2009).

8 | FAMILY POULTRY AND MATERNAL AND CHILD NUTRITION: CHALLENGES AND SOLUTIONS

Sustainable, food-based approaches to improved maternal and child nutrition will vary according to local conditions. In urban and peri-urban areas, it may be that promoting the purchase and consumption of commercially produced chicken eggs represents the optimal benefit-cost investment. In rural areas where the inputs required to support efficient and humane intensive production of chicken eggs are not readily available, consideration can be given to supporting semi-intensive and extensive chicken production. These systems may contribute to nutrition security directly and indirectly through the sale and home consumption of chickens and eggs at both the household and community levels.

In many rural areas, farming households are reluctant to eat surplus chickens or eggs, and in some regions, the consumption of eggs is prohibited for children and women by tradition (Alders et al., 2003). As mentioned above, the conservation of eggs and the hatching of chickens are important in situations of high chicken mortality, where replacement birds are essential. Following the introduction of effective improved family poultry production programs, it can take up to 2 years for households to feel confident that their poultry will no longer die in large numbers enabling them to consume poultry and poultry products in increased quantities (Harun et al., 2009). Additionally, in some communities despite efforts to improve maternal diet quality during pregnancy, the ability to influence maternal diets goes well beyond food availability. In many locations, maternal and child undernutrition is accompanied by inadequate obstetrical support services, a situation which contributes to customs recommending the avoidance of foods, such as eggs, which could lead to increased birth weight and obstructed labour (Arzoaquoi et al., 2015). If the benefits of the consumption of eggs and other ASFs are to be fully realized during the 1,000-day window of opportunity, then interventions that enable women to make sound dietary choices during pregnancy are essential.

9 | CONCLUSIONS

For thousands of years, poultry raising has been, and continues to be, a significant component of human civilization with differing breeds and production systems arising in association with local cultures and agroecological systems. To ensure that bird, human, and environmental health can flourish, it is essential for interdisciplinary research and development teams to work in collaboration with communities to ensure the long-term environmental and economic sustainability of family poultry production enterprises that are a good fit with local circumstances.

Achieving sustainable improvements to household nutrition security in resource-poor settings is a major challenge, as rural households frequently face multiple issues from extreme poverty to environmental degradation. Consequently, attaining household nutrition security requires a multipronged approach that is feasible in the long-term under local conditions and which may include improved family poultry production that provides increased numbers of birds and eggs for sale as well as home consumption; improved linkages between family poultry producers and public and private animal health service providers; and nutrition education targeting men and women.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

RA led the conceptualization and preparation of the review paper with contributions from SED (conceptualization, primary authorship of sections on poultry nutrition, poultry shelter, and risks to human health); ER (sanitation and food safety); GM (food safety and toxins); WM (poultry nutrition); JJ (animal health regulations); and RC (infectious disease and biosecurity). All authors contributed to and approved the final manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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SUPPLEMENT ARTICLE

WILEY Maternal & Child Nutrition

An egg for everyone: Pathways to universal access to one of nature's most nutritious foods

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Abstract

Eggs are a highly nutritious food but have been shown to be infrequently consumed in many low-income countries, especially by women and children. We collate country-level data on egg production, availability, consumption, prices, industry structure, and contextual trends and use these to estimate current patterns and likely future outcomes under four alternative scenarios. These scenarios are as follows: incremental change based on expected economic growth and urbanisation (the base scenario); enhanced productivity of independent small producers; aggregated production in egg hubs; and the accelerated spread of large-scale intensive production. All scenarios are modelled out to 2030 using a mix of regression and deterministic models. We find that children's consumption of eggs is highly correlated with national availability, and both are a function of egg prices. Eggs are unavailable, expensive, and infrequently consumed by children in much of South Asia and sub-Saharan Africa. The base scenario results in modest increases in production in low-income regions. Focusing efforts on independent small producers can only boost rural consumption in a handful of countries where poultry ownership is unusually high and would be expensive and logistically challenging to scale. Aggregation of production, with minimum flock sizes of 5,000 layers per farm, is a more promising pathway to increasing availability in rural areas. To meet the needs of urban populations, large-scale intensive production is needed. Intensive production brings down prices significantly, allowing many more poor households to access and consume eggs. Recent experience in countries such as Thailand confirms that this is both feasible and impactful.

KEYWORDS

developing countries, diet/economics, eggs, infants, programme appropriateness, young children

1 | INTRODUCTION

Eggs are a highly nutritious food, rich in Essential Fatty Acids, choline, vitamins A and B12, and bioavailable iron, zinc, and iodine (Iannotti, Lutter, Bunn, & Stewart, 2014). The protein in the albumen is abundant, digestible, and complete, and the whole food is naturally "packaged" in a protective "container." With a few notable exceptions, almost all human populations enjoy eating them. They are uniquely positioned to advance the second of the world's Sustainable Development Goals (SDGs)—to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture (United Nations, 2015).

Consumption of eggs, however, falls far below optimal levels among mothers and children living in poorer countries. Lutter and Iannotti, writing in the first paper in this supplement (Lutter, Iannotti, & Stewart, 2018), have shown that in most of Africa and in India, only 13–15% of young children eat egg over a 24-hr recall period. In much of the rest of low- and middle-income Asia, only one fifth to one third of children were given egg, and levels of consumption among women of reproductive age were also found to be very low, especially among women from households in the lower wealth quintiles. This is in spite of the fact that global egg production is substantial and growing: The Food and Agriculture Organisation (FAO) of the United Nations estimates that 1,387 bn eggs were produced in 2016, which is nearly one egg for every two humans on the planet each day (FAO, 2017).

Previous papers in this supplement (Dumas, Lewis, & Travis, 2018; Marquis et al., 2018) have shown that it is possible for poor rural communities in developing countries to increase their egg production and that increased egg consumption for young children can result. While not a focus of this supplement, other authors have documented the rise of large-scale commercial egg producers, which are expanding rapidly in countries such as Thailand, India, Saudi Arabia, and South Africa (Mehta & Nambiar, 2007; Narrod, Tiongco, & Costales, 2007; WATTAgNet, 2017; Windhorst, 2014). In this paper, we (a) summarise information on the current status of egg availability and consumption, (b) identify the most important demand- and supply-side barriers to greater consumption of eggs, especially by children, and (c) determine which interventions could accelerate egg consumption by 2030, the end of the SDG period.

Key messages

- Eggs are cheap, available, and frequently consumed by young children in high- and middle-income countries; they are expensive, scarce, and rarely consumed by children in much of Africa and South Asia.
- Most countries produce eggs almost exclusively in intensive systems once Gross Domestic Product per capita reaches USD 10,000. This brings down prices, making eggs accessible to poor consumers.
- Trying to improve the productivity of individual small-scale producers is unlikely to significantly improve egg consumption at national level.
- An egg hub model that aggregates clusters of medium-scale producers might increase access to eggs for many poorer countries.

2 | METHODS

This paper synthesises existing knowledge from peer-reviewed and grey literature and supplements it with new analyses taking the country as the primary unit of analysis.

2.1 | Data

Data on poultry ownership and recent consumption of eggs among young children are from the representative household surveys of the Demographic and Health Survey series (www.dhsprogram.com). Data on egg availability are taken from the Food Balance Sheets of the FAO (www.fao.org/faostat) and refer to the most recent year available (2013). These estimates start with domestic production, add net imports, and subtract losses and nonfood uses to determine the quantities available for domestic consumption. Divided by the total population, as estimated by the United Nations Population Division (2014), we treat this quantity as a measure of per capita egg availability for consumption. Where egg statistics are reported by weight, we convert to egg units on the assumption of one egg = 50 g.

Egg prices at the national level are expressed relative to the price of the cheapest cereal staple in each country (market cost per kilocalorie equivalent of produce, in each case). This approach follows Headey and Alderman (2017), who argue that these cereal-relative prices capture the cost of diversifying the diet away from starchy staples. Price data are principally sourced from the World Bank-led International Comparison Program data for 2011 (World Bank, 2015).

We distinguish between eggs produced under extensive, versus intensive, conditions. Extensive production systems are village or backyard poultry with minimal biosecurity and birds and eggs consumed locally; this is referred to by FAO as "Sector 4" (FAO, 2004). Intensive production systems are commercial operations with larger flock sizes, higher investment in inputs, and a market orientation. Gilbert et al. (2015) have estimated the proportion of chicken kept under extensive and intensive systems in each country, and we use the same data. We assume that, on average, 50% of intensive chickens are broilers and 50% layers.

For the development of predictive scenarios for 2030, we use the United Nations predictions of population totals disaggregated by urban and rural domicile (United Nations Population Division 2014) and the U.S. Department of Agriculture Economic Research Service predictions of real Gross Domestic Product (GDP; USDA, 2017). For our base scenario, we use FAO estimates of total future egg production (FAO, 2011). These forecasts are based on spatially mapped projections of both supply and demand, taking into account expected population change, economic growth, and environmental characteristics.

2.2 | Statistical methods

For descriptive analyses by region, we aggregate individual country data using population-weighted means, with each country's weight equal to the ratio of a country's population relative to the region's total population. Regional groupings are as per the World Bank.

We use robust regression (Verardi & Croux, 2009) to explain cross-country patterns in two measures of consumption: (a) egg availability for consumption, because this incorporates potential consumption by both adults and children; and (b) recent reported consumption by children aged 12–23 months. We model these two consumption indicators as a function of GDP per capita (an income proxy), urbanisation (proportion of the population living in urban areas, which reflects improved market access), egg prices relative to the cheapest cereal staple food (which reflects the cost of diversifying consumption out of cereals into eggs), and a dummy variable for India, which has unique cultural restrictions on egg consumption. This dummy variable tests whether India is a significant outlier compared with the rest of the sample. We then also use robust regression to elucidate why some countries have much higher relative egg prices than others. To do so, we regress egg prices on GDP per capita, urbanisation, and a key measure of commercialisation in the poultry sector: the predominance of intensive versus extensive poultry farming systems (proportion of chicken raised in intensive systems). We use out-of-sample predictions to estimate potential changes in national levels of availability and consumption given expected future levels of the independent variables.

Regression analyses were undertaken using Stata v.14 (College Station, TX).

3 | RESULTS

3.1 | Current status of egg production, availability, and consumption

In sub-Saharan Africa and South Asia (excluding India), 40–50% of rural households report owning poultry (Table 1). However, flock sizes are very small—typically from five to 20 birds (Birola et al., 2010; Guèye, 1998; Pica-Ciamarra & Dhawan, 2010)—and productivity is also very low—30–80 eggs per hen per year in unimproved systems (Wong et al., 2017). Although intensive production systems bring together far larger flocks and achieve much high egg yields, there are relatively few commercial egg producers in the world's poorest countries. In fact, Gilbert et al. (2015) find that "below 1,000 USD [GDP] per capita, over 90% of chicken are raised under extensive systems and the transition from extensive to intensive production really occurs between 1,000 and 10,000 USD per capita; above which most chickens are raised in intensive systems." Based on their mapping, Gilbert and colleagues estimate that 96% of the world's chicken are raised under intensive conditions. This number falls to 70% in sub-Saharan Africa as a whole and 15% in Burkina Faso, for example. Adjusting for the (assumed) proportion of chicken raised for meat ("broiler" chickens) and the differential productivity of intensive and extensive production systems, we estimate that 93% of the world's *eggs* are produced in intensive systems. Three quarters of the world's egg production is concentrated in just 14 countries; none of these are in Africa (FAO, 2017), but India is the third largest egg producer in the world.

As expected, egg availability and consumption also vary greatly across the world's major regions, and we find that availability and children's consumption levels are highly correlated (r = 0.55, p < 0.01). The only sub-Saharan African countries with egg availability in excess of 70 per person per year are South Africa, Cabo Verde, and Mauritius (Figure 1); in South Asia, only Sri Lanka exceeds this threshold. Egg consumption in the past 24 hr is not available for high-income countries, but almost half of young children in Latin America and the Caribbean consumed eggs in the 24 hr prior to the survey, and egg consumption is also reasonably prevalent in other predominantly middle-income regions (Table 1). However, in Africa, just 12.6% of children consumed eggs prior to the survey, and in India—where around one third of adults classify themselves as vegetarians who never consume eggs or flesh foods (2014 Sample Registration Survey cited in Bose, 2016; NHFS IV cited in Bansal & Kishore, 2018)—just 14.7% of children consumed eggs in a 24-hr period, a level much lower than other South Asian countries (25.0%). Children's egg consumption in India is not particularly high even among households where the mother states that she does consume eggs (19.0%).

3.2 | Prices and other constraints to demand

Across the world, eggs are expensive relative to staple cereal crops. In high-income countries, egg calories are 2.3 times as expensive as the cheapest cereal in a country, reflecting the tremendous gains in layer chicken productivity in rich countries in the 20th century, as well as large economies of scale achieved through commercialisation (Narrod et al., 2007). In other more developed regions such as Latin America, Eastern Europe, and Central Asia, a calorie of eggs is three to five

TABLE 1 Regional variation in poultry ownership, egg consumption (children), egg relative prices, and national income

	Chicken ownership (% of households)[a]	Per capita egg availability for consumption per year[b]	Egg consumed in the past 24 hr, children 6–23 m (%)[a]	Ratio of egg price to cereal price (in calorie terms)[c]
High-income countries	NA	265	NA	2.3
Latin America and Caribbean	12.8%	218	42.8%	4.8
Middle East and North Africa[d]	20.5%	129	30.8%	5.4
Eastern Europe and Central Asia	28.8%	238	34.0%	3.6
East Asia[d]	65.6%	241	20.8%	7.1
South Asia, excluding India	43.4%	50	25.0%	5.9
India	16.3%	52	14.7%	4.7
Sub-Saharan Africa	49.2%	40	12.6%	9.5
Cross-country correlation with egg availability per capita[e]	−0.06	N/A	0.55***	−0.59***

Note. FAO: Food and Agriculture Organisation.

[a]Sourced from the Demographic Health Surveys (ICF-International, 2015) for 46 countries. [b]FAO food balance sheets (FAO, 2017), assuming average egg weight of 50 g. [c]Sourced from Headey and Alderman (2017) estimates from the 2011 International Comparison Program data on food prices in 151 countries and various estimates of calorie content of egg and various staple cereals. [d]For these regions, Demographic and Health Survey data are only available for a handful of countries and should therefore not be treated as representative. [e]Bivariate correlations with FAO food balance sheets (FAO, 2017) estimates of egg consumption per capita for 177 countries.

***P < 0.01.

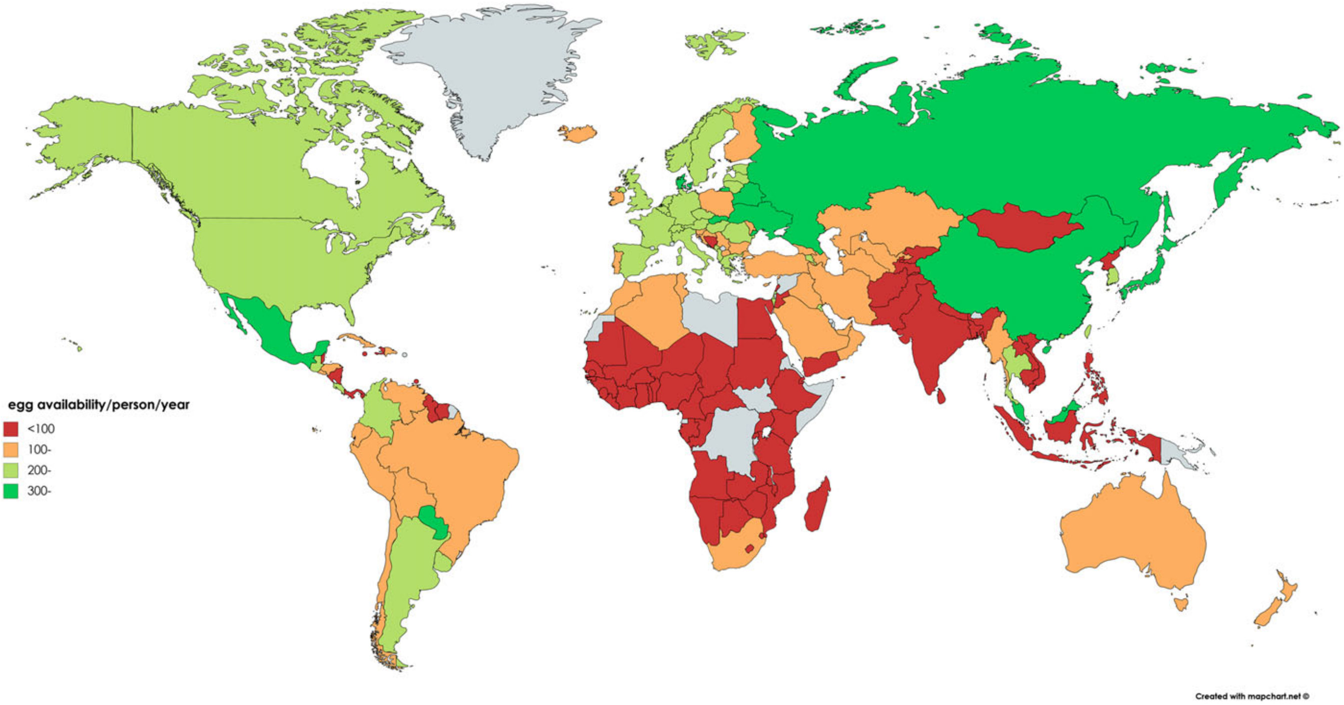

FIGURE 1 Current egg availability by country

times as expensive as the cheapest staple cereal. In India, the poultry sector has commercialised rapidly in recent decades and been one of the fastest growing sectors in the agricultural economy (Mehta & Nambiar, 2007). This, along with relatively modest growth in demand, has kept egg prices lower in India (4.7 times as expensive as rice) than in many other economies at a comparative level of development. In the rest of South Asia, eggs are around six times as expensive as cereals, implying that high prices will be a constraint for many households. In sub-Saharan Africa, the world's poorest region, eggs are 9.5 times as expensive as cereals, on average.

We hypothesised that international variation in egg consumption indicators would be highly sensitive to the price difference between eggs and cereal staples. We tested this in a regression model, controlling for national income (GDP per capita) and the proportion of the population living in urban areas (Table 2). We looked at both per capita availability, using the FAO indicator, and actual consumption of children aged 6–23 months. The first regression model in Table 2 suggests that every 2.5% increase in GDP per capita, or in the proportion of the population residing in urban areas, leads to approximately a one-egg (50 g) increase in per capita availability per year. And although relative egg prices are strongly correlated with GDP per capita ($r = -0.66^{***}$) and urbanisation ($r = -0.47^{***}$), relative prices remain a strong independent predictor of egg consumption, even after controlling for these other factors: A one-unit decline in the egg price ratio relative to cereals predicts an increase in per capita availability of approximately four eggs per year, based on standard egg weights. Hence, transitioning from a price ratio of 12 (Burkina Faso) to a level of six (Bangladesh/Indonesia) would predict a 1.3 kg/year increase in per capita availability for consumption or around 24 eggs more per capita per year, based on standard weights. We observe similar patterns of association for the egg consumption among children 6–23 months: Moving from Burkina Faso to Bangladesh price levels

TABLE 2 Robust regressions exploring the relationships between egg availability, consumption (children), and various demand- and supply-side determinants

Regression number		(1)	(2)	(3)
Observations (# countries)		*N* = 150	*N* = 60	*N* = 84
Dependent variable		Per capita egg availability (kg/year)	Children 6–23 months of age consuming eggs in the past 24 hr (%)	Relative egg calorie price (ratio to cereal calorie price)
Log GDP per capita	Coefficient	1.86*** (1.26 to 2.46)	9.21*** (3.01 to 15.41)	−0.36 (−1.13 to 0.40)
Log urban share	Coefficient	2.15*** (0.87 to 3.43)	4.40 (−6.00 to 14.80)	1.18* (−0.14 to 2.51)
Relative egg calorie price	Coefficient	−0.21** (−0.38 to −0.04)	−1.48** (−2.66 to −0.30)	
India dummy	Coefficient	−1.75 (−7.40 to 3.89)	−17.64 (−46.45 to 11.13)	−1.26 (−4.78 to 2.27)
Log intensive share of production	Coefficient			−0.08*** (−0.10 to 0.05)
R-squared		0.63	0.50	0.72

Note. GDP: Gross Domestic Product.

***p < 0.01, ***p* < 0.05, **p* < 0.1. The three regressions are independent of each other.

would predict a nine-percentage-point increase in the prevalence of egg consumption in the past 24 hr (the result of multiplying a price change of six units by the regression coefficient of 1.48).

The low level of consumption of eggs among Indian children highlights the fact that cultural preferences can limit demand for eggs. Simoons (1994), in a wide-ranging review of food avoidances from prehistory to the present, notes that Hindus avoid eggs, motivated both by vegetarian beliefs and the view that the domestic chicken is an unclean animal. Vegetarianism in India is strongest in states, such as Rajasthan (Bose, 2016), and among particular castes. In Africa, Simoons describes a "bewildering diversity" of avoidance norms for both chicken and eggs. "In many places, the avoidance applies to the entire group, but elsewhere it varies with the sex, age, and social position of the individual, and in the case of eggs, with their state of decay and method of preparation. Women are more generally subject to prohibitions than men." However, Lutter et al. (2018) suggest that these stated beliefs are unlikely to prove a binding constraint to increased consumption in Africa; by implication, they are merely a post hoc rationalisation of what is fundamentally an economic constraint.

3.3 | Supply constraints and feedback to lower demand

All forms of poultry production are subject to marked economies of scale (Narrod et al., 2007, document this for broiler chickens, which use similar inputs). Scavenger production systems can operate at small scale because fodder is free, but they have extraordinarily low egg productivity, as noted above. Higher-yield systems require several thousand layer chickens to break even (e.g., Ymeri, Sahiti, Musliu, Shaqiri, & Pllana, 2017), and this requires capital for infrastructure (barns/cages, etc.) and working capital to purchase feed and other inputs, as discussed in detail by Beesabathuni, Lingala, and Kraemer (2018). The lack of access to rural credit is likely a major constraint to the transition to intensive production units, as is the lack of well-developed markets for inputs such as feed. Intensive production units are also at high risk of loss of assets due to disease outbreaks such as Newcastle disease and avian influenza. The H5N1 strain of avian influenza caused millions of birds to be culled after emerging in Asia in December 2003, and many countries in Africa have lost a large proportion of their egg production industry (e.g., BBC, 2017). Large egg producers may also struggle to distribute their production in environments in which the formal retail sector is underdeveloped.

Although, for many products, lack of local supply could be compensated by imports, this is usually not the case for eggs, which are easily damaged, highly perishable, and subject to multiple food safety controls at ports of entry in many countries.

We estimated the extent to which local prices (again, relative to staple cereals) were determined by the presence of intensive production in the country and found that the share of birds in intensive systems accounts for 60% of the international variation in relative egg prices, and a 10-point increase in the intensive share predicts a 0.8 decline in the price ratio. This relationship is robust, even after controlling for GDP per capita and urbanisation (Regression 3 in Table 2).

4 | SCENARIOS FOR 2030

In this section, we look forward to the end of the SDG period and try to identify pathways to greater availability and consumption of eggs, particularly in sub-Saharan Africa and South Asia, where current levels are lowest.

4.1 | Base scenario

In our base scenario, we use FAO forecasts for total egg production in 2030 (FAO, 2011).

We then estimate the proportion of production in each country expected to come from intensive systems, based on the relationship identified by Gilbert et al. (2015) between this variable and GDP per capita, in this case, using expected future national income (USDA, 2017). We find that the total global production of eggs is expected to increase by 44% to just under 2,000 bn eggs a year, but the increase in per capita consumption will be less than that give the concurrent 15% increase in the world population. We assume that in sub-Saharan Africa and South Asia, increases in extensive production are consumed by rural populations and increases in intensive production are consumed by urban populations. The resulting changes in per capita egg production, for each region of the world, are shown in Table 3. There are relatively large increases (>33%) in East Asia, Europe and Central Asia, and North America, all regions that already enjoy high access to eggs. South Asia and sub-Saharan Africa, however, see only minor increases (or even a decrease in rural South Asia) leaving per capita production in both regions well below 100 eggs per person per year. In sub-Saharan Africa, a large projected increase in the urban population leaves per capita production for urban areas unchanged despite a near doubling of intensive egg production.

4.2 | Scenario 2: Improved extensive farming

This scenario envisages a programme of support to enhance the productivity of the many households in Africa and Asia who already rear backyard or scavenging poultry. It builds on models from Ethiopia and

TABLE 3 Current and future (2030) per capita egg production by global region. Base scenario

Region	Current	2030	Change (%)
East Asia and the Pacific	299	401	+34.2
Europe and Central Asia	240	355	+47.7
Latin America and the Caribbean	256	310	+20.9
Middle East and North Africa	144	174	+20.8
North America	303	413	+36.4
South Asia	64	76	+18.8
Rural	23	14	−39.1
Urban	149	169	+13.4
Sub-Saharan Africa	40	47	+17.5
Rural	26	31	+19.2
Urban	63	65	+3.2

Note. Assume that all intensive production in South Asia and sub-Saharan Africa is for urban consumption and all extensive production in these areas is for rural consumption.

India described earlier in this supplement (Beesabathuni et al., 2018). In these models, a farmer rears a maximum of 20 birds in a backyard setting with improved breeds (vaccinated day-old chicks or point-of-lay hens), supplemental feed, and shelter. A government extension agent (or a private brooding entrepreneur) would provide this input package to the households, servicing, on average, 150 households per agent and increasing productivity to 100 eggs per layer per year. Further details of this model are provided in Table S1.

We assume that this intervention is implemented throughout all rural areas, covering all backyard farmers in 57 low- and middle-income countries (LMIC) in Asia and Sub-Saharan Africa. We further assume that all of the eggs produced are consumed in rural areas. Despite the high level of effort, we find that eggs available per capita in rural areas in this scenario remains low in most countries (Table 4). Only eight countries where poultry ownership is already high are likely to benefit with improved productivity. These are Afghanistan in South Asia, Laos in South East Asia; and Senegal, São Tomé and Príncipe, Liberia, Nigeria, Zambia, and Burkina Faso in Sub-Saharan Africa, where per capita availability per week increases to three to four eggs. Countries with medium poultry ownership end up with two to three eggs available per capita per week. These are Bangladesh, Myanmar, Benin, Côte d'Ivoire, Ghana, Guinea, Mali, Mauritania, and Sierra Leone.

TABLE 4 Egg availability in rural areas of 56 low- and middle-income countries in Asia and Africa, by region and level of poultry ownership, following an intervention to increase the productivity of individual small-scale producer households by the year 2030

South Asia		
Poultry ownership	Countries	# of eggs/ capita/year
High	Afghanistan	158
Medium	Bangladesh	121
Low	Bhutan, India, Nepal, Pakistan, and Sri Lanka	Less than 50
East Asia and Pacific		
Poultry ownership	Countries	# of eggs/ capita/year
High	Lao People's Democratic Republic	152
Medium	Myanmar	102
Low	Cambodia, Indonesia, Micronesia (Federated States of), Mongolia, Papua New Guinea, Philippines, Solomon Islands, and Vanuatu	Less than 50
Sub-Saharan Africa		
Poultry ownership	Countries	# of eggs/ capita/year
High	Burkina Faso, Liberia, Nigeria, Sao Tome and Principe, and Senegal	160 to 215
Medium	Benin, Cabo Verde, Côte d'Ivoire, Ghana, Guinea, Mali, Mauritania, and Sierra Leone	100 to 150
Low	Angola, Burundi, Cameroon, Central African Republic, Chad, Comoros, Congo, Democratic Republic of the Congo, Eritrea, Ethiopia, Gambia, Guinea-Bissau, Kenya, Lesotho, Madagascar, Mozambique, Niger, Rwanda, Sudan, Swaziland, Togo, Uganda, and United Republic of Tanzania	6 to 100

Note. Poultry ownership: High: two to three birds per capita; Medium: one to two birds per capita; Low: <1 bird per capita in the year 2030.

4.3 | Scenario 3: Egg hubs

The third scenario again addresses rural markets but envisages a model in which smallholder farmers are organised into groups to facilitate input supply and better reap economies of scale.

In this model, groups of five smallholder farmers constitute one group and are trained to operate a small-scale farm with 5,000 birds, thereby simplifying supply chain coordination of inputs to the farm while also ensuring minimal losses in the transport of eggs to a market closest to the community. Farms with a flock size of 5,000 birds or more are viable in 3 years and are more profitable than those with smaller flock sizes (Beesabathuni et al., 2018; Ymeri et al., 2017). Each farmer group has access to credit, building materials, cages, start-up flock and relevant materials, biosecurity measures, protective clothing, and training in best practices. Several of these farms can be managed together as a hub. The hub acts as the aggregator of inputs and provides training, insurance, and credit to the farmer groups. In typical LMIC conditions, we estimate that each hub can efficiently serve a land area of 5,000 km^2, but beyond that, transporting eggs across long distances becomes a challenge (Beesabathuni et al., 2018). In densely populated rural areas, a land area of 5,000 km^2 could be home to millions of people, and the hub would need to coordinate a thousand or more farmer groups. In less densely populated countries, the population within the same land area might be 100,000 or even less, and the hub might comprise no more than a few dozen farmer groups. Further details of this model are provided in Table S1.

We forecast this scenario for 45 LMIC countries in Asia and Africa where data for rural land area are available. Countries with smaller land area such as Swaziland or Gambia would need to operate only two or three hubs. Large countries such as Indonesia and India would, in theory, need nearly 400 and 600 hubs, respectively. We use rural population data to estimate how many eggs would have to be produced by each such hub to provide the equivalent of one egg per individual per day. Based on the standard farm size of 5,000 layers per farm and a conservative assumption that average layer productivity would be 70%, or 255 eggs per bird, we deduce how many farms would have to be brought under one hub in each setting (Table 5). This ranges from three farms per hub in Mauritania to more than 1,000 in Bangladesh, which is the extreme outlier. The median distance each farm covers is only 3 km, meaning that every rural household can easily access fresh eggs daily or weekly as per their convenience.

4.4 | Large scale commercialisation

The previous discussion is framed in terms of access for rural populations and probably could not meet the needs of rapidly expanding

TABLE 5 Number of egg hubs and number of participating small-scale farms required in rural areas of 45 low- and middle-income countries in Asia and Africa to produce an egg a day for each rural inhabitant by the year 2030

No. of rural farms/hub	<100	100–200	>200
No. of egg hubs			
>200	Indonesia, Angola, Democratic Republic of Congo, Mali, Mauritania, and Sudan	Ethiopia	India
100–200	Myanmar, Madagascar, Mozambique, and Tanzania	Kenya and Nigeria	Pakistan
<100	Lao, Micronesia, Papua New Guinea, Solomon Islands, Vanuatu, Benin, Cabo Verde, Cameroon, Congo, Côte d'Ivoire, Eritrea, Ghana, Guinea, Guinea-Bissau, Liberia, Sao Tome and Principe, Senegal, and Sierra Leone	Afghanistan, Cambodia, Gambia, Swaziland, and Togo	Bangladesh, Sri Lanka, Philippines, Vietnam, Central African Republic, Comoros, and Malawi

Note. Minimum land area an egg hub covers assuming very poor road connectivity = 5,000 km^2; minimum flock size for a viable farm = 5,000 birds.

urban areas. For example, the built-up area around Kampala currently has 2.4-m people and will have over 4 m by the year 2030. Nearly 700 farmer groups would be required to provide all the current population with eggs at 5,000 layers per farm; this is unlikely to be feasible to organise within easy reach of the city; a handful of large-scale intensive producers would be better placed to meet this need. Because market incentives for large-scale commercialisation are strong, policy interventions could be limited to ensuring an attractive investment environment for commercial firms.

We have previously noted that egg prices are responsive to the proportion of all production that is intensive and that consumers are highly sensitive to egg prices. Using the regression results shown in Table 2, we estimate the impact of a significant shift towards intensive egg production in Africa and South Asia. Specifically, we let countries with existing intensive production shares of less than 80% (Indonesia's level) move up to 80%, and we let countries with existing shares of 80% or more converge to 100% (the norm in higher income economies). We find that this strategy increases per capita egg availability in Africa by 49 eggs per person per year and doubles the proportion of children receiving an egg in a 24-hr period; in South Asia, the strategy leads to an increase in egg availability of 28 eggs per person per year and results in a 50% increase in the proportion of children receiving eggs.

5 | DISCUSSION

Our analysis finds that in middle- and high-income countries, eggs are highly available and (relatively) cheap, and mothers regularly give eggs to their young children. In sub-Saharan Africa and South Asia, on the other hand, eggs are rarely given to young children. In these geographies, eggs are produced in quantities only sufficient to provide each inhabitant with a few eggs each month, and long-distance transportation of shell eggs is generally not possible due to the fragile and perishable nature of the product. Relative to other food items that the household might purchase, eggs are remarkably expensive. We show that the high cost of eggs is a direct result of the dominant production system: Extensive poultry rearing is inefficient and low-yield, and associated with high egg prices and low consumption. Intensive production of eggs, on the other hand, is much more efficient and associated with much higher laying rates and much lower market prices. Although cultural avoidance of egg consumption is clearly important in some geographies (notably northern and western India), we believe that cost is by far the biggest global constraint to greater consumption, even when it comes to consumption by young children.

We examine a number of different pathways to greater consumption of eggs by 2030, the end of the SDG period. Our base scenario is essentially “business as usual,” with economic growth enhancing purchasing power and urbanisation moving people in less developed regions from rural areas to cities. It does little to improve the availability of eggs in sub-Saharan Africa and South Asia, because predicted growth rates are too anaemic and are partly offset by population growth. Because large-scale intensive poultry rearing typically takes root at GDP levels of around USD 10,000 per annum (Gilbert), this scenario leaves the global structure of egg production largely unchanged.

In the 20th century, non-governmental organisations were keen to promote productivity-enhancing inputs for very small-scale extensive egg production. A previous paper in this supplement (Nordhagen & Klemm, 2018) shows just how challenging this can be. For the beneficiary households, wafer-thin margins are unlikely to justify the necessary expense in vaccines, feed, and better breeds, and scaling this approach would require establishing a vast network of extension agents, which would be expensive and hard to manage and sustain. Our analyses suggest that this model cannot bring down egg prices significantly (except perhaps in a handful of countries where poultry ownership is unusually high), and without this, major increases in egg consumption are impossible—the income/alternative expenditure foregone from giving an egg to a child is simply too great to contemplate for most families living in areas where eggs are extremely expensive.

On the other hand, the establishment of egg “hubs” could be a promising approach to meeting the need in rural areas as it drastically reduces the number of clusters of training centres and delivery points required, as well as the number of farmers involved in adopting and following best practices. Margins are adequate, with a net income per farmer of USD 144 per month. A similar approach is described in two previous papers in this supplement (Beesabathuni et al., 2018; Dumas et al., 2018). For countries with large rural land areas, which, as we have seen, would require more than 200 hubs to ensure an egg for everyone, creating incentives for private companies to set up the hubs is the likely accelerated pathway to scale. Thailand is a good example for creating a large and fair open market economy in broiler production with smallholders (Farrelly, 1996). The key innovation that Thailand implemented historically was institutionalising a system of contracts for farmers and integrators.

Meeting the needs of urban populations will undoubtedly require very large-scale poultry industries. This path to scale spread half a century ago from Europe and North America to countries such as China and Japan (Windhorst, 2014), which now have the highest per capita availability in the world. More recently, countries such as Thailand, India, and the Philippines have developed very large-scale poultry industries (WATTAgNet, 2017), but there are relatively few examples in Africa outside South Africa. Preisinger (2013) has estimated that in order to meet growing demand for eggs (most of it from the world's growing urban middle class), about 50 million additional laying chickens will have to go into production each year. These growing and new companies will confront all the usual challenges of doing business in developing countries, plus industry-specific challenges relating to the cost of feed and the risk of disease spread from local to hybrid breeds (and to humans). Companies will also have to assess their commitment to animal welfare, as raising chickens in battery cages is increasingly viewed as unacceptable in parts of the world.

Although we have focused on increasing access to eggs, in countries that already enjoy relatively cheap egg prices it may also be worth investing in demand creation. Colombia is a country that led the way in doing this, with the National Federation of Poultry Producers (FENAVI) investing heavily in egg promotion campaigns with a significant focus on television and radio advertisement and cooking shows highlighting the health benefits of eggs. India also has a long history of egg promotion campaigns, although this contends with significant opposition to egg consumption from some conservative cultural and political groups. In general, promotion of egg consumption in low- or middle-income countries lags far behind promotion of dairy, for example. There is a particular case for promoting egg consumption for infants aged 6–11 months, who often do not receive eggs even in households which provide them to older children.

Our analyses are subject to a number of limitations. The egg market in less developed countries has not been well characterised and we rely heavily on modelled estimates, including FAO food supply measures, which have well-documented challenges when interpreted as a measure of dietary habits (del Gobbo et al., 2015). We also extrapolate from cross-sectional relationships that may or may not prove to be causal. For our future scenarios, we rely additionally on input estimates for future values of national income and population, which are themselves associated with high levels of uncertainty. Finally, we are basing our business model assumptions on a relatively small number of case studies that may or may not turn out to be more broadly representative. All of this means that the exact magnitude of our findings is highly contestable, but we believe that the broad inferences from the scenarios are instructive and very likely to be valid. We should also emphasise that we have analysed the poultry landscape purely in relation to its potential to increase the consumption of eggs; rural households may have other, very legitimate, reasons for keeping poultry (particularly related to their meat value), and we are not suggesting that extensive poultry raising is per se undesirable.

Future studies should look in detail at price differentials between rural and urban areas and factor this in to scenario modelling. It would be of great use to develop an economy-wide model for egg production and consumption, which also allows researchers to investigate the differential impacts of policies on rural and urban populations. It would also be important to examine how medium-scale production such as egg hubs can evolve over time into the industrial scale production needed to meet the needs of growing urban areas.

Eggs are one of our best tools to help end hunger, achieve food security, and improve nutrition. In order to reap the benefits of this opportunity, it is essential that aggressive action be taken to increase their availability and affordability in sub-Saharan Africa and South Asia. This can only be done by investing heavily in production systems that can bring down prices significantly across the entire economy, rather than focusing effort on limited benefits for individual farmers.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

SM conceived the paper, modelled the base scenario, and drafted the Introduction, Methods, and Discussion sections. KB modelled the individual smallholder and egg hub scenarios and contributed text on supply-side constraints. DH modelled demand-side constraints and the large-scale intensification option. All authors reviewed and approved the final text.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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