BMJ Open

A statistical model to predict the performance of factors involved in reducing childhood stunting

Journal:	*BMJ Open*
Manuscript ID	bmjopen-2022-067961
Article Type:	Original research
Date Submitted by the Author:	01-Sep-2022

Complete List of Authors:	Haque, Md; ICDDRB Choudhury, Nuzhat; ICDDRB Wahid, Barbie Zaman; ICDDRB Ahmed, SM Tanvir ; Save the Children Bangladesh Farzana, Fahmida Dil; ICDDRB Ali, Mohammad; ICDDRB Naz, Farina; ICDDRB Siddiqua, Towfida Jahan ; Johns Hopkins University, Bangladesh Rahman, Shahed ; Save the Children Bangladesh Faruque, ASG; ICDDRB Ahmed, Tahmeed; ICDDRB

Keywords:	Nutrition < TROPICAL MEDICINE, STATISTICS & RESEARCH METHODS, EPIDEMIOLOGY, PUBLIC HEALTH

I, the Submitting Author has the right to grant and does grant on behalf of all authors of the Work (as defined in the below author licence), an exclusive licence and/or a non-exclusive licence for contributions from authors who are: i) UK Crown employees; ii) where BMJ has agreed a CC-BY licence shall apply, and/or iii) in accordance with the terms applicable for US Federal Government officers or employees acting as part of their official duties; on a worldwide, perpetual, irrevocable, royalty-free basis to BMJ Publishing Group Ltd ("BMJ") its licensees and where the relevant Journal is co-owned by BMJ to the co-owners of the Journal, to publish the Work in this journal and any other BMJ products and to exploit all rights, as set out in our licence.

The Submitting Author accepts and understands that any supply made under these terms is made by BMJ to the Submitting Author unless you are acting as an employee on behalf of your employer or a postgraduate student of an affiliated institution which is paying any applicable article publishing charge ("APC") for Open Access articles. Where the Submitting Author wishes to make the Work available on an Open Access basis (and intends to pay the relevant APC), the terms of reuse of such Open Access shall be governed by a Creative Commons licence – details of these licences and which Creative Commons licence will apply to this Work are set out in our licence referred to above.

Other than as permitted in any relevant BMJ Author's Self Archiving Policies, I confirm this Work has not been accepted for publication elsewhere, is not being considered for publication elsewhere and does not duplicate material already published. I confirm all authors consent to publication of this Work and authorise the granting of this licence.

A statistical model to predict the performance of factors involved in reducing childhood stunting

Md Ahshanul Haque[1*], Nuzhat Choudhury[1,4], Barbie Zaman Wahid[1], SM Tanvir Ahmed[2], Fahmida Dil Farzana[1], Mohammad Ali[1], Farina Naz[1], Towfida Jahan Siddiqua[3], Sheikh Shahed Rahman[2], ASG Faruque[1], Tahmeed Ahmed[1]

[1] Nutrition and Clinical Services Division, icddr,b, Dhaka, 1212, Bangladesh
[2] Child Poverty Sector, Save the Children Bangladesh, Dhaka, Bangladesh
[3] Johns Hopkins University, Bangladesh
[4] Durham University, Durham, United Kingdom

*** Correspondence:** Md Ahshanul Haque, Assistant Scientist, Nutrition and Clinical Services Division, ICDDRB, 68, Shaheed Tajuddin Ahmed Sarani, Mohakhali, Dhaka 1212, Bangladesh, Email: ahshanul.haque@icddrb.org

Word count: 3656

Abstract

Objective The goal of this study was to construct a predictive modelling approach using logistic regression analysis. We propose that such a model may help to develop an intervention study to significantly reduce the prevalence of stunting among children aged 12-23 months.

Design A cluster randomized pre-post design was followed to measure the impacts on several indicators of livelihood, health, and nutrition. The study comprised a large dataset that was collected from two cross-sectional studies (baseline and endline).

Setting This study was conducted in Sylhet, a population in the northeast of Bangladesh that is vulnerable to both natural catastrophes and the consequences of poverty. It specifically targeted children between the ages of 12 and 23 months.

Main outcome measures The outcome variable in this study was childhood stunting, which was defined as a length-for-age z-score (LAZ) <-2. A multiple logistic regression model was established to predict the factors associated with childhood stunting. The predictive performance of the model was assessed by computing classification status based on model sensitivity and specificity, and area under the receiver operating characteristic (ROC) curve analysis.

Results The prevalence of stunting at baseline survey was 52.7%, whereas 50.0% were stunted at endline survey. We found that several factors were associated with childhood stunting. The sensitivity and specificity of the model were 61% and 56%, respectively. The correctly classified rate was 59%, and the area under ROC curve was 0.615.

Conclusion We predict that childhood stunting can only be reduced once the associated factors are improved by programmes or interventions. Importantly, based on the post-estimation findings and area under the ROC curve analysis, the predictive performance of the model was low. As a result, the other factors that significantly influence childhood stunting that are not included in our model urgently need to be identified.

Study registration: RIDIE-STUDY-ID-5d5678361809b

Keywords: Nutrition, Statistics, epidemiology, public health

Strengths and limitations of this study

- More precise anthropometry tools were used to measure the child's length
- The predictive performance of the logistic regression model was calculated
- To avoid seasonality, we conducted the baseline and endline surveys at the same time of year
- We did not collect food intake data, but only gathered recall data from the previous 24 hours
- Biological data were not collected

Introduction

Childhood stunting, which is defined as a height/length-for-age z-score (HAZ/LAZ) < -2, is a major concern for public health and has been widely used as an indicator of chronic malnutrition in children [1]. Although childhood stunting scenarios have much improved globally, the prevalence of child malnutrition is still very high in low-resource settings, including countries such as Bangladesh. According to the 2018 Global Nutrition Report, 150.8 million children (22.2%) under five years-of-age are stunted globally, compared to 198.4 million (32.6%) and 165 million children in 2000 and 2011, respectively [2 3]. Asian countries have observed a decline in the rate of stunting among children under five from 38.1% to 23.2% between 2000 and 2018; however, the prevalence of stunting in South Asia is 38.9%, which is reported to be the highest level across this region [2]. In Bangladesh, about 5.5 million (36%) children under five were stunted in 2014 [4], and in 2018, childhood stunting reduced to about 31% of this population [5]. As the World Health Organization (WHO) considers a childhood stunting rate of 15% to be an emergency situation, the current prevalence of childhood stunting in Bangladesh reflects an alarming situation of chronic undernutrition [28].

Undernutrition during childhood has several causes, including poor maternal health and nutrition, low maternal education, and inadequate infant and young child feeding (IYCF) practices [28]. Moreover, evidence suggests that a number of characteristics at the household level, which relate to both children and mothers, can influence childhood stunting. The characteristics of the household head, household food insecurity, the presence of unhygienic latrines, hand-washing status, household income and savings, household involvement in several earning activities, maternal healthcare service-seeking during pregnancy, household dietary diversity, number of children, maternal nutritional profile, as well as the age and sex of the child are most often reported to be associated with stunting in the literature [6-11]. However, these findings are mostly based on nationally representative cross-sectional and cohort studies, or studies conducted in urban settings [12 13]. Therefore, a knowledge gap exists on whether similar results would be obtained when nationwide data are compared with data for study populations from poor or very poor rural households in specific vulnerable regions.

Sylhet is one such vulnerable region of north-east Bangladesh, and is comprised of diverse terrain such as plain land, hilly land, *Haor* (wetland), and flash flood-prone areas. This region is reported to perform poorly for all important maternal healthcare indicators [14], despite the fact that Bangladesh has made substantial progress in improving the overall health of the population [15]. Moreover, the socio-economic profile of the inhabitants in Sylhet region includes both very rich and extremely poor people. This scenario may worsen without implementation of appropriate strategies in the near future. Sylhet region is also performing poorly compared to the national averages for a number of health and nutritional indicators. Critical indicators such as the infant mortality rate and unemployment status of women are high [12]. In comparison to the overall situation of Bangladesh, where stunting among children under five has decreased, the Bangladesh Demographic and Health Survey (BDHS) 2014 indicates the prevalence of childhood stunting in Sylhet is astonishingly high, at 50% [12]. This alarming figure provided the rationale for implementation of a comprehensive intervention programme in this region. A large-scale nutrition programme, *Suchana: Ending the Cycle of Undernutrition in Bangladesh; a multi-sectoral nutrition programme,* was undertaken with the aim to prevent chronic malnutrition in Sylhet. The primary objective of the *Suchana* programme was to reduce the prevalence of childhood stunting in the intervention areas. The secondary objectives were to assess the changes in *Suchana* beneficiaries' households, in terms of an increase and diversification of household income, food security status, optimal infant and young child feeding (IYCF) practices, haemoglobin status of children, the empowerment of women, and adolescents' nutritional knowledge and practices.

The *Suchana* programme substantially improved nutritional behaviour, maternal healthcare practices, women's empowerment, household income, and household food security in the intervention area compared to the control area [16]. Contrary to predictions, however, *Suchana* did not result in any significant reduction in the prevalence of childhood stunting. Therefore, although most other factors related to childhood stunting improved, this raises the question of why the prevalence of stunting did not reduce after the intervention. An important observation from the *Suchana* survey was that the proportion of households in this study population using hygienic latrines was quite low. This factor was associated with stunting in children, and did not significantly improve by endline in the intervention areas compared to the control areas.

In this study, we aimed to construct a predictive model to attempt to explain whether any improvements in associated factors may promote a significant reduction in stunting among children aged 12-23 months from poor and extremely poor households in Sylhet region. Thus, we constructed a predictive model using logistic regression analysis. This model could help to inform the development and design of future intervention studies that aim to significantly reduce the prevalence of stunting in children aged 12-23 months from poor and extremely poor households in vulnerable regions.

Methods

Study design and population

Source of data: The data for this study was extracted from the evaluation data of *Suchana,* a large-scale nutrition programme. This study was performed in the population resident in Sylhet (targeting children aged 12–23 months); this region in the north-east of Bangladesh is vulnerable to natural disasters as well as the consequences of poverty [17,18]. A pre-post design was followed to measure the impacts on several indicators of livelihood, health, and nutrition. The study comprised a large dataset that was collected from two cross-sectional studies (baseline and endline). The baseline survey was conducted between November 2016 and February 2017, while the endline survey was undertaken three years later, during the same months. The sample size for this analysis was 9600 mother-child pairs (baseline: 3200, and endline: 6400). This sample size was estimated to be required to effectively test the hypothesis that the *Suchana* intervention would lead to a significant reduction in stunting among children aged 12–23 months [17].

Variables under study: The outcome variable in this study was childhood stunting, which was defined as a length-for-age z-score (LAZ) <-2. Initially, a list of several independent variables was finalized through results obtained from descriptive and bi-variate analyses, as well as a comprehensive literature review. These included characteristics pertaining to children (age, sex, whether they received colostrum), maternal characteristics (nutritional status, whether they received at least four ANC visits by a skilled service provider, if delivery was assisted by a skilled birth attendant in a facility, their involvement in earning activities, consumption of fleshy foods, number of children in the family) and household characteristics (household food insecurity access scale [HFIAS], household size, hygienic latrine availability, water and soap available at handwashing place, household income, savings at the household level, sex of the head of the household, and active participation in aquaculture). HFIAS was measured using the Food and Nutrition Technical Assistance's Guideline, which categorizes household food insecurity into four levels: a) food secure, b) mildly food insecure, c) moderately food insecure, and d) severely food insecure [19]. In the analysis herein, this indicator was redefined as a binary indicator: severely food insecure or not severely food insecure.

Statistical analysis

Descriptive statistics: Stata-14 software (StataCorp LP, College Station, TX, USA) was used to analyse the data. Several statistical plots were used for data visualization. Descriptive statistics, such as frequency and proportions for categorical variables and mean and standard deviations for quantitative variables, were used to summarize the data at baseline and endline.

Regression model: Due to the dichotomous outcome variable, a binary logit model was used in regression analysis to investigate which factors were significantly associated with childhood stunting, and estimate their effect size, in order to predict whether changes in behavioural practices might potentially help to achieve targeted reductions in stunting. Then, *union* was adjusted for as a cluster variable to control intra-cluster correlation. First, simple logistic regression models were used to examine the bivariate associations between stunting and all possible explanatory variables. In the second step, variables with *p*-values <0.25 in the simple model were included in the multiple regression models [20]. In the final step, any independent variables thought to be likely predictors were added to the multiple regression model using the stepwise forward selection method. Some indicators, e.g., age, sex, and maternal nutritional status, were added regardless of their *p*-value due to their scientific plausibility. Furthermore, for the explanation of the regression model, a *p*-value <0.05 was considered as significant, and the confidence interval (CI) of 95% was also reviewed. From the fitted model, the adjusted effect size or adjusted prevalence adjusted risk difference (aRD) against all predictors was estimated using the Stata "*adjrr*" package.

Model evaluation: The Hosmer-Lemeshow Chi-Square test was used to test the goodness-of-fit of the model. The predictive performance was assessed by computing the classification status using model sensitivity and specificity, area under the receiver operating curve (ROC) analysis. Data were randomly split into a training set (75% of the data) and a test set (25%) to calculate the accuracy of the algorithm. The same training and test datasets were used for all algorithms and performance predictions.

Patient and public involvement

Patients and public were not actively involved in formulating the research question and or protocol development, including the outcome measures. To expedite the field implementation, however, local elites e.g. teachers, religious person, and local government council members were informed about the study.

Results

General characteristics: With respect to the outcome indicator, stunting in children aged 12-23 months, 52.7% of children were stunted at the baseline survey (intervention group: 52.6%; control group: 52.8%), whereas the proportion of children exhibiting stunting at endline was 50.0% (intervention: 49.9%; control: 50.1%; Figure 1). Figure 2 describes some other output indicators related to maternal and child health. Status of consuming minimum acceptable diet (intervention: 35.2%; control: 14.9%), minimum dietary diversity (intervention: 42.8%; control: 20.4%), maternal decision making (intervention: 45.0%; control: 31.0%), at least four maternal ANC visits by a skilled service provider (intervention: 36.1%; control: 17.7%), minimum dietary diversity for women (intervention: 52.6%; control: 33.5%), a household dietary diversity score of at least seven (intervention: 88.9%; control: 78.3%), and household food security status (intervention: 26.6%; control: 20.2%) were significantly improved in the intervention group compared to the control group at endline survey. The availability of hygienic latrines (intervention: 44.0%; control: 44.0%) did not increase after the intervention. The households' socio-demographic characteristics, women's general characteristics, and children's characteristics at baseline and endline are shown in Table 1.

Table 1. General characteristics of the *Suchana* beneficiaries

Indicators, *n* (%)	Baseline *N*=3200	Endline *N*=6300	Total *N*=9500
At least four ANC visits by a skilled service provider			
Yes	408 (12.8)	1530 (24.3)	1938 (20.4)
No	2792 (87.3)	4771 (75.7)	7563 (79.6)
Delivery at skilled birth attendant/facility			
Yes	1000 (31.3)	2769 (44)	3769 (39.7)

Indicators, *n* (%)	Baseline *N*=3200	Endline *N*=6300	Total *N*=9500
No	2200 (68.8)	3532 (56.1)	5732 (60.3)
Had tetanus toxoid injection			
No	834 (26.1)	1131 (18)	1965 (20.7)
Yes	2366 (73.9)	5170 (82.1)	7536 (79.3)
Mother involved in income-generating activities			
No	3102 (96.9)	5665 (89.9)	8767 (92.3)
Yes	98 (3.1)	639 (10.1)	737 (7.8)
Maternal BMI			
BMI ≥18.5	1859 (58.1)	4073 (64.6)	5932 (62.4)
BMI <18.5	1341 (41.9)	2231 (35.4)	3572 (37.6)
Mother completed primary education			
Yes	1721 (53.8)	3808 (60.4)	5529 (58.2)
No	1479 (46.2)	2496 (39.6)	3975 (41.8)
Maternal age			
Age <30 years	2145 (67)	3559 (56.5)	5704 (60)
Age ≥30 years	1055 (33)	2745 (43.5)	3800 (40)
Type of delivery			
Normal	2879 (90)	5529 (87.8)	8408 (88.5)
Caesarean	321 (10)	772 (12.3)	1093 (11.5)
PNC			
No	2152 (67.3)	4128 (65.5)	6280 (66.1)
Yes	1048 (32.8)	2173 (34.5)	3221 (33.9)
Household severely food insecure			
Yes	912 (28.5)	1016 (16.12)	1928 (20.3)
No	2288 (71.5)	5285 (83.9)	7573 (79.7)
Household monthly income ≥15000 BDT			
Yes	424 (13.3)	1015 (16.1)	1439 (15.1)
No	2776 (86.8)	5289 (83.9)	8065 (84.9)
Household involved with aquaculture			
Yes	161 (5)	561 (8.9)	722 (7.6)
No	3039 (95)	5740 (91.1)	8779 (92.4)
Hygienic latrine			
Yes	1121 (35)	2782 (44.2)	3903 (41.1)
No	2079 (65)	3519 (55.9)	5598 (58.9)
Water and soap available in handwashing place			
Yes	862 (26.9)	3170 (50.3)	4032 (42.4)
No	2338 (73.1)	3131 (49.7)	5469 (57.6)
Household savings			
No	1080 (33.8)	2876 (45.6)	3956 (41.6)
Yes	2120 (66.3)	3425 (54.4)	5545 (58.4)
Sex of household head			
Female	110 (3.4)	501 (8)	611 (6.4)
Male	3090 (96.6)	5799 (92.1)	8889 (93.6)
Source of drinking water			
Tube well	2748 (85.9)	5713 (90.7)	8461 (89.1)
Others	452 (14.1)	588 (9.3)	1040 (11)
Household dietary diversity score			
HDDS ≥7	2182 (68.2)	5322 (84.5)	7504 (79)
HDDS <7	1018 (31.8)	979 (15.5)	1997 (21)

Indicators, *n* (%)	Baseline *N*=3200	Endline *N*=6300	Total *N*=9500
Household monthly income (Thousand BDT)[1]	6.7 (5, 10)	7.5 (5.1, 10.8)	7.1 (5, 10.4)
Per capita income (Thousand)[1]	2.6 (1.8, 3.7)	2.9 (2, 4.1)	2.8 (2, 4)
Household size[1]	6.2±2.4	5.9±2.1	6±2.2
Child's age in months[2]	17.9±3.5	17.3±3.6	17.5±3.6
Length-for-age z-score[2]	-2.1±1.2	-2±1.1	-2±1.1
Weight-for-age z-score[2]	-1.7±1.1	-1.5±1.0	-1.5±1.0
Weight-for-length z-score[2]	-0.9±1.0	-0.7±0.9	-0.7±1.0
Child's age			
Age <18 months	1745 (54.5)	3710 (58.9)	5455 (57.4)
Age ≥18 months	1455 (45.5)	2594 (41.2)	4049 (42.6)
Child's sex			
Female	1567 (49)	3044 (48.3)	4611 (48.5)
Male	1633 (51)	3257 (51.7)	4890 (51.5)
Child experienced respiratory illness in last 15 days			
Yes	2867 (89.6)	5763 (91.5)	8630 (90.8)
No	333 (10.4)	538 (8.5)	871 (9.2)

[1]Median (IQR); [2]Mean ± SD.

Associated factors: The factors associated with childhood stunting as determined by model fitting are shown in Table 2. Less than four ANC visits [aOR: 1.16 (95% CI: 1.05, 1.30); *P*=0.005], unskilled birth attendant/facility [aOR: 1.11 (95% CI: 1.02, 1.20); *P*=0.012], mother involved in income-generating activities [aOR: 1.18 (95% CI: 1.02, 1.37); *P*=0.030], maternal BMI <18.5 [aOR: 1.23 (95% CI: 1.12, 1.36); *P*<0.001], maternal education: no schooling [aOR: 1.31 (95% CI: 1.20, 1.42); *P*<0.001], household severely food insecure [aOR: 1.12 (95% CI: 1.00, 1.24); *P*=0.041], household monthly income <15000 BDT [aOR: 1.12 (95% CI: 1.01, 1.25); *P*=0.037], household not involved with aquaculture [aOR: 1.19 (95% CI: 1.03, 1.38); *P*=0.018], having an unhygienic latrine [aOR: 1.20 (95% CI: 1.10, 1.30); *P*<0.001], no soap available in handwashing place [aOR: 1.19 (95% CI: 1.08, 1.30); *P*<0.001], household size >7 [aOR: 1.20 (95% CI: 1.11, 1.31); *P*<0.001], household dietary diversity score <7 [aOR: 1.17 (95% CI: 1.07, 1.29); *P*=0.001], child's age >18 months [aOR: 1.52 (95% CI: 1.39, 1.67); P<0.001], child's sex: male [aOR: 1.22 (95% CI: 1.11, 1.34); *P*<0.001], childhood illness in the last 15 days [aOR: 1.20 (95% CI: 1.06, 1.36); *P*=0.003], and no access to mass media [aOR: 1.15 (95% CI: 1.02, 1.30); *P*=0.025] were associated with childhood stunting. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) are given in Supplementary Table 1.

Table 2. Logistic regression of factors influencing stunting in children aged 12-23 months.

Indicators	Unadjusted OR (95% CI)	p-value	Adjusted OR (95% CI)	p-value
At least four ANC visits by a skilled service provider				
Yes	Reference		Reference	
No	1.40 (1.26, 1.56)	<0.001	1.16 (1.05, 1.30)	0.005
Birth attendant/facility				
Skilled	Reference		Reference	
Unskilled	1.29 (1.20, 1.39)	<0.001	1.11 (1.02, 1.20)	0.012
Mother involved in income-generating activities				
No	Reference		Reference	
Yes	1.12 (0.97, 1.29)	0.116	1.18 (1.02, 1.37)	0.030
Maternal BMI				
BMI ≥18.5				
BMI <18.5	1.31 (1.19, 1.45)	<0.001	1.23 (1.12, 1.36)	<0.001
Maternal education was primary completed				
Yes	Reference		Reference	
No	1.51 (1.39, 1.64)	<0.001	1.31 (1.20, 1.42)	<0.001
HH food insecurity				
Below severe				
Severe	1.34 (1.21, 1.48)	<0.001	1.12 (1.00, 1.24)	0.041
HH monthly income ≥15000 BDT				
Yes	Reference		Reference	
No	1.25 (1.13, 1.37)	<0.001	1.12 (1.01, 1.25)	0.037
Involved with aquaculture				
Yes	Reference		Reference	
No	1.34 (1.16, 1.54)	<0.001	1.19 (1.03, 1.38)	0.018
Hygienic latrine				
Yes	Reference		Reference	
No	1.38 (1.28, 1.50)	<0.001	1.20 (1.10, 1.30)	<0.001
Water and soap available in handwashing place				
Yes	Reference		Reference	
No	1.38 (1.26, 1.52)	<0.001	1.19 (1.08, 1.30)	<0.001
HH size				
Below seven	Reference		Reference	
Seven or above	1.19 (1.10, 1.29)	<0.001	1.20 (1.11, 1.31)	<0.001
HH dietary diversity				
HDDS ≥7	Reference		Reference	
HDDS <7	1.32 (1.20, 1.44)	<0.001	1.17 (1.07, 1.29)	<0.001
Child's age				
Age ≤18 months	Reference		Reference	
Age >18 months	1.49 (1.36, 1.63)	<0.001	1.52 (1.39, 1.67)	<0.001
Child's sex				
Female	Reference		Reference	
Male	1.23 (1.12, 1.34)	<0.001	1.22 (1.11, 1.34)	<0.001
Childhood illness in the last 15 days				
No	Reference		Reference	
Yes	1.16 (1.03, 1.31)	0.016	1.20 (1.06, 1.36)	0.003
Access of mass media				
Yes	Reference		Reference	
No	1.39 (1.22, 1.58)	<0.001	1.15 (1.02, 1.30)	0.025

Unions were adjusted as clusters. Baseline and endline were adjusted as time variables.

Model diagnostics: The Chi-square value for the Hosmer-Lemeshow goodness-of-fit test was 9482 (P=0.430), which indicated that the model was a good fit. Figure 3A describes the model validation based on sensitivity, specificity, and whether the model was correctly classified for the overall dataset, as well as the training and test datasets. The sensitivity and specificity of the model were 61% and 56%, respectively. The correctly classified rate was 59%, and the area under ROC curve was 0.615 (Figure 3B). We found that these values were approximately equal among the three datasets (main, training, and test datasets); however, the predictive performance of the model was low.

Discussion

This study examined data collected during the baseline and endline surveys of the *Suchana* programme to identify factors significantly associated with childhood stunting, with the goal of understanding why this programme did not significantly reduce the prevalence of childhood stunting. After controlling for *union* as a cluster variable, we found numerous factors were significantly associated with stunting, including less than four maternal ANC visits by a skilled service provider, unskilled birth attendant in facility, mothers being involved in earning activities, maternal BMI <18.5, maternal education: no schooling, households being severely food insecure, household monthly income <15000 BDT, no household involvement with aquaculture, having an unhygienic latrine, unavailability of soap in handwashing place, male head of the household, household size >7, household dietary diversity score <7, child's age in months, if the child was male, or if the child experienced respiratory illness in the last 15 days.

Of these indicators, the status of ANC visits by a skilled service provider, household dietary diversity, household food security, and household monthly income improved after the intervention. Notably, household food security status did not reach its target value of 50%, and this is an important factor associated with childhood stunting [6 21 22]. Other *Suchana* outcome indicators, such as the dietary diversity of children, maternal dietary diversity, and maternal empowerment, were not associated with stunting in this study. We found a negative association between stunting and maternal involvement in income-generating activities, which means the risk of stunting was higher among children whose mothers were involved in various types of earning activities. The proportion of mothers involved in income-generating activities increased after the study, although the increase was very small.

The current study indicates that although some programme indicators improved significantly after the intervention, the *Suchana* programme did not lead to a significant reduction in the prevalence of childhood stunting. The most important factors associated with childhood stunting, such as maternal nutrition and education, having a hygienic latrine, soap being available in handwashing places, and improved sources of drinking water, were not improved after the intervention. More so, both maternal education and nutrition are factors that can only be improved on the large-scale when appropriate measures are taken at the policy-level.

This study will help programme managers to prioritize attention when designing appropriate interventions to reduce childhood stunting. In our evaluation study, some important indicators such as maternal undernutrition, low levels of maternal education, household food insecurity, households not being involved with aquaculture, unsanitary latrines, lack of soap in the handwashing place, and child morbidity did not improve—as expected. Therefore, one would only expect childhood stunting to reduce to the target level once these factors are improved or addressed by future programmes/interventions. Implementing short-term initiatives could help to improve some of these factors. *Per se*, attending courtyard workshops and campaigns organized by healthcare practitioners can boost ANC visits, skilled birth attendance and handwashing practices. Greater access to the media can help people in these vulnerable communities to receive the full benefits of government welfare programs. Simply purchasing media and information gadgets can boost households' access to mass media. Food security, income, sanitation, aquaculture, and illness are all time-dependent factors. For instance, to reduce household food insecurity, the yields of produce need to be increased through self-production or purchases to fulfil the dietary demands of all household members. However, a family's ability to acquire appropriate food is also impacted by the family's wealth index, not to mention the number of accessible marketplaces nearby; however, amelioration of all these elements takes a considerable amount of time. Increasing production yields through self-production is also time-consuming. Promotion of aquaculture during the *Suchana* programme increased the availability of fish and provided a viable source of protein, which resulted in better nutrition and food security; however, establishing such facilities also takes a significant amount of time. Furthermore, improved sanitation can only be facilitated by improving socioeconomic status, which is also a time-intensive process. National surveys, including the BDHS and The Food Security and National Surveillance Project (FSNSP) have indicated a substantial amount of time is required to improve stunting. To improve maternal nutrition, women should be provided with adequate food to improve their nutritional status during adolescence, as children born to malnourished mothers are at a higher risk of malnutrition. Moreover, according to a previous literature review, a mother's education is a strong predictor of her child's nutritional status. Childhood stunting is significantly associated with the level of maternal education, with the children of mothers with either no or less than secondary education at higher risk of stunting compared to the children of mothers that have completed secondary education or more. Moreover, emphasis on the education of female children may contribute to breaking the vicious cycle of poverty and childhood stunting in developing countries like Bangladesh. However, both maternal education and nutrition can only be improved on the large-scale only when appropriate measures are taken at the policy level. In addition, comprehensive initiatives to encourage income-generating activities among women and address domestic violence against women should be implemented to help reduce childhood stunting in developing countries.

Another important finding based on the post-estimation findings as well as the value of the area under the ROC curve was that the predictive performance of the model was low. Thus, we need to identify other the indicators that influence childhood stunting that were not included in our model. From the literature, environmental enteropathy has been implicated in poor growth among children in rural Bangladesh [23]. Environmental enteropathy may also represent an important hidden factor with respect to the *Suchana* study population. While it was not assessed in this study, some indicators of the enteropathogen burden—such as unsanitary latrines, low education, unimproved floors, and a lack of handwashing practice—were available in this study [13 24]. Poultry was one of the intervention components. Our qualitative findings revealed that the people in the majority of households were living in the same place as their poultry, ducks, or other animals, which may increase the risk of infections with *Campylobacter* species, a leading food-borne pathogen [13 25].

Studies have provided evidence of a strong association between stunting and enteropathy among children who fail to respond to nutritional interventions [26]. Findings from rural Bangladesh have also shown significant associations between environmental conditions and stunting in children [27] [28]. However, assessment of environmental enteropathy was beyond the scope of the *Suchana* evaluation. For evaluation purposes, evaluation teams could collect data on indicators of enteropathy in the intervention and control areas, and then use the model to assess the impact of appropriate interventions.

The large sample size, randomization, and appropriate sampling techniques were among the major strengths of this study. There was a dedicated quality control team who were involved in checking data by re-visiting randomly selected households which had been used to previously collect data. We used highly precise anthropometry instruments, and the anthropometry measurement team received separate training from a qualified trainer. To avoid seasonality, we conducted the baseline and endline surveys at the same time of year. Among the limitations of this study is the fact that we did not collect food intake data, but only gathered recall data from the previous 24 hours. These data may be subject to recall bias, thus caution is necessary when drawing conclusions, especially for indicators such as dietary diversity, household food insecurity, domestic violence, and maternal healthcare.

Conclusion

By acknowledging that undernutrition is a complex problem caused by a variety of factors, the *Suchana* model offers a holistic and integrated approach to tackling food and nutrition security. The endline survey showed many of the programme indicators improved considerably as a result of the intervention. Our model revealed that ANC visits, being attended by an unskilled birth attendant, maternal income-generating activities, maternal undernutrition, maternal education, food security, household income, participation in aquaculture, an unhygienic latrine, a lack of soap availability, male household head, household size, dietary diversity score, child's age, a male child, and childhood respiratory illness were all associated with stunting. However, the performance of our predictive model was low. Ultimately, the design of *Suchana* offers a meaningful solution to tackle undernutrition through a multi-sector approach. However, some additional recommendations related to both nutrition-sensitive and specific activities can be made, which could be taken on board and put into action by policy makers. Food security status should be improved through sustainable mechanisms. Climate-resilient agricultural technologies should be constantly promoted and effectively monitored as a component of recommended improved agricultural strategies. Improved capacity for preparedness and response plans against flooding are also required, so that poor people are not continuously set back by shocks. Coverage for water, sanitation, and hygiene must be increased at the community level. However, the *Suchana* programme, one of the largest nutrition interventions ever implemented globally, successfully led to positive changes in most critical study indicators. Long-term positive changes in the health and livelihoods of the beneficiaries are expected in the years to follow.

Acknowledgments: The study analyzed baseline survey data of *Suchana*; this intervention has been implemented by a consortium led by Save the Children, with support from the Foreign, Commonwealth and Development Office (FCDO) and European Union (EU). icddr,b acknowledges with gratitude the commitment of Save the Children, FCDO and EU to its research efforts. We also acknowledge with gratitude the commitment of the Government of the People's Republic of Bangladesh to icddr,b's research activities. We also acknowledge the following donors for providing unrestricted support to icddr,b's efforts and advancement of its strategic plan: Canada, Sweden and the United Kingdom. We gratefully acknowledge our core donors for their support and commitment to icddr,b's research efforts. We would like to acknowledge the invaluable contributions of Save the Children as lead agency, our technical partners Helen Keller International, World Fish, and International Development Enterprises, and the implementing partners Friends In Village Development Bangladesh (FIVDB), Rangpur Dinajpur Rural Services (RDRS), and the Center for Natural Resource Studies (CNRS) who played critical roles in generating and refining the data-collection tools. We would also like to acknowledge Andrea Devlin of Science Editing Experts for editing and linguistic revision of the manuscript.

Funding: (i) This study was made possible by the committed contribution of Foreign, Commonwealth and Development Office (Grant number: 204131-103), and (ii) icddr,b (N/A).

Conflicts of Interest: The authors declare no conflict of interest.

Author Contributions: TA and NC originated the idea for the study and led the protocol design. MAH conceptualized the manuscript. SMTA, SSR, MJR, MAH, NC, FDF, and TA contributed to the survey design. MAH performed statistical analysis and drafted the manuscript. NC and ASGF supervised the work, and critically reviewed and provided feedback for revising the manuscript. MAH, NC, MA, FDF, FN, AK, RA, BZW, TJS, ASGF, TA, and SSR contributed to the revision of the final draft for submission. All authors are responsible for the final content of the manuscript.

Ethics approval: This study was approved by the Research Review Committee and Ethical Review Committee, the two obligatory components of the Institutional Review Board (IRB) of icddr,b (PR-16020). Informed written consent was obtained from study participants.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

Reference

1. Bari A, Nazar M, Iftikhar A, et al. Comparison of Weight-for-Height Z-score and Mid-Upper Arm Circumference to Diagnose Moderate and Severe Acute Malnutrition in children aged 6-59 months. *Pakistan journal of medical sciences* 2019;35(2):337-41. doi: 10.12669/pjms.35.2.45 [published Online First: 2019/05/16]

2. Development Initiatives. 2018 Global Nutrition Report: Shining a light to spur action on nutrition. Bristol, UK: Development Initiatives, 2018.

3. United Nations Children's Fund (UNICEF), World Health Organization, International Bank for Reconstruction and Development/The World Bank. Levels and trends in child malnutrition: Key Findings of the 2020 Edition of the Joint Child Malnutrition Estimates. Geneva: World Health Organization; 2020. Licence: CC BY-NC-SA 3.0 IGO., 2020.

4. USAID. Bangladesh: Nutrition Profile, 2018.

5. National Institute of Population Research and Training (NIPORT), ICF. Bangladesh Demographic and Health Survey 2017-18: Key Indicators. NIPORT and ICF: Dhaka, Bangladesh and Rockville, Maryland, USA, 2019.

6. Choudhury N, Raihan MJ, Sultana S, et al. Determinants of age-specific undernutrition in children aged less than 2 years-the Bangladesh context. *Maternal & child nutrition* 2017;13(3) [published Online First: 2016/10/19]

7. Hasan M, Sutradhar I, Shahabuddin A, et al. Double Burden of Malnutrition among Bangladeshi Women: A Literature Review. *Cureus* 2017;9(12)

8. Balarajan Y, Villamor E. Nationally representative surveys show recent increases in the prevalence of overweight and obesity among women of reproductive age in Bangladesh, Nepal, and India. *The Journal of nutrition* 2009;139(11):2139-44. [published Online First: 2009/09/25]

9. Khan MM, Kraemer A. Factors associated with being underweight, overweight and obese among ever-married non-pregnant urban women in Bangladesh. *Singapore medical journal* 2009;50(8):804-13. [published Online First: 2009/08/28]

10. Kamal SM, Hassan CH, Alam GM. Dual burden of underweight and overweight among women in Bangladesh: patterns, prevalence, and sociodemographic correlates. *Journal of Health, Population and Nutrition* 2015;33(1):92-105. [published Online First: 2015/05/23]

11. Corsi DJ, Kyu HH, Subramanian SV. Socioeconomic and geographic patterning of under- and overnutrition among women in Bangladesh. *The Journal of nutrition* 2011;141(4):631-8. [published Online First: 2011/02/25]

12. National Institute of Population Research and Training - NIPORT/Bangladesh, Mitra and Associates, ICF International. Bangladesh Demographic and Health Survey 2014. NIPORT, Mitra and Associates, and ICF International: Dhaka, Bangladesh and Rockville, Maryland, USA, 2016.

13. Haque MA, Platts-Mills JA, Mduma E, et al. Determinants of Campylobacter infection and association with growth and enteric inflammation in children under 2 years of age in low-resource settings. *Scientific reports* 2019;9(1):17124. [published Online First: 2019/11/22]

14. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH). State of food security and nutrition in Bangladesh 2013. HKI and JPGSPH, 2014.

15. Yaya S, Bishwajit G, Ekholuenetale M, et al. Awareness and utilization of community clinic services among women in rural areas in Bangladesh: A cross-sectional study. *PLOS ONE* 2017;12(10):e0187303. doi: 10.1371/journal.pone.0187303

16. Haque MA, Choudhury N, Ahmed SMT, et al. The large-scale community-based programme 'Suchana' improved maternal healthcare practices in north-eastern Bangladesh: Findings from a cluster randomized pre-post study. *Maternal & child nutrition* 2022;18(1):e13258. doi: https://doi.org/10.1111/mcn.13258

17. Choudhury N, Raihan MJ, Ahmed SMT, et al. The evaluation of Suchana, a large-scale development programme to prevent chronic undernutrition in north-eastern Bangladesh. *BMC public health* 2020;20(1):744. [published Online First: 2020/05/24]

18. Haque MA, Choudhury N, Ahmed SMT, et al. Factors associated with domestic violence in rural Bangladesh. *Journal of Interpersonal Violence* 2020;37(3-4):1248-69.

19. Coates J, Swindale A, Bilinsky P. Household Food Insecurity Access Scale (HFIAS) for measurement of food access: indicator guide (v. 3). Washington, D.C.: Food and Nutrition Technical Assistance Project, Academy for Educational Development 2007.

20. Bursac Z, Gauss CH, Williams DK, et al. Purposeful selection of variables in logistic regression. *Source code for biology and medicine* 2008;3:17.

21. Weatherspoon DD, Miller S, Ngabitsinze JC, et al. Stunting, food security, markets and food policy in Rwanda. *BMC public health* 2019;19(1):882. doi: 10.1186/s12889-019-7208-0 [published Online First: 2019/07/06]

22. Agho KE, Mukabutera C, Mukazi M, et al. Moderate and severe household food insecurity predicts stunting and severe stunting among Rwanda children aged 6-59 months residing in Gicumbi district. *Maternal & child nutrition* 2019;15(3):e12767. doi: 10.1111/mcn.12767 [published Online First: 2018/12/15]

23. Lin A, Arnold BF, Afreen S, et al. Household environmental conditions are associated with enteropathy and impaired growth in rural Bangladesh. *The American journal of tropical medicine and hygiene* 2013;89(1):130-37. doi: 10.4269/ajtmh.12-0629 [published Online First: 2013/05/01]

24. Amour C, Gratz J, Mduma E, et al. Epidemiology and Impact of Campylobacter Infection in Children in 8 Low-Resource Settings: Results From the MAL-ED Study. *Clin Infect Dis* 2016;63(9):1171-79. doi: 10.1093/cid/ciw542 [published Online First: 08/07]

485 25. Smith S, Meade J, Gibbons J, et al. The impact of environmental conditions on Campylobacter jejuni survival in broiler faeces and litter. *Infect Ecol Epidemiol* 2016;6:31685-85. doi: 10.3402/iee.v6.31685

488 26. Chen RY, Kung VL, Das S, et al. Duodenal Microbiota in Stunted Undernourished Children with Enteropathy. 2020;383(4):321-33.

490 27. George CM, Oldja L, Biswas SK, et al. Fecal markers of environmental enteropathy are associated with animal exposure and caregiver hygiene in Bangladesh. 2015;93(2):269-75.

492 28. Perin J, Burrowes V, Almeida M, et al. A Retrospective Case–Control Study of the Relationship between the Gut Microbiota, Enteropathy, and Child Growth. 2020:tpmd190761.

494
495

Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline.

Figure 2. Results framework and *Suchana* log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

Figure 3. (A) Predictive performance of the model for stunting based on classification, sensitivity, and specificity in the full, training and test datasets. (B) Area under the receiver operating characteristic (ROC) curve analysis of the predictive performance of the logistic regression model for stunting.

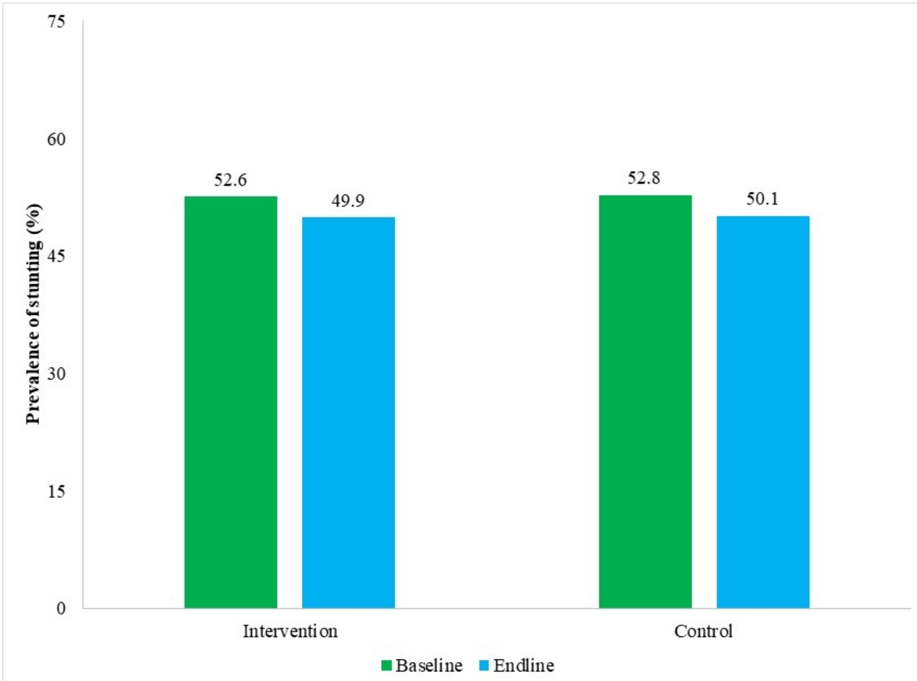


Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline.

254x190mm (96 x 96 DPI)

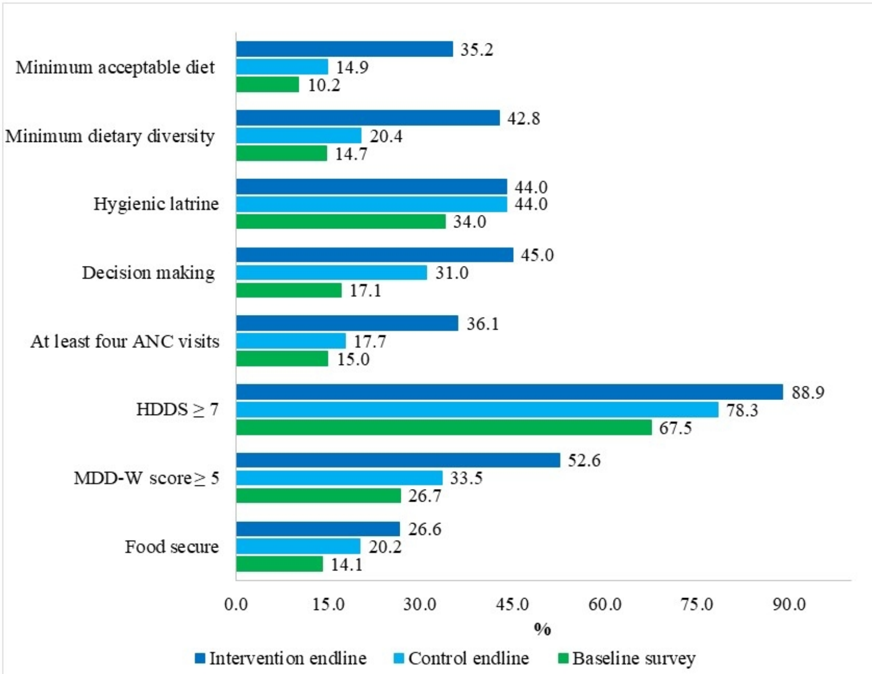
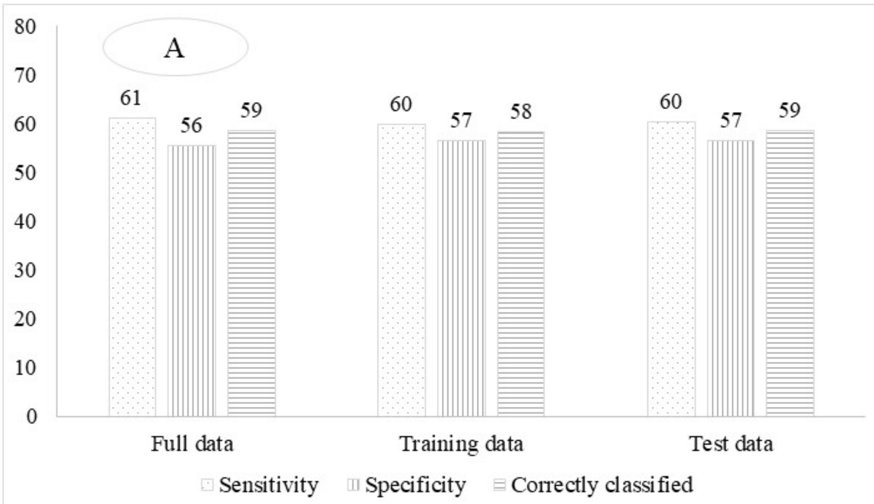


Figure 2. Results framework and Suchana log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

254x190mm (96 x 96 DPI)



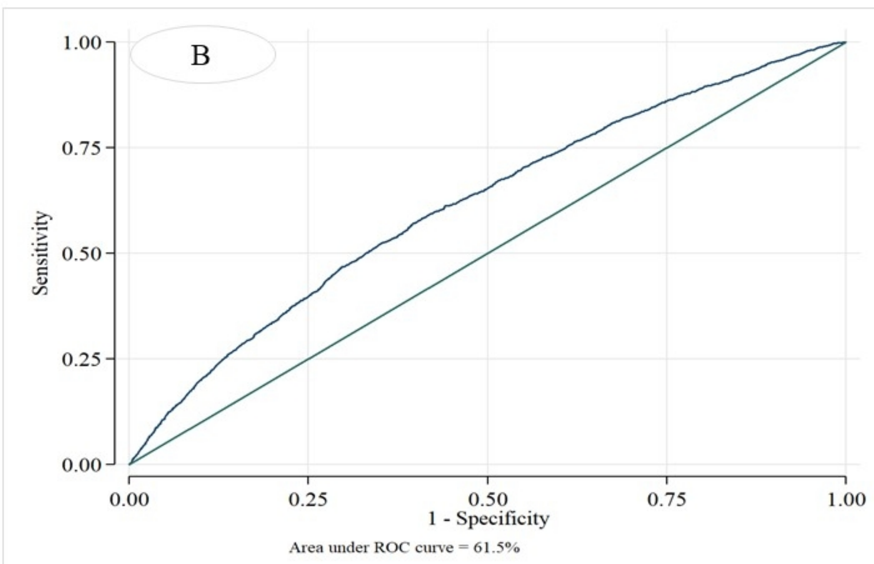


Figure 3. (A) Predictive performance of the model for stunting based on classification, sensitivity, and specificity in the full, training and test datasets. (B) Area under the receiver operating characteristic (ROC) curve analysis of the predictive performance of the logistic regression model for stunting.

203x254mm (96 x 96 DPI)

Supplementary Table 1 Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple logistic regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.07, 6.22)	0.006
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	0.000
Unskilled	49.42 (47.48, 51.36)	2.45 (0.55, 4.35)	0.012
Mother involved in income-generating activities			
No	54.55 (50.90, 58.19)	Reference	0.000
Yes	50.59 (49.08, 52.11)	3.95 (0.40, 7.51)	0.029
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	0.000
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.41)	0.000
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	0.000
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.40)	0.000
HH food insecurity			
Below severe	53.03 (50.91, 55.15)	Reference	0.000
Severe	50.36 (48.63, 52.09)	2.66 (0.11, 5.22)	0.041
HH monthly income ≥15000 BDT			
Yes	51.31 (49.79, 52.84)	Reference	0.000
No	48.58 (45.86, 51.30)	2.73 (0.17, 5.30)	0.037
Involved with aquaculture			
Yes	51.22 (49.72, 52.72)	Reference	0.000
No	46.99 (43.30, 50.69)	4.23 (0.73, 7.73)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	0.000
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	0.000
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	0.000
No	48.54 (46.74, 50.33)	4.10 (1.83, 6.38)	0.000
HH size			
Below seven	53.86 (51.98, 55.74)	Reference	0.000
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	0.000
HH dietary diversity			
HDDS ≥7	53.92 (51.25, 56.60)	Reference	0.000
HDDS <7	50.10 (48.70, 51.50)	3.83 (1.63, 6.02)	0.000
Child's age			
Age ≤18 months	56.72 (54.77, 58.67)	Reference	0.000
Age >18 months	46.59 (44.82, 48.35)	10.1 (7.94, 12.32)	0.000
Child's sex			
Female	53.25 (51.17, 55.34)	Reference	0.000
Male	48.40 (46.78, 50.03)	4.85 (2.59, 7.10)	0.000
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.77)	Reference	0.000
Yes	50.49 (48.94, 52.05)	4.41 (1.48, 7.34)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	0.000
No	48.13 (45.39, 50.88)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package.

STROBE Statement—Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	1-2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-5
Objectives	3	State specific objectives, including any prespecified hypotheses	5
Methods			
Study design	4	Present key elements of study design early in the paper	5
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	5-6
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	5-6
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	5-6
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	*5-6*
Bias	9	Describe any efforts to address potential sources of bias	10
Study size	10	Explain how the study size was arrived at	5
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	5-6
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	6-7
		(*b*) Describe any methods used to examine subgroups and interactions	
		(*c*) Explain how missing data were addressed	
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	6-7
		(*e*) Describe any sensitivity analyses	
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	7
		(b) Give reasons for non-participation at each stage	
		(c) Consider use of a flow diagram	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	7
		(b) Indicate number of participants with missing data for each variable of interest	
Outcome data	15*	Report numbers of outcome events or summary measures	7
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	7-8

		(*b*) Report category boundaries when continuous variables were categorized	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	7-8
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
Discussion			
Key results	18	Summarise key results with reference to study objectives	8-9
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	10
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	9-10
Generalisability	21	Discuss the generalisability (external validity) of the study results	9-10
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	13

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

BMJ Open

A predictive modelling approach to illustrate factors correlating with stunting

Journal:	*BMJ Open*
Manuscript ID	bmjopen-2022-067961.R1
Article Type:	Original research
Date Submitted by the Author:	03-Jan-2023
Complete List of Authors:	Haque, Md; ICDDRB Choudhury, Nuzhat; ICDDRB Wahid, Barbie Zaman; ICDDRB Ahmed, SM Tanvir ; Save the Children Bangladesh Farzana, Fahmida Dil; ICDDRB Ali, Mohammad; ICDDRB Naz, Farina; ICDDRB Siddiqua, Towfida Jahan ; Johns Hopkins University, Bangladesh Rahman, Shahed ; Save the Children Bangladesh Faruque, ASG; ICDDRB Ahmed, Tahmeed; ICDDRB
Primary Subject Heading:	Epidemiology
Secondary Subject Heading:	Public health
Keywords:	Nutrition < TROPICAL MEDICINE, STATISTICS & RESEARCH METHODS, EPIDEMIOLOGY, PUBLIC HEALTH

I, the Submitting Author has the right to grant and does grant on behalf of all authors of the Work (as defined in the below author licence), an exclusive licence and/or a non-exclusive licence for contributions from authors who are: i) UK Crown employees; ii) where BMJ has agreed a CC-BY licence shall apply, and/or iii) in accordance with the terms applicable for US Federal Government officers or employees acting as part of their official duties; on a worldwide, perpetual, irrevocable, royalty-free basis to BMJ Publishing Group Ltd ("BMJ") its licensees and where the relevant Journal is co-owned by BMJ to the co-owners of the Journal, to publish the Work in this journal and any other BMJ products and to exploit all rights, as set out in our licence.

The Submitting Author accepts and understands that any supply made under these terms is made by BMJ to the Submitting Author unless you are acting as an employee on behalf of your employer or a postgraduate student of an affiliated institution which is paying any applicable article publishing charge ("APC") for Open Access articles. Where the Submitting Author wishes to make the Work available on an Open Access basis (and intends to pay the relevant APC), the terms of reuse of such Open Access shall be governed by a Creative Commons licence – details of these licences and which Creative Commons licence will apply to this Work are set out in our licence referred to above.

Other than as permitted in any relevant BMJ Author's Self Archiving Policies, I confirm this Work has not been accepted for publication elsewhere, is not being considered for publication elsewhere and does not duplicate material already published. I confirm all authors consent to publication of this Work and authorise the granting of this licence.

A predictive modelling approach to illustrate factors correlating with stunting

Md Ahshanul Haque[1*], Nuzhat Choudhury[1,4], Barbie Zaman Wahid[1], SM Tanvir Ahmed[2], Fahmida Dil Farzana[1], Mohammad Ali[1], Farina Naz[1], Towfida Jahan Siddiqua[3], Sheikh Shahed Rahman[2], ASG Faruque[1], Tahmeed Ahmed[1]

[1] Nutrition and Clinical Services Division, icddr,b, Dhaka, 1212, Bangladesh
[2] Child Poverty Sector, Save the Children Bangladesh, Dhaka, Bangladesh
[3] Johns Hopkins University, Bangladesh
[4] Durham University, Durham, United Kingdom

*** Correspondence:** Md Ahshanul Haque, Assistant Scientist, Nutrition and Clinical Services Division, icddr,b, 68, Shaheed Tajuddin Ahmed Sarani, Mohakhali, Dhaka 1212, Bangladesh, Email: ahshanul.haque@icddrb.org

Word count: 4165

Abstract

Objective The goal of this study was to construct a predictive modelling approach using logistic regression analysis. We propose that such a model may help to develop an intervention study to significantly reduce the prevalence of stunting among children aged 12-23 months.

Design A cluster randomized pre-post design was followed to measure the impacts on several indicators of livelihood, health, and nutrition. The study comprised a large dataset that was collected from two cross-sectional studies (baseline and endline).

Setting This study was conducted in the northeastern Bangladeshi city of Sylhet, which is vulnerable to both natural catastrophes and the consequences of poverty. It specifically targeted children between the ages of 12 and 23 months.

Main outcome measures The outcome variable in this study was childhood stunting, which was defined as a length-for-age z-score (LAZ) <-2. A multiple logistic regression model was established to predict the factors associated with childhood stunting. The predictive performance of the model was assessed by computing classification status based on model sensitivity and specificity, and area under the receiver operating characteristic (ROC) curve analysis.

Results The prevalence of stunting at baseline survey was 52.7%, whereas 50.0% were stunted at endline survey. We found that several factors were associated with childhood stunting. The sensitivity and specificity of the model were 61% and 56%, respectively. The correctly classified rate was 59%, and the area under the ROC curve was 0.615.

Conclusion Based on the post-estimation findings and area under the ROC curve analysis, the predictive performance of the model was low. As a result, it is urgently necessary to identify the other factors that significantly influence on childhood stunting but are not included in our model and were unavailable in the database.

Study registration: RIDIE-STUDY-ID-5d5678361809b

Keywords: Nutrition, Statistics, Epidemiology, Public health

Strengths and limitations of this study

- More precise anthropometry tools were used to measure the child's length
- Both parametric and non-parametric models were used and the predictive performance of the analytical models was calculated
- To avoid seasonality, we conducted the baseline and endline surveys at the same time of year
- We did not collect food intake data, but only gathered recall data from the previous 24 hours
- Biological data were not collected

Introduction

Childhood stunting, which is defined as length-for-age z-score (LAZ) < -2, is a major concern for public health and has been widely used as an indicator of chronic malnutrition in children [1]. Although childhood stunting scenarios have much improved globally, the prevalence of child malnutrition is still very high in low-resource settings, including countries such as Bangladesh. According to the 2018 Global Nutrition Report, 150.8 million children (22.2%) under five years-of-age are stunted globally, compared to 198.4 million (32.6%) and 165 million children in 2000 and 2011, respectively [2 3]. Asian countries have observed a decrease in the rate of stunting among children under five from 38.1% to 23.2% between 2000 and 2018; nevertheless, South Asia still has the highest prevalence of stunting across the region, at 38.9%. [2]. In Bangladesh, about 5.5 million (36%) children under five were stunted in 2014 [4], however by 2018, childhood stunting has reduced to about 31% [5]. As the World Health Organization (WHO) considers a childhood stunting rate of 15% to be an emergency situation, the current prevalence of childhood stunting in Bangladesh reflects an alarming situation of chronic undernutrition [28].

Undernutrition during childhood has several causes, including poor maternal health and nutrition, low maternal education, and inadequate infant and young child feeding (IYCF) practices [28]. Moreover, evidence suggests that a number of characteristics at the household level, which relate to both children and mothers, can influence childhood stunting. The characteristics of the household head, household food insecurity, the presence of unhygienic latrines, hand-washing status, household income and savings, household involvement in several earning activities, maternal healthcare service-seeking during pregnancy, household dietary diversity, number of children, maternal nutritional profile, as well as the age and sex of the child are most often reported to be associated with stunting in the literature [6-11]. However, these findings are mostly based on nationally representative cross-sectional and cohort studies, or studies conducted in urban settings [12 13]. Therefore, a knowledge gap exists on whether similar results would be obtained when nationwide data are compared with data for study populations from poor or very poor rural households in specific vulnerable regions.

Sylhet is one such vulnerable region of north-east Bangladesh, comprising diverse terrains such as plain land, hilly land, *Haor* (wetland), and flash flood-prone areas. This region is reported to perform poorly for all important maternal healthcare indicators [14], despite the fact that Bangladesh has made substantial progress in improving the overall health of the population [15]. Moreover, the socio-economic profile of the inhabitants in Sylhet region includes both very rich and extremely poor people. This scenario may worsen without the implementation of appropriate strategies in the near future. Sylhet region is also performing poorly compared to the national averages for a number of health and nutritional indicators. Critical indicators such as the infant mortality rate and unemployment status of women are high [12]. In comparison to the overall situation of Bangladesh, where stunting among children under five has decreased, the Bangladesh Demographic and Health Survey (BDHS) 2014 indicates the prevalence of childhood stunting in Sylhet is astonishingly high, at 50% [12]. This alarming figure provided the rationale for implementation of a comprehensive intervention programme in this region. A large-scale nutrition programme, *Suchana: Ending the Cycle of Undernutrition in Bangladesh; a multi-sectoral nutrition programme,* was undertaken with the aim to prevent chronic malnutrition in Sylhet.

In general, *Suchana* nutrition interventions can be divided into two types: nutrition-sensitive and nutrition-specific. The concept of nutrition-sensitive intervention refers to an intervention that benefits the beneficiaries in terms of food and nutrition security, and also influences the underlying determinants of nutrition. This type of intervention is largely delivered through the agricultural sector (homestead vegetable and fruit production, pro-poor nutrition-sensitive aquaculture), improved technology (mono-sex tilapia and carp-tilapia polyculture, subsistence fishing, fish dying), demonstrations (village model farms and demo ponds, livestock, food security, promotion of climate-smart technologies), and supported income-generating activities (skill development in business management, engagement with the private sector and other sectors). As nutrition-specific interventions were delivered through nutrition-sensitive interventions, their coverage, effectiveness, and scale can be increased. It can meet the targets by lowering them and implementing nutrition-specific interventions. A nutrition-specific intervention addresses the immediate cause of malnutrition. Direct determinants of nutrition are the focus of this intervention. There is a strong focus on nutrition-specific interventions in the health sector. Whether implemented alone or jointly, nutrition-specific interventions improve health outcomes. Some examples of nutrition-specific interventions are: counselling for mothers at the household level, community-based nutrition education for spouses and in-laws, growth monitoring and promotion

(GMP) sessions integrated with EPI in communities, GoB health facilities equipped with severe acute malnutrition (SAM) service delivery, and support for NNS service delivery through community clinics, FWCs, and UHCs.

The primary objective of the *Suchana* programme was to reduce the prevalence of childhood stunting in the intervention areas. The secondary objectives were to assess the changes in *Suchana* beneficiaries' households, in terms of an increase and diversification of household income, food security status, optimal infant and young child feeding (IYCF) practices, haemoglobin status of children, the empowerment of women, and adolescents' nutritional knowledge and practices.

The *Suchana* programme substantially improved nutritional behaviour, maternal healthcare practices, women's empowerment, household income, and household food security in the intervention area compared to the control area [16]. Contrary to predictions, however, *Suchana* did not result in any significant reduction in the prevalence of childhood stunting. Therefore, although most other factors related to childhood stunting improved, this raises the question of why the prevalence of stunting did not reduce after the intervention. An important observation from the *Suchana* survey was that the proportion of households in this study population using hygienic latrines was quite low. This factor was associated with stunting in children [6], and did not significantly improve by endline in the intervention areas compared to the control areas.

In this study, we aimed to construct a predictive model to attempt to explain whether any improvements in associated factors may promote a significant reduction in stunting among children aged 12-23 months from poor and extremely poor households in the Sylhet region.

Methods

Implementation design

Suchana was implemented in 157 unions over 20 sub-districts in the Sylhet region in the north-east of Bangladesh The *Suchana* program's protocol has been previously thoroughly explained [17]. Union, the smallest local government and administrative entity in rural Bangladesh, was classified as a cluster. Unions were sorted into one of four phases at random. For this study, Phase-1 was the study's intervention group, while Phase-4 was the control group [17] and other Phases were treated as learning Phases. For implementation purposes, vulnerable villages were selected within. The staff of the programme chose vulnerable villages in each union based on their vulnerability (e.g., frequent floods or submerging, little or no intervention from other development programmes, poverty or household living circumstances, remoteness and accessibility issues, a high prevalence of superstitions and social taboos). After consultation with local government representatives, elected officials, and local elites as well as field visits, this selection method was decided upon.

Evaluation design

Setting: The impacts of the intervention on livelihood, health, and nutrition were measured using a pre-post design. A large dataset was collected from two cross-sectional studies (baseline and endline) for the study. The baseline survey was conducted in November 2016 and February 2017, followed by the endline survey in the same months three years later.

***Sample size*:** The sample size was calculated with STATA "*clustersampsi*" command module and considered the number of clusters in the surveys (Supplementary file). It was assumed that the expected prevalence of childhood stunting in the control group was 47%. Hypothesis was that the prevalence would be reduced to 41% after three years of intervention. The estimated sample size per arm was 1520 when considering 5% level of significance, 80% power, 40 clusters per arm, and an intra cluster correlation coefficient (ICC) of 0.01. After considering the rounding figure, the estimated sample size per arm was 1620.The 2nd arm has an equal sample size since it was assumed that the sampling ratio between control and intervention groups is 1:1. Then total sample size is 3200 at the baseline survey. However, for evaluation purposes, the sample size at endline was doubled due to stratification of the intervention component. Finally, 9600 mother-child pairs were included in this analysis (baseline: 3200, and endline: 6400) [17].

Sampling: Eight villages at baseline survey and twelve villages at endline survey were randomly selected from each union using a list of vulnerable villages provided by Save the Children. Once the villages were identified, the most vulnerable households were identified, listed and verified following the *Suchana* programme inclusion criteria (Supplementary Table 1) and, if eligible for the study, given an identification number to prepare the sampling frame. Then, required households were systematically selected for the surveys from the frame.

Data collection: The Suchana data collection software contained built-in validation rules. As the data were entered at the interviewer level and the records were uploaded to a server at the icddr,b using the built-in internet connectivity of the devices, maximum validation rules were set in the data system to prevent errors during data entry, which reduced the data entry burden. This allowed the data analysis team to review the consistency of the data every day. Data were synchronized to the central server "Web Service" developed in Asp.Net based on the C# (C Sharp) code. Activities such as editing (after receiving any feedback from field staff members), updating, range checks, duplication checks, consistency checks, frequency checks and cross tabulation were regularly performed during the data entry period. In case of any unusual observations, the issues were discussed and resolved.

Variables under study: The outcome variable in this study was childhood stunting, which was defined as a length-for-age z-score (LAZ) <-2. Initially, a list of several independent variables was finalized through results obtained from descriptive and bi-variate analyses, as well as a comprehensive literature review (Table 1). These included at least four ANC visits by a skilled service provider, additional resting during pregnancy, additional food consumption during pregnancy, consumption of at least 100 IFA tablets during pregnancy, receiving vitamin A capsule after last delivery, birth attendant/facility, mother involved in income-generating activities, maternal BMI, maternal education, HH food insecurity, HH monthly income >15000 BDT, involved with aquaculture, hygienic latrine, water and soap available in handwashing place, HH size, HH dietary diversity, sex of household head, religion, received any grant/allowance/stipend from the government, access of mass media, child's age, child's sex, childhood illness in the last 15 days, minimum dietary diversity, early initiation of breastfeeding, and received colostrum. HFIAS was measured using the Food and Nutrition Technical Assistance's Guideline, which categorizes household food insecurity into four levels: a) food secure, b) mildly food insecure, c) moderately food insecure, and d) severely food insecure [18]. In the analysis herein, this indicator was redefined as a binary indicator: severely food insecure or not severely food insecure.

Statistical analysis

Descriptive statistics: Stata-14 software (StataCorp LP, College Station, TX, USA) and R 4.2.2 (*rpart*) were used to analyse the data. Several statistical plots were used for data visualization. Descriptive statistics, such as frequency and proportions for categorical variables and mean and standard deviations for quantitative variables, were used to summarize the data at baseline and endline.

Predictive model: Three statistical models were used as predictive models. Two parametric models, such as Logistic and Probit regression models, and Decision Tree as a non-parametric model. Logistic and Probit regression models were used as predictive models as well as classifier models. The models were also used to investigate which factors were significantly associated with childhood stunting, and estimate their effect size, in order to predict whether changes in behavioural practices might potentially help to achieve targeted reductions in stunting. Using those variables, a decision tree was applied, and the predictive performance was compared to other models.

For the parametric models, first, Chi-Square test was used to examine the bivariate associations between stunting and all possible explanatory variables. In the second step, variables with *p*-values <0.25 in the simple model were included in the multiple regression models [19]. In the final step, any independent variables thought to be likely predictors were added to the multiple regression model using the stepwise forward selection method. Some indicators, e.g., age, sex, and maternal nutritional status, were added regardless of their *p*-value due to their scientific plausibility. The mathematical equation of logistic and probit regression models were given in the supplementary file. As a cluster variable, union was used to adjust the standard errors. Furthermore, for the explanation of the regression model, a *p*-value <0.05 was considered as significant, and the confidence interval (CI) of 95% was also reviewed. From the fitted model, the adjusted effect size (adjusted prevalence difference) against all predictors was estimated using the Stata "*adjrr*" package. The list of independent variables with the values used in the model is given in Table 1.

Table 1. List of all independent variables

Indicators	Label	Value/Code	Selection in the model
At least four ANC visits by a skilled service provider			Selected
	At least four ANC visits by a skilled service provider	0	

	Less than four ANC visits by a skilled service provider	1	
Additional resting during pregnancy			Not selected
	Took more rest	0	
	Did not take more rest	1	
Additional food consumption during pregnancy			Not selected
	Consumed more food	0	
	Did not consumed more food	1	
Consumption of at least 100 IFA tablets during pregnancy			Not selected
	Consumed at least 100 IFA tablets	0	
	Did not consumed at least 100 IFA tablets	1	
Received vitamin A capsule after last delivery			Not selected
	Received	0	
	Did not receive	1	
Birth attendant/facility			Selected
	Skilled	0	
	Unskilled	1	
Mother involved in income-generating activities			Selected
	No	0	
	Yes	1	
Maternal BMI			Selected
	BMI ≥18.5	0	
	BMI <18.5	1	
Maternal education			Selected
	At least one-year formal education	0	
	No schooling	1	
HH food insecurity			Selected
	Below severe	0	
	Severe	1	
HH monthly income ≥15000 BDT			Selected
	>=15000 BDT	0	
	<15000 BDT	1	
Involved with aquaculture			Selected
	Involved	0	
	Did not involved	1	
Hygienic latrine			Selected
	Hygienic latrine	0	
	Unhygienic latrine	1	
Water and soap available in handwashing place			Selected
	Available	0	
	Unavailable	1	
HH size			Selected
	Below seven	0	
	Seven or above	1	
HH dietary diversity			Selected
	HDDS ≥7	0	
	HDDS <7	1	
Sex of household head			Not selected
	Female	0	
	Male	1	
Maternal education			Not selected
	At least one-year formal education	0	
	No schooling	1	
Religion			Not selected

	Muslim	0	
	Non-Muslim	1	
Received any grant/allowance/stipend from the government			
	Received	0	
	Did not receive	1	
Access of mass media			Selected
	Access	0	
	No access	1	
Child's age			Selected
	Age ≤18 months	0	
	Age >18 months	1	
Child's sex			Selected
	Female	0	
	Male	1	
Childhood illness in the last 15 days			Selected
	No	0	
	Yes	1	
Minimum dietary diversity			Not selected
	Received	0	
	Did not receive	1	
Early initiation of breastfeeding			Not selected
	Received	0	
	Did not receive	1	
Received colostrum			Not selected
	Received	0	
	Did not receive	1	

Model evaluation: The predictive performance was assessed by computing the classification status using model sensitivity and specificity, area under the receiver operating curve (ROC) analysis. Data were randomly split into a training set (75% of the data) and a test set (25%) with random-number seed 113843 to calculate the accuracy of the algorithm. The same training and test datasets were used for all algorithms and performance predictions.

Patient and public involvement

Patients and public were not actively involved in formulating the research question and or protocol development, including the outcome measures. To expedite the field implementation, however, local elites e.g. teachers, religious persons, and local government council members were informed about the study.

Results

General characteristics: With respect to the outcome indicator, stunting in children aged 12-23 months, 52.7% of children were stunted at the baseline survey (intervention group: 52.6%; control group: 52.8%), whereas the proportion of children exhibiting stunting at endline was 50.0% (intervention: 49.9%; control: 50.1%; Figure 1). Figure 2 describes some other output indicators related to maternal and child health. Status of consuming minimum acceptable diet (intervention: 35.2%; control: 14.9%), minimum dietary diversity (intervention: 42.8%; control: 20.4%), maternal decision making (intervention: 45.0%; control: 31.0%), at least four maternal ANC visits by a skilled service provider (intervention: 36.1%; control: 17.7%), minimum dietary diversity for women (intervention: 52.6%; control: 33.5%), a household dietary diversity score of at least seven (intervention: 88.9%; control: 78.3%), and household food security status (intervention: 26.6%; control: 20.2%) were significantly improved in the intervention group compared to the control group at endline survey. The availability of hygienic latrines (intervention: 44.0%; control: 44.0%) did not increase after the intervention. The households' socio-demographic characteristics, women's general characteristics, and children's characteristics at baseline and endline are shown in Table 2.

Table 2. General characteristics of the *Suchana* beneficiaries

Indicators, *n* (%)	Baseline *N*=3200	Endline *N*=6300	Total *N*=9500
At least four ANC visits by a skilled service provider			
Yes	408 (12.8)	1530 (24.3)	1938 (20.4)
No	2792 (87.3)	4771 (75.7)	7563 (79.6)
Delivery at skilled birth attendant/facility			
Yes	1000 (31.3)	2769 (44)	3769 (39.7)
No	2200 (68.8)	3532 (56.1)	5732 (60.3)
Had tetanus toxoid injection			
No	834 (26.1)	1131 (18)	1965 (20.7)
Yes	2366 (73.9)	5170 (82.1)	7536 (79.3)
Mother involved in income-generating activities			
No	3102 (96.9)	5665 (89.9)	8767 (92.3)
Yes	98 (3.1)	639 (10.1)	737 (7.8)
Maternal BMI			
BMI ≥18.5	1859 (58.1)	4073 (64.6)	5932 (62.4)
BMI <18.5	1341 (41.9)	2231 (35.4)	3572 (37.6)
Mother completed primary education			
Yes	1721 (53.8)	3808 (60.4)	5529 (58.2)
No	1479 (46.2)	2496 (39.6)	3975 (41.8)
Maternal age			
Age <30 years	2145 (67)	3559 (56.5)	5704 (60)

Indicators, *n* (%)	**Baseline** *N*=3200	**Endline** *N*=6300	**Total** *N*=9500
Age ≥30 years	1055 (33)	2745 (43.5)	3800 (40)
Type of delivery			
Normal	2879 (90)	5529 (87.8)	8408 (88.5)
Caesarean	321 (10)	772 (12.3)	1093 (11.5)
PNC			
No	2152 (67.3)	4128 (65.5)	6280 (66.1)
Yes	1048 (32.8)	2173 (34.5)	3221 (33.9)
Household severely food insecure			
Yes	912 (28.5)	1016 (16.12)	1928 (20.3)
No	2288 (71.5)	5285 (83.9)	7573 (79.7)
Household monthly income ≥15000 BDT			
Yes	424 (13.3)	1015 (16.1)	1439 (15.1)
No	2776 (86.8)	5289 (83.9)	8065 (84.9)
Household involved with aquaculture			
Yes	161 (5)	561 (8.9)	722 (7.6)
No	3039 (95)	5740 (91.1)	8779 (92.4)
Hygienic latrine			
Yes	1121 (35)	2782 (44.2)	3903 (41.1)
No	2079 (65)	3519 (55.9)	5598 (58.9)
Water and soap available in handwashing place			
Yes	862 (26.9)	3170 (50.3)	4032 (42.4)
No	2338 (73.1)	3131 (49.7)	5469 (57.6)
Household savings			
No	1080 (33.8)	2876 (45.6)	3956 (41.6)
Yes	2120 (66.3)	3425 (54.4)	5545 (58.4)
Sex of household head			
Female	110 (3.4)	501 (8)	611 (6.4)
Male	3090 (96.6)	5799 (92.1)	8889 (93.6)
Source of drinking water			
Tube well	2748 (85.9)	5713 (90.7)	8461 (89.1)
Others	452 (14.1)	588 (9.3)	1040 (11)
Household dietary diversity score			
HDDS ≥7	2182 (68.2)	5322 (84.5)	7504 (79)
HDDS <7	1018 (31.8)	979 (15.5)	1997 (21)
Household monthly income (Thousand BDT)[1]	6.7 (5, 10)	7.5 (5.1, 10.8)	7.1 (5, 10.4)
Per capita income (Thousand)[1]	2.6 (1.8, 3.7)	2.9 (2, 4.1)	2.8 (2, 4)
Household size[1]	6.2±2.4	5.9±2.1	6±2.2
Child's age in months[2]	17.9±3.5	17.3±3.6	17.5±3.6
Length-for-age z-score[2]	-2.1±1.2	-2±1.1	-2±1.1
Weight-for-age z-score[2]	-1.7±1.1	-1.5±1.0	-1.5±1.0
Weight-for-length z-score[2]	-0.9±1.0	-0.7±0.9	-0.7±1.0
Child's age			
Age <18 months	1745 (54.5)	3710 (58.9)	5455 (57.4)
Age ≥18 months	1455 (45.5)	2594 (41.2)	4049 (42.6)
Child's sex			
Female	1567 (49)	3044 (48.3)	4611 (48.5)
Male	1633 (51)	3257 (51.7)	4890 (51.5)
Child experienced respiratory illness in last 15 days			
Yes	2867 (89.6)	5763 (91.5)	8630 (90.8)

Indicators, *n* (%)	Baseline *N*=3200	Endline *N*=6300	Total *N*=9500
No	333 (10.4)	538 (8.5)	871 (9.2)

[1]Median (IQR); [2]Mean ± SD.

Associated factors: The correlates of childhood stunting as determined using two parametric predictive models are shown in Table 3 and Figure 3. Less than four ANC visits by a skilled service provider, unskilled birth attendant/facility, mother involved in income-generating activities, maternal BMI <18.5, maternal education: no schooling, household severely food insecure, household monthly income <15000 BDT, household not involved with aquaculture, having an unhygienic latrine, no soap available in handwashing place, household size >7, household dietary diversity score <7, child's age >18 months, child's sex: male, childhood illness in the last 15 days, and no access to mass media were significantly correlated with childhood stunting. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) are given in Supplementary Table 2a and 2b.

Table 3. Factors influencing stunting in children aged 12-23 months, computed using logistic and probit regression analyses

Indicators	Logistic Adjusted OR (95% CI)	Logistic p-value	Probit Adjusted Coef. (95% CI)	Probit p-value
At least four ANC visits by a skilled service provider				
Yes	Reference		Reference	
No	1.16 (1.05, 1.30)	0.005	0.09 (0.03, 0.16)	0.005
Birth attendant/facility				
Skilled	Reference		Reference	
Unskilled	1.11 (1.02, 1.20)	0.012	0.06 (0.01, 0.11)	0.012
Mother involved in income-generating activities				
No	Reference		Reference	
Yes	1.18 (1.02, 1.37)	0.030	0.10 (0.01, 0.19)	0.030
Maternal BMI				
BMI ≥18.5				
BMI <18.5	1.23 (1.12, 1.36)	0.000	0.13 (0.07, 0.19)	0.000
Maternal education was primary completed				
Yes	Reference		Reference	
No	1.31 (1.20, 1.42)	0.000	0.17 (0.12, 0.22)	0.000
HH food insecurity				
Below severe				
Severe	1.12 (1.00, 1.24)	0.041	0.07 (0.00, 0.13)	0.042
HH monthly income ≥15000 BDT				
Yes	Reference		Reference	
No	1.12 (1.01, 1.25)	0.037	0.07 (0.00, 0.14)	0.035

Involved with aquaculture				
Yes	Reference		Reference	
No	1.19 (1.03, 1.38)	0.018	0.11 (0.02, 0.20)	0.018
Hygienic latrine				
Yes	Reference		Reference	
No	1.20 (1.10, 1.30)	0.000	0.11 (0.06, 0.16)	0.000
Water and soap available in handwashing place				
Yes	Reference		Reference	
No	1.19 (1.08, 1.30)	0.000	0.11 (0.05, 0.16)	0.000
HH size				
Below seven	Reference		Reference	
Seven or above	1.20 (1.11, 1.31)	0.000	0.12 (0.06, 0.17)	0.000
HH dietary diversity				
HDDS ≥7	Reference		Reference	
HDDS <7	1.17 (1.07, 1.29)	0.001	0.10 (0.04, 0.16)	0.001
Child's age				
Age ≤18 months	Reference		Reference	
Age >18 months	1.52 (1.39, 1.67)	0.000	0.26 (0.2, 0.32)	0.000
Child's sex				
Female	Reference		Reference	
Male	1.22 (1.11, 1.34)	0.000	0.13 (0.07, 0.18)	0.000
Childhood illness in the last 15 days				
No	Reference		Reference	
Yes	1.20 (1.06, 1.36)	0.003	0.11 (0.04, 0.19)	0.003
Access of mass media				
Yes	Reference		Reference	
No	1.15 (1.02, 1.30)	0.025	0.09 (0.01, 0.16)	0.025

Unions were adjusted as clusters. Baseline and endline were adjusted as time variables.

Predictive performance: Table 4 describes the model validation based on sensitivity, specificity, and whether the model was correctly classified for the overall dataset, as well as the training and test datasets. The sensitivity and specificity of the model were around 60% and 55%, respectively for all models. The correctly classified rate was 59%, and the area under the ROC curve was around 61%. We found that these values were approximately equal among the three datasets (main, training, and test datasets); however, the predictive performance of the model was low.

Table 4. Predictive performance of the model for stunting based on classification, sensitivity, and specificity in the full, training and test datasets with area under the receiver operating characteristic curve analysis

	Full dataset			**Training Dataset**			**Test Dataset**		
	LR	**PR**	**DT**	**LR**	**PR**	**DT**	**LR**	**PR**	**DT**
Overall accuracy	58.46	58.38	56.51	58.83	58.62	57.66	58.11	58.19	56.67

Sensitivity	61.21	61.25	61.15	61.59	61.70	63.93	60.23	60.23	61.58
Specificity	55.61	55.41	51.70	55.36	55.42	51.61	55.90	56.07	51.94
Area under the curve	61.54	61.54	56.72	61.37	61.37	58.44	61.76	61.77	58.01

LR: Logistic regression, PR: Probit regression, DT: Decision tree

Discussion

In order to demonstrate why the *Suchana* programme did not significantly lower the prevalence of childhood stunting after intervention, this study examined data from the baseline and endline surveys of the programme to identify factors that significantly correlate with childhood stunting and compute the predictive performance. After controlling for *union* as a cluster variable, we found numerous factors that were significantly correlated with stunting. Of these indicators, the status of ANC visits by a skilled service provider, household dietary diversity, household food security, and household monthly income improved as outcome indicators after the intervention. Notably, household food security status did not reach its target value of 50%, though this is an important factor associated with childhood stunting [6 20 21]. Other *Suchana* outcome indicators, such as dietary diversity of children, maternal dietary diversity, and maternal empowerment were not associated with stunting in this study.

The current study indicates that although some programme indicators improved significantly after the intervention, the *Suchana* programme did not lead to a significant reduction in the prevalence of childhood stunting. The most important factors associated with childhood stunting, such as maternal nutrition and education, household food security, involvement with aquaculture, having a hygienic latrine, soap being available in handwashing places, and improved sources of drinking water did not improve after the intervention. We found a negative association between stunting and maternal involvement in income-generating activities, which means the risk of stunting was higher among children whose mothers were involved in various types of earning activities. The proportion of mothers involved in income-generating activities increased after the study, although the increase was very small. The essential necessities of the child should not be impeded by the mother's working status.

This study will help programme managers in prioritizing attention while designing appropriate interventions to reduce childhood stunting. Sustainable interventions should be implemented as per the beneficiary's need. Implementing short-term initiatives could help to improve some of these factors. *Per se*, attending courtyard workshops and campaigns organized by healthcare practitioners can boost ANC visits, skilled birth attendance, and handwashing practices. The establishment of women's health care services with a focus on women's health before and during pregnancy as well as child nutrition and health would also aid in lowering the extent of growth retardation in both the mother and children. Greater access to the media can help people in these vulnerable communities receive the full benefits of government welfare programs. Food security, income, sanitation, aquaculture, and illness are all time-dependent factors. To satisfy the nutritional needs of every household member, for instance, it is necessary to increase production yields through self-production or purchasing in order to lower household food insecurity. However, a family's wealth index and the quantity of easily accessible marketplaces nearby have an impact on their ability to buy nutritious food as well. In agriculture, climate change adaptation is essential to minimise current risks, and prepare for future climatic uncertainties. In addition, in today's climate, using organic fertilizer inputs in agricultural areas has significant environmental benefits over using chemical fertilizers. It can reduce the demand for pesticides, minimize threats to human health and biodiversity, and reduce the risk of water contamination. Because of the reductions, this may lead to cost savings or cost neutrality. Promotion of aquaculture during the *Suchana* programme increased the availability of fish, and provided a viable source of protein, which resulted in better nutrition and food security; however, establishing such facilities requires a significant amount of time. Furthermore, improved sanitation can only be facilitated by improving socioeconomic status, which is also a time-intensive process. National surveys, including the BDHS and the Food Security and National Surveillance Project (FSNSP) have indicated that a substantial amount of time is required to improve stunting. To improve maternal nutrition, women should be provided with adequate food to improve their nutritional status during adolescence, as children born to malnourished mothers are at a higher risk of malnutrition. Moreover, according to a previous literature review, a mother's education is a strong predictor of her child's nutritional status. The level of maternal education has a significant impact on the risk of childhood stunting, with children of mothers with no or only a secondary education being more at risk than those whose mothers have completed secondary education or more. Moreover, placing emphasis on the education of female children may contribute to breaking the vicious cycle of poverty and childhood stunting in developing countries like Bangladesh. Therefore, an intricate intervention along with nutritional support and food security as well as maternal education might be worthwhile for short and long-term prevention of childhood stunting. In addition, comprehensive initiatives to encourage income-generating activities among women and address domestic violence against women should be implemented to help reduce childhood stunting in developing countries.

Another important finding based on the post-estimation findings as well as the value of the area under the ROC curve was that the predictive performance of the model was low. Thus, we need to identify other indicators influencing childhood stunting that were not included in our model. From the literature, environmental enteropathy has been implicated in poor growth among children in rural Bangladesh [22]. Environmental enteropathy may also represent an important hidden factor with respect to the *Suchana* study population. While it was not assessed in this study, some indicators of the enteropathogen burden—such as unsanitary latrines, unimproved floors, lack of handwashing practice, and low education were available in this study [13 23]. It is possible to reduce the burden of stunting in young children if improvements are made in WASH variables, particularly the latrine facilities and handwashing practices. Poultry was one of the intervention components. Our qualitative findings revealed that people in majority of the households were sharing their living place with poultry, ducks, or other animals, which may increase the risk of infections with *Campylobacter* species, a leading food-borne pathogen [13 24]. Studies have provided evidence of a strong association between stunting and enteropathy among children who fail to respond to nutritional interventions [25]. Findings from rural Bangladesh have also shown significant association between environmental conditions and stunting in children [26 27]. However, assessment of environmental enteropathy was beyond the scope of the *Suchana* evaluation. For evaluation purposes, evaluation team could collect data on indicators of enteropathy in the intervention and control areas, and then use the model to assess the impact of appropriate interventions.

Recommendation: The *Suchana* model offers a holistic and integrated approach in tackling food and nutrition security by acknowledging undernutrition as a complex problem caused by a variety of factors. The endline survey of *Suchana* showed that many of the programme indicators have considerably improved as a result of the intervention. Ultimately, the design of Suchana offers a meaningful solution to confront undernutrition through multi-sector approach. However, some additional recommendations related to both nutrition-sensitive and specific activities can be made which could be undertaken by the policy makers. Climate-resilient agricultural technologies should be promoted and effectively monitored as a component of improved agricultural strategies. Improved capacity on preparedness and response plan against flooding is compulsory, so that poor people are not continuously set back by the shocks. Food security situation should be improved through a sustainable mechanism. Coverage for water, sanitation and hygiene must be increased at the community level. Innovative approaches need to be tailored to maintain a safe distance and proper management of livestock and human habitations to prevent pathogens exposed through poultry droppings from entering the human body. Also, the awareness of seasonal diseases/infections associated with livestock and poultry should be emphasized through veterinary treatment and should complete the worming dose or follow-up. Additionally, some indicators such as child sex, maternal education and nutrition could be adjusted during randomization at the design level. The *Suchana* programme, one of the largest nutrition interventions ever implemented globally, successfully led to positive changes in most critical study indicators. Long-term positive changes in the health and livelihood of the beneficiaries are expected in the years to follow, even after the programme ends.

Strength and limitation: The large sample size, randomization, and appropriate sampling techniques were among the major strengths of this study. A dedicated quality control team was involved in checking the data by re-visiting randomly selected households. We used highly precise anthropometry instruments, and the anthropometry measurement team received separate training from a qualified trainer. To avoid seasonality, we conducted the baseline and endline surveys at the same time of the year. Among the limitations of this study is the fact that, we did not collect food intake data, but only gathered recall data of previous 24 hours. These data may be subject to recall bias; thus, caution is necessary while concluding, especially for indicators such as dietary diversity, household food insecurity, domestic violence, and maternal healthcare.

Conclusion

Childhood stunting is heavily influenced by a number of factors that were not included in this model due to being unavailable in the questionnaire and urgently need to be identified. Policy makers and programme planners should consider, and enhance the collaboration and coordination between nutrition-sensitive and specific activities designed to alleviate nutritional deficiencies and family health programmes.

Acknowledgments: The study analyzed baseline survey data of *Suchana*; this intervention has been implemented by a consortium led by Save the Children, with support from the Foreign, Commonwealth and Development Office (FCDO) and European Union (EU). icddr,b acknowledges with gratitude the commitment of Save the Children, FCDO and EU to its research efforts. We also acknowledge with gratitude the commitment of the Government of the People's Republic of Bangladesh to icddr,b's research activities. We also acknowledge the following donors for providing unrestricted support to icddr,b's efforts and advancement of its strategic plan: Canada, Sweden and the United Kingdom. We gratefully acknowledge our core donors for their support and commitment to icddr,b's research efforts. We would like to acknowledge the invaluable contributions of Save the Children as lead agency, our technical partners Helen Keller International, World Fish, and International Development Enterprises, and the implementing partners Friends In Village Development Bangladesh (FIVDB), Rangpur Dinajpur Rural Services (RDRS), and the Center for Natural Resource Studies (CNRS) who played critical roles in generating and refining the data-collection tools. We would also like to acknowledge Tasnia Alam, Research Assistant and Md Maniruzzaman, Assistant Professor, Khulna University, Khulna-9208, Bangladesh as the internal reviewers, and Andrea Devlin of Science Editing Experts for editing and linguistic revision of the manuscript.

We would also like to acknowledge Andrea Devlin of Science Editing Experts for editing and linguistic revision of the manuscript.

Funding: (i) This study was made possible by the committed contribution of Foreign, Commonwealth and Development Office (Grant number: 204131-103), and (ii) icddr,b (N/A).

Conflicts of Interest: The authors declare no conflict of interest.

Author Contributions: TA and NC originated the idea for the study and led the protocol design. MAH conceptualized the manuscript. SMTA, SSR, MAH, NC, FDF, and TA contributed to the survey design. MAH performed statistical analysis and drafted the manuscript. NC and ASGF supervised the work, and critically reviewed and provided feedback for revising the manuscript. MAH, NC, MA, FDF, FN, BZW, TJS, ASGF, TA, and SSR contributed to the revision of the final draft for submission. All authors are responsible for the final content of the manuscript.

Ethics approval: This study was approved by the Research Review Committee and Ethical Review Committee, the two obligatory components of the Institutional Review Board (IRB) of icddr,b (PR-16020). Informed written consent was obtained from study participants.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

Reference

1. Bari A, Nazar M, Iftikhar A, et al. Comparison of Weight-for-Height Z-score and Mid-Upper Arm Circumference to Diagnose Moderate and Severe Acute Malnutrition in children aged 6-59 months. *Pakistan journal of medical sciences* 2019;35(2):337-41. doi: 10.12669/pjms.35.2.45 [published Online First: 2019/05/16]

2. Development Initiatives. 2018 Global Nutrition Report: Shining a light to spur action on nutrition. Bristol, UK: Development Initiatives, 2018.

3. United Nations Children's Fund (UNICEF), World Health Organization, International Bank for Reconstruction and Development/The World Bank. Levels and trends in child malnutrition: Key Findings of the 2020 Edition of the Joint Child Malnutrition Estimates. Geneva: World Health Organization; 2020. Licence: CC BY-NC-SA 3.0 IGO., 2020.

4. USAID. Bangladesh: Nutrition Profile, 2018.

5. National Institute of Population Research and Training (NIPORT), ICF. Bangladesh Demographic and Health Survey 2017-18: Key Indicators. NIPORT and ICF: Dhaka, Bangladesh and Rockville, Maryland, USA, 2019.

6. Choudhury N, Raihan MJ, Sultana S, et al. Determinants of age-specific undernutrition in children aged less than 2 years-the Bangladesh context. *Maternal & child nutrition* 2017;13(3) [published Online First: 2016/10/19]

7. Hasan M, Sutradhar I, Shahabuddin A, et al. Double Burden of Malnutrition among Bangladeshi Women: A Literature Review. *Cureus* 2017;9(12)

8. Balarajan Y, Villamor E. Nationally representative surveys show recent increases in the prevalence of overweight and obesity among women of reproductive age in Bangladesh, Nepal, and India. *The Journal of nutrition* 2009;139(11):2139-44. [published Online First: 2009/09/25]

9. Khan MM, Kraemer A. Factors associated with being underweight, overweight and obese among ever-married non-pregnant urban women in Bangladesh. *Singapore medical journal* 2009;50(8):804-13. [published Online First: 2009/08/28]

10. Kamal SM, Hassan CH, Alam GM. Dual burden of underweight and overweight among women in Bangladesh: patterns, prevalence, and sociodemographic correlates. *Journal of Health, Population and Nutrition* 2015;33(1):92-105. [published Online First: 2015/05/23]

11. Corsi DJ, Kyu HH, Subramanian SV. Socioeconomic and geographic patterning of under- and overnutrition among women in Bangladesh. *The Journal of nutrition* 2011;141(4):631-8. [published Online First: 2011/02/25]

12. National Institute of Population Research and Training - NIPORT/Bangladesh, Mitra and Associates, ICF International. Bangladesh Demographic and Health Survey 2014. NIPORT, Mitra and Associates, and ICF International: Dhaka, Bangladesh and Rockville, Maryland, USA, 2016.

13. Haque MA, Platts-Mills JA, Mduma E, et al. Determinants of Campylobacter infection and association with growth and enteric inflammation in children under 2 years of age in low-resource settings. *Scientific reports* 2019;9(1):17124. [published Online First: 2019/11/22]

14. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH). State of food security and nutrition in Bangladesh 2013. HKI and JPGSPH, 2014.

15. Yaya S, Bishwajit G, Ekholuenetale M, et al. Awareness and utilization of community clinic services among women in rural areas in Bangladesh: A cross-sectional study. *PLOS ONE* 2017;12(10):e0187303. doi: 10.1371/journal.pone.0187303

16. Haque MA, Choudhury N, Ahmed SMT, et al. The large-scale community-based programme 'Suchana' improved maternal healthcare practices in north-eastern Bangladesh: Findings from a cluster randomized pre-post study. *Maternal & child nutrition* 2022;18(1):e13258. doi: https://doi.org/10.1111/mcn.13258

17. Choudhury N, Raihan MJ, Ahmed SMT, et al. The evaluation of Suchana, a large-scale development programme to prevent chronic undernutrition in north-eastern Bangladesh. *BMC public health* 2020;20(1):744. [published Online First: 2020/05/24]

18. Coates J, Swindale A, Bilinsky P. Household Food Insecurity Access Scale (HFIAS) for measurement of food access: indicator guide (v. 3). Washington, D.C.: Food and Nutrition Technical Assistance Project, Academy for Educational Development 2007.

19. Bursac Z, Gauss CH, Williams DK, et al. Purposeful selection of variables in logistic regression. *Source code for biology and medicine* 2008;3:17.

20. Weatherspoon DD, Miller S, Ngabitsinze JC, et al. Stunting, food security, markets and food policy in Rwanda. *BMC public health* 2019;19(1):882. doi: 10.1186/s12889-019-7208-0 [published Online First: 2019/07/06]

21. Agho KE, Mukabutera C, Mukazi M, et al. Moderate and severe household food insecurity predicts stunting and severe stunting among Rwanda children aged 6-59 months residing in Gicumbi district. *Maternal & child nutrition* 2019;15(3):e12767. doi: 10.1111/mcn.12767 [published Online First: 2018/12/15]

22. Lin A, Arnold BF, Afreen S, et al. Household environmental conditions are associated with enteropathy and impaired growth in rural Bangladesh. *The American journal of tropical medicine and hygiene* 2013;89(1):130-37. doi: 10.4269/ajtmh.12-0629 [published Online First: 2013/05/01]

23. Amour C, Gratz J, Mduma E, et al. Epidemiology and Impact of Campylobacter Infection in Children in 8 Low-Resource Settings: Results From the MAL-ED Study. *Clin Infect Dis* 2016;63(9):1171-79. doi: 10.1093/cid/ciw542 [published Online First: 08/07]

24. Smith S, Meade J, Gibbons J, et al. The impact of environmental conditions on Campylobacter jejuni survival in broiler faeces and litter. *Infect Ecol Epidemiol* 2016;6:31685-85. doi: 10.3402/iee.v6.31685

25. Chen RY, Kung VL, Das S, et al. Duodenal Microbiota in Stunted Undernourished Children with Enteropathy. 2020;383(4):321-33.

26. George CM, Oldja L, Biswas SK, et al. Fecal markers of environmental enteropathy are associated with animal exposure and caregiver hygiene in Bangladesh. 2015;93(2):269-75.

27. Perin J, Burrowes V, Almeida M, et al. A Retrospective Case–Control Study of the Relationship between the Gut Microbiota, Enteropathy, and Child Growth. 2020:tpmd190761.

559 Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline.

562 Figure 2. Results framework and *Suchana* log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

565 Figure 3. Factors influencing stunting in children aged 12-23 months, computed using decision tree analysis

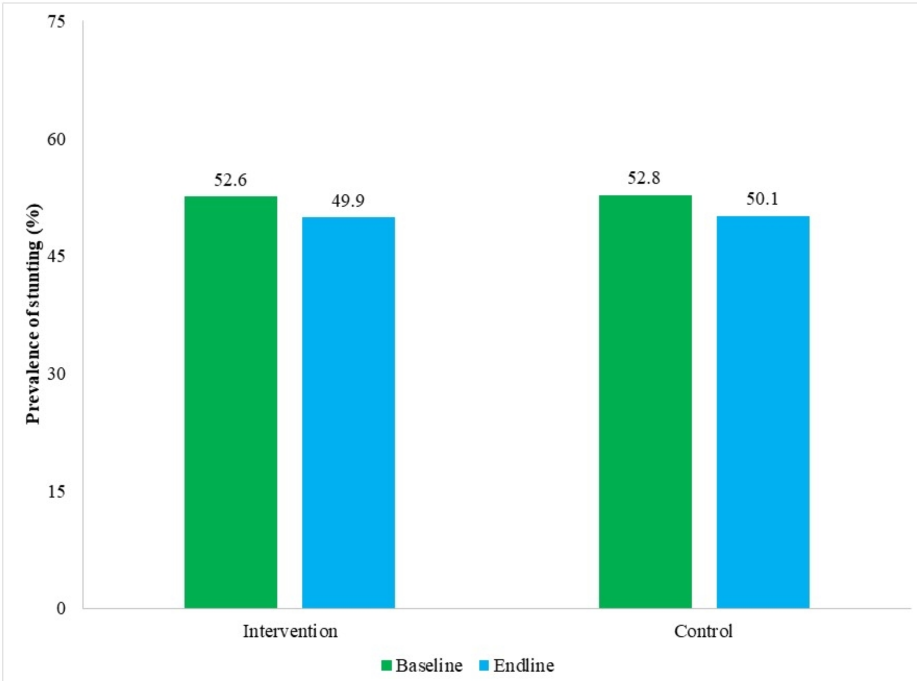


Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline

254x190mm (96 x 96 DPI)

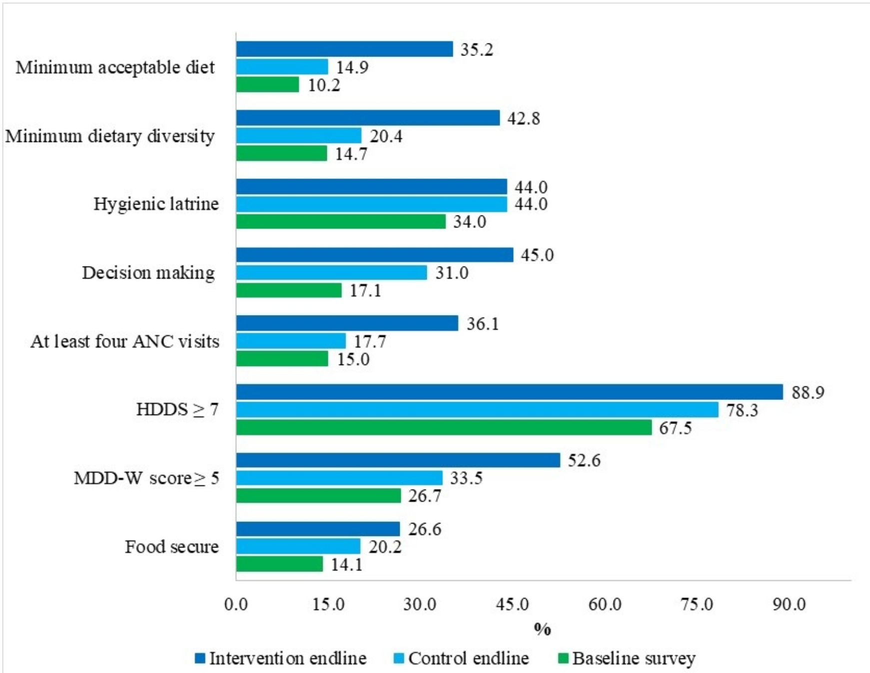


Figure 2. Results framework and Suchana log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women

254x190mm (96 x 96 DPI)

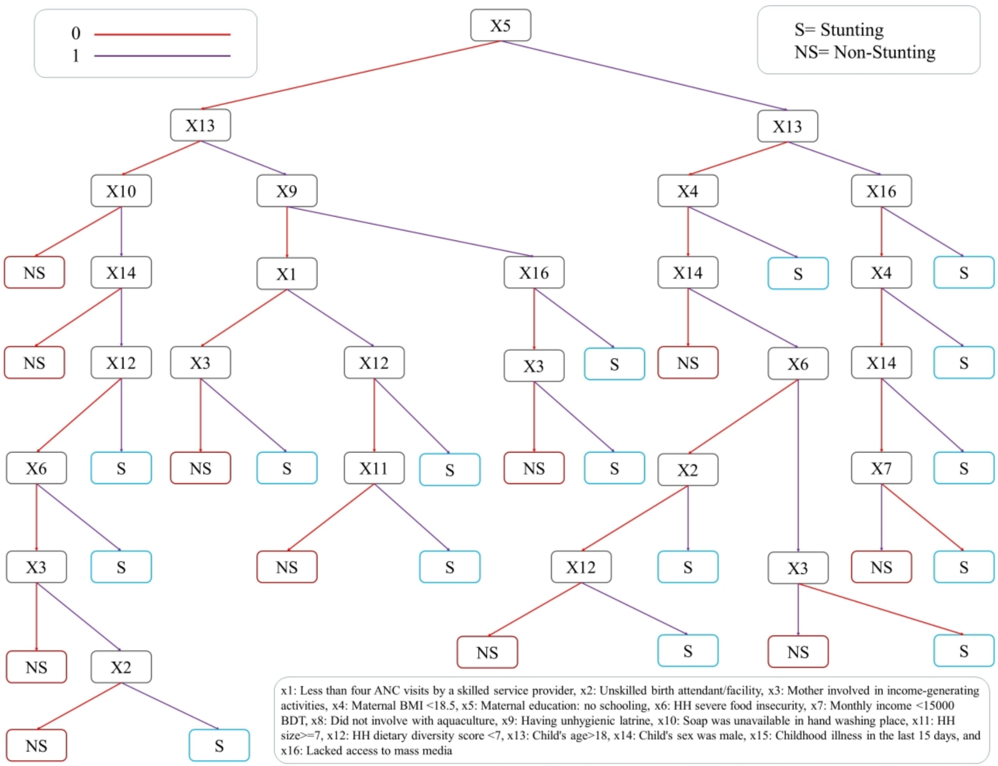


Figure 3. Factors influencing stunting in children aged 12-23 months, computed using decision tree analysis

325x254mm (300 x 300 DPI)

Sample size calculation

```
clustersampsi, binomial samplesize p1(0.47) p2(0.41) k40) rho0.01)alpha(0.05) beta(0.8)
```

Output of the STATA command for sample size calculation

```
Sample size calculation to determine number of observations required per cluster, for a two-
sample comparison of proportions (using normal approximations) without continuity correction.

For the user specified parameters:
      p1: 0.4700
      p2: 0.4100
      significance level:  0.05
      power:  0.80
      number of clusters available:  40
      intra cluster correlation (ICC):  0.0100
clustersampsi estimated parameters:
      Firstly, assuming individual randomisation: sample size per arm: 1071
      Then, allowing for cluster randomisation: average cluster size required:  38
      sample size per arm:   1520
```

Supplementary Table 1. *Suchana* inclusion criteria for registration of enrolling as vulnerable households

Vulnerable household verification questions	Inclusion criteria
Step 1 • Households currently participating/member of any livelihood, food security or asset transfer program	If "NO" go ahead for next questions
Step 2 • Ability to afford three (3) full meals per day for all family members round the year • Households monthly income BDT 7,500 or more • Household productive asset value worth BDT 15,000 or more (excluding land, pond and homestead) • Ownership of homestead land 10 decimals or more • Ownership of cultivable land 50 decimals or more (excluding homestead or pond)	If anyone is "NO" go ahead for next questions
Step 3 • Households have married women with in child bearing age (15 to 45 years) • Households have pregnant women (including abandoned or widowed woman) • Households have 0-23 months old children • Households have adolescent girls (15-19 years)	If anyone is 'Yes' go ahead for registration of enrolling as vulnerable Household
Sampling frame was prepared for collecting data from mother-child pair if the households had 0-23 months old children	

Supplementary Equation of logistic and probit regression

$$logit(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

$$probit(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

Where,

x1: Less than four ANC visits by a skilled service provider
x2: Unskilled birth attendant/facility
x3: Mother involved in income-generating activities
x4: Maternal BMI <18.5
x5: Maternal education: no schooling
x6: HH severe food insecurity
x7: Monthly income <15000 BDT
x8: Did not involve with aquaculture
x9: Having unhygienic latrine
x10: Soap was unavailable in hand washing place
x11: HH size≥7
x12: HH dietary diversity score <7
x13: Child's age>18
x14: Child's sex was male
x15: Childhood illness in the last 15 days
x16: Lacked access to mass media

and

$$logit(y) = \log[y/(1-y)]$$

Supplementary Table 2a. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple logistic regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.07, 6.22)	0.006
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.55, 4.35)	0.012
Mother involved in income-generating activities			
No	54.55 (50.90, 58.19)	Reference	
Yes	50.59 (49.08, 52.11)	3.95 (0.40, 7.51)	0.029
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.41)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.40)	<0.001
HH food insecurity			
Below severe	53.03 (50.91, 55.15)	Reference	
Severe	50.36 (48.63, 52.09)	2.66 (0.11, 5.22)	0.041
HH monthly income ≥15000 BDT			
Yes	51.31 (49.79, 52.84)	Reference	
No	48.58 (45.86, 51.30)	2.73 (0.17, 5.30)	0.037
Involved with aquaculture			
Yes	51.22 (49.72, 52.72)	Reference	
No	46.99 (43.30, 50.69)	4.23 (0.73, 7.73)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.54 (46.74, 50.33)	4.10 (1.83, 6.38)	<0.001
HH size			
Below seven	53.86 (51.98, 55.74)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.92 (51.25, 56.60)	Reference	
HDDS <7	50.10 (48.70, 51.50)	3.83 (1.63, 6.02)	<0.001
Child's age			
Age ≤18 months	56.72 (54.77, 58.67)	Reference	
Age >18 months	46.59 (44.82, 48.35)	10.1 (7.94, 12.32)	<0.001
Child's sex			
Female	53.25 (51.17, 55.34)	Reference	
Male	48.40 (46.78, 50.03)	4.85 (2.59, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.77)	Reference	
Yes	50.49 (48.94, 52.05)	4.41 (1.48, 7.34)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.39, 50.88)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

Supplementary Table 2b. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple probit regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.08, 6.22)	0.007
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.54, 4.35)	0.011
Mother involved in income-generating activities			
No	54.55 (50.90, 58.16)	Reference	
Yes	50.59 (49.08, 52.11)	3.93 (0.39, 7.48)	0.024
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.40)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.41)	<0.001
HH food insecurity			
Below severe	53.01 (50.89, 55.12)	Reference	
Severe	50.37 (48.64, 52.10)	2.64 (0.09, 5.19)	0.042
HH monthly income ≥15000 BDT			
Yes	51.32 (49.79, 52.84)	Reference	
No	48.56 (45.84, 51.28)	2.75 (0.19, 5.32)	0.035
Involved with aquaculture			
Yes	51.22 (49.73, 52.71)	Reference	
No	46.99 (43.28, 50.69)	4.24 (0.73, 7.74)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.53 (46.74, 50.33)	4.11 (1.83, 6.39)	<0.001
HH size			
Below seven	53.86 (51.98, 55.73)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.90 (51.23, 56.57)	Reference	
HDDS <7	50.10 (48.71, 51.50)	3.79 (1.60, 5.98)	<0.001
Child's age			
Age ≤18 months	56.72 (54.76, 58.67)	Reference	
Age >18 months	46.59 (44.83, 48.35)	10.1 (7.93, 12.3)	<0.001
Child's sex			
Female	53.25 (51.17, 55.33)	Reference	
Male	48.41 (46.78, 50.03)	4.85 (2.60, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.75)	Reference	
Yes	50.50 (48.94, 52.05)	4.40 (1.47, 7.33)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.40, 50.86)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

STROBE Statement—Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	1-2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-5
Objectives	3	State specific objectives, including any prespecified hypotheses	5
Methods			
Study design	4	Present key elements of study design early in the paper	5-6
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	5-6
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	*5-6*
Bias	9	Describe any efforts to address potential sources of bias	10
Study size	10	Explain how the study size was arrived at	5
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	7-8
		(*b*) Describe any methods used to examine subgroups and interactions	
		(*c*) Explain how missing data were addressed	
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	8
		(*e*) Describe any sensitivity analyses	
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	11
		(b) Give reasons for non-participation at each stage	
		(c) Consider use of a flow diagram	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	11
		(b) Indicate number of participants with missing data for each variable of interest	
Outcome data	15*	Report numbers of outcome events or summary measures	11
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	11-14

		(*b*) Report category boundaries when continuous variables were categorized	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	11-14
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
Discussion			
Key results	18	Summarise key results with reference to study objectives	15
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	15
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	15
Generalisability	21	Discuss the generalisability (external validity) of the study results	15-18
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	20

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

BMJ Open

A predictive modelling approach to illustrate factors correlating with stunting

Journal:	*BMJ Open*
Manuscript ID	bmjopen-2022-067961.R2
Article Type:	Original research
Date Submitted by the Author:	11-Feb-2023
Complete List of Authors:	Haque, Md; ICDDRB Choudhury, Nuzhat; ICDDRB Wahid, Barbie Zaman; ICDDRB Ahmed, SM Tanvir ; Save the Children Bangladesh Farzana, Fahmida Dil; ICDDRB Ali, Mohammad; ICDDRB Naz, Farina; ICDDRB Siddiqua, Towfida Jahan ; Johns Hopkins University, Bangladesh Rahman, Shahed ; Save the Children Bangladesh Faruque, ASG; ICDDRB Ahmed, Tahmeed; ICDDRB
Primary Subject Heading:	Epidemiology
Secondary Subject Heading:	Public health
Keywords:	Nutrition < TROPICAL MEDICINE, STATISTICS & RESEARCH METHODS, EPIDEMIOLOGY, PUBLIC HEALTH

SCHOLARONE™
Manuscripts

A predictive modelling approach to illustrate factors correlating with stunting

Md Ahshanul Haque[1*], Nuzhat Choudhury[1], Barbie Zaman Wahid[1], SM Tanvir Ahmed[2], Fahmida Dil Farzana[1], Mohammad Ali[1], Farina Naz[1], Towfida Jahan Siddiqua[1], Sheikh Shahed Rahman[2], ASG Faruque[1], Tahmeed Ahmed[1]

[1] Nutrition and Clinical Services Division, icddr,b, Dhaka, 1212, Bangladesh
[2] Child Poverty Sector, Save the Children Bangladesh, Dhaka, Bangladesh

*** Correspondence:** Md Ahshanul Haque, Assistant Scientist, Nutrition and Clinical Services Division, icddr,b, 68, Shaheed Tajuddin Ahmed Sarani, Mohakhali, Dhaka 1212, Bangladesh, Email: ahshanul.haque@icddrb.org

Word count: 4539

Abstract

Objective The aim of this study was to construct a predictive model in order to develop an intervention study to reduce the prevalence of stunting among children aged 12-23 months.

Design The study followed a cluster randomized pre-post design and measured the impacts on various indicators of livelihood, health, and nutrition. The study was based on a large dataset collected from two cross-sectional studies (baseline and endline).

Setting The study was conducted in the north-eastern region of Bangladesh under the Sylhet division, which is vulnerable to both natural disasters and poverty. The study specifically targeted children between the ages of 12 and 23 months.

Main outcome measures Childhood stunting, defined as a length-for-age z-score (LAZ)<-2, was the outcome variable in this study. Logistic and probit regression models and a decision tree were constructed to predict the factors associated with childhood stunting. The predictive performance

of the models was evaluated by computing the area under the receiver operating characteristic (ROC) curve analysis.

Results The baseline survey showed a prevalence of 52.7% stunting, while 50.0% were stunted at endline. Several factors were found to be associated with childhood stunting. The model's sensitivity was 61% and specificity was 56%, with a correctly classified rate of 59% and an area under the ROC curve of 0.615.

Conclusion The study showed that childhood stunting in the study area was largely influenced by factors such as maternal nutrition and education, food insecurity, and hygiene practices. Despite efforts to address these factors, they remain largely unchanged. The study suggests that a more effective approach may be developed in future to target adolescent mothers, as maternal nutrition and education are age-dependent variables. Policymakers and programme planners need to consider incorporating both nutrition-sensitive and specific activities and enhancing collaboration in their efforts to improve the health of vulnerable rural populations.

Study registration: RIDIE-STUDY-ID-5d5678361809b

Keywords: Predictive model, Nutrition, Statistics, Logistic regression, Probit regression, Decision tree

Strengths and limitations of this study

- Both parametric and non-parametric models were used and the predictive performance of the analytical models was calculated
- The study was designed to mitigate potential impact of seasonal factors by conducting the baseline and endline surveys at the same time of the year
- Use of recall data from the previous 24 hours for dietary diversity, household food insecurity, domestic violence, and maternal healthcare may be subject to recall bias
- Biological data has not been collected such as enteropathogen and environmental enteric dysfunction, which could have been related to childhood stunting

Introduction

Childhood stunting, which is defined as length-for-age z-score (LAZ)<-2, is a major concern for public health and has been widely used as an indicator of chronic malnutrition in children.[1] Although childhood stunting scenarios have much improved globally, the prevalence of childhood stunting is still very high in low-resource settings, including countries such as Bangladesh. According to the 2018 Global Nutrition Report, 150.8 million children (22.2%) under five years-of-age are stunted globally, compared to 198.4 million (32.6%) and 165 million children in 2000 and 2011, respectively.[2 3] Asian countries have observed a decrease in the rate of stunting among children under five from 38.1% to 23.2% between 2000 and 2018; nevertheless, South Asia still has the highest prevalence of stunting across the region, at 38.9%.[2] In Bangladesh, about 5.5 million (36%) children under five were stunted in 2014,[4] however by 2018, childhood stunting has reduced to about 31%.[5] As the World Health Organization (WHO) considers a childhood stunting rate of 15% to be an emergency situation, the current prevalence of childhood stunting in Bangladesh reflects an alarming situation of chronic undernutrition.[6]

Literature suggests that the prevalence of stunting is higher in children whose mothers receive appropriate antenatal care, take more rest, consume additional food, and take iron-folic acid (IFA) tablets during pregnancy.[7-9] Mass media exposure, receive a vitamin A capsule; have a skilled birth attendant; and have maternal nutritional status and maternal education, both of which are linked to childhood stunting.[6 8 10-12] On the other hand, in poor households in Bangladesh, children's stunting status is higher among the employed mothers.[13] Moreover, evidence suggests that a number of characteristics at the household level, which relate to both children and mothers, can influence childhood stunting. The characteristics of the household head, household food insecurity and lower dietary diversity, household lower-income, household involvement in several earning activities, availability of sanitation facility at home, hand-washing status, family size, religion, and receive several types of allowance from government are most often reported to be associated with stunting in the literature.[6 8 11 14-16]

Based on child characteristics, several indicators are associated with stunting. This status is associated with two basic characteristics: a child's gender and age.[8] Children are commonly affected by the co-occurrence of illness in low- and middle-income countries, which is one of the most common causes of stunting.[17] Inadequate infant and young child feeding (IYCF) practices also reduce child growth.[8 15] However, these findings are mostly based on nationally representative cross-sectional and cohort studies, or studies conducted in urban settings.[18 19] Therefore, a knowledge gap exists on whether similar results would be obtained when nationwide data are compared with data for study populations from poor or very poor rural households in specific vulnerable regions.

Sylhet is one such vulnerable region of north-east Bangladesh, comprising diverse terrains such as plain land, hilly land, *Haor* (wetland), and flash flood-prone areas. This region is reported to perform poorly for all important maternal healthcare indicators,[20] despite the fact that Bangladesh has made substantial progress in improving the overall health of the population.[21] Moreover, the socio-economic profile of the inhabitants in Sylhet region includes both very rich and extremely poor people. This scenario may worsen without the implementation of appropriate strategies in the near future. Sylhet region is also performing poorly compared to the national averages for a number of health and nutritional indicators. Critical indicators such as the infant mortality rate and unemployment status of women are high.[19] In comparison to the overall situation of Bangladesh, where stunting among children under five has decreased, the Bangladesh Demographic and Health Survey (BDHS) 2014 indicates the prevalence of childhood stunting in Sylhet is astonishingly high, at 50%.[19] This alarming figure provided the rationale for implementation of a comprehensive intervention programme in this region. A large-scale nutrition programme, *Suchana: Ending the Cycle of Undernutrition in Bangladesh; a multi-sectoral nutrition programme,* was undertaken with the aim to prevent chronic malnutrition in Sylhet.

In general, *Suchana* nutrition interventions can be divided into two types: nutrition-sensitive and nutrition-specific.[22] The concept of nutrition-sensitive intervention refers to an intervention that benefits the beneficiaries in terms of food and nutrition security, and also influences the underlying determinants of nutrition. This type of intervention is largely delivered through the agricultural sector (homestead vegetable and fruit production, pro-poor nutrition-sensitive aquaculture), improved technology (mono-sex tilapia and carp-tilapia polyculture, subsistence fishing, fish drying), demonstrations (village model farms and demo ponds, livestock, food security, promotion of climate-smart technologies), and supported income-generating activities (skill development in business management, engagement with the private sector and other sectors). As nutrition-specific interventions were delivered through nutrition-sensitive interventions, their coverage, effectiveness, and scale can be increased. It can meet the targets by lowering them and implementing nutrition-specific interventions. A nutrition-specific intervention addresses the immediate cause of malnutrition. Direct determinants of nutrition are the focus of this intervention. There is a strong focus on nutrition-specific interventions in the health sector. Whether implemented alone or jointly, nutrition-specific interventions improve health outcomes. Some examples of nutrition-specific interventions are: counselling for mothers at the household level, community-based nutrition education for spouses and in-laws, growth monitoring and promotion sessions integrated with *Expanded Programme on Immunization* in communities, *Government of Bangladesh* health facilities equipped with *severe acute malnutrition* service delivery, and support for *National Nutrition Services* service delivery through community clinics, Union Health and Family Welfare Centers, and Upazila health complexes.

The primary objective of the *Suchana* programme was to reduce the prevalence of childhood stunting in the intervention areas. The secondary objectives were to assess the changes in *Suchana* beneficiaries' households, in terms of an increase and diversification of household income, food security status, optimal IYCF practices, haemoglobin status of children, the empowerment of women, and adolescents' nutritional knowledge and practices.[22]

The *Suchana* programme substantially improved nutritional behaviour, maternal healthcare practices, women's empowerment, household income, and household food security in the intervention area compared to the control area.[23] Contrary to predictions, however, *Suchana* did not result in any significant reduction in the prevalence of childhood stunting. Therefore, although most other factors related to childhood stunting improved, this raises the question of why the prevalence of stunting did not reduce after the intervention. An important observation from the *Suchana* survey was that the proportion of households in this study population using hygienic latrines was quite low. This factor was associated with stunting in children,[8] and did not significantly improve by endline in the intervention areas compared to the control areas.

In this study, we aimed to construct a predictive model to attempt to explain whether any improvements in associated factors may promote a significant reduction in stunting among children aged 12-23 months from poor and extremely poor households in the Sylhet region.

Methods

Study design and setting

The *Suchana* programme was implemented in 157 *Unions* over 20 sub-districts in the Sylhet region in the north-east of rural Bangladesh. The *Suchana* programme's protocol has been thoroughly explained elsewhere.[22] *Union*, the smallest local government and administrative entity in rural Bangladesh, was considered as a cluster and divided into four phases at random. Phase-1 was designated as the intervention group, while Phase-4 was the control group, and the other phases were treated as learning phases.[22] For implementation purposes, vulnerable villages were selected within Phase-1 and Phase-4 areas. The staff of the programme chose vulnerable villages in each *Union* based on their vulnerability (e.g., frequent floods or submerging, little or no intervention from other development programmes, poverty or household living circumstances, remoteness and accessibility issues, a high prevalence of superstitions and social taboos). After consultation with the local government representatives, elected officials, and local elites as well as field visits, this selection method was decided upon. The impacts of the intervention on livelihood, health, and nutrition were measured using a pre-post design. A large dataset was collected from two cross-sectional surveys (baseline and endline) under this study. The baseline survey was conducted in November 2016 and February 2017, followed by the endline survey in the same months three years later among the same population and different participants (Supplementary Figure 1).

Outcome variable

The outcome variable in this study was childhood stunting, which was defined as a length-for-age z-score (LAZ)<-2.[5]

Independent variables

Initially, a list of independent variables was finalized through results obtained from descriptive and bi-variate analyses, as well as a comprehensive literature review (Table 1). These included at least four antenatal care (ANC) visits by a skilled service provider, additional resting during pregnancy, additional food consumption during pregnancy, consumption of at least 100 IFA tablets during pregnancy, receiving vitamin A capsule after last delivery, birth attendant/facility, mother involved in income-generating activities, maternal BMI, maternal education, household food insecurity, household monthly income >15000 BDT, involved with aquaculture, hygienic latrine, water and soap available in handwashing place, household size, household dietary diversity, sex of household head, religion, received any grant/allowance/stipend from the government, access of mass media, child's age, child's sex, childhood illness in the last 15 days, minimum dietary diversity, early initiation of breastfeeding, and received colostrum. Household food insecurity access scale was measured using the Food and Nutrition Technical Assistance's Guideline, which categorizes household food insecurity into four levels: a) food secure, b) mildly food insecure, c) moderately food insecure, and d) severely food insecure.[24] In the analysis herein, this indicator was redefined as a binary indicator: severely food insecure or not severely food insecure.

Sample size

The sample size for this study was calculated with the STATA "*clustersampsi*" command module, considering the number of clusters in the surveys and considering the expected prevalence of childhood stunting in the control group (Supplemental Appendix 1). It was estimated that the expected prevalence of stunting was 47%, which was hypothesized to be reduced to 41% after three years of intervention. A sample size of 1520 per arm was calculated based on a 5% level of significance, 80% power, 40 clusters per arm, and an intra-cluster correlation coefficient (ICC) of 0.01. After rounding, the estimated sample size per arm was 1620, and the total sample size was 3200 at baseline, with an equal number of participants in the control and intervention groups. For evaluation purposes, the sample size at endline was doubled to ensure a stratified intervention component, resulting in a total sample size of 9600 mother-child pairs (baseline: 3200 and endline: 6400).[22]

Sampling

The baseline and endline surveys were conducted in a total of eight and twelve villages respectively, which were randomly selected from each *Union* using a list of vulnerable villages provided by Save the Children. The most vulnerable households were identified and verified using the inclusion criteria of the *Suchana* programme (Supplementary Table 1). These households were then given an identification number to prepare the sampling frame and required households were systematically selected for the surveys from the frame. The method of data collection is explained in detail in the Supplemental Appendix 2.

Statistical analysis

Descriptive statistics: Stata-14 software (StataCorp LP, College Station, TX, USA) and R 4.2.2 (*rpart*) were used to analyse the data. Several statistical plots were used for data visualization. Descriptive statistics, such as frequency and proportions for categorical variables and mean and standard deviations for quantitative variables, were used to summarize the data at baseline and endline.

Predictive model: Three statistical models were used as predictive models. Two parametric models, such as Logistic and Probit regression models, and Decision Tree as a non-parametric model. Logistic and Probit regression models were used as predictive models as well as classifier models. The models were also used to investigate which factors were significantly associated with childhood stunting, and estimate their effect size, in order to predict whether changes in behavioural practices might potentially help to achieve targeted reductions in stunting. Using those variables, a decision tree was applied, and the predictive performance was compared to other models.

For the parametric models, first, Chi-Square test was used to examine the bivariate associations between stunting and all possible explanatory variables. In the second step, variables with *p*-values <0.25 in the simple model were included in the multiple regression models.[25] In the final step, any independent variables thought to be likely predictors were added to the multiple regression model using the stepwise forward selection method. Some indicators, e.g., age, sex, and maternal nutritional status were added regardless of their *p*-value due to their scientific plausibility. The mathematical equation of logistic and probit regression models were given in the Supplemental Appendix 3. As a cluster variable, *Union* was used to adjust the standard errors. Furthermore, for the explanation of the regression model, a *p*-value <0.05 was considered as statistically significant, and the confidence interval (CI) of 95% was also reviewed. From the fitted model, the adjusted effect size (adjusted prevalence difference) against all predictors was estimated using the "*adjrr*" package in Stata. The list of independent variables with the value labels used in the model is given in Table 1.

Table 1. List of all independent variables

Indicators	Code	Stunting Status*	Selection in the model
At least four ANC visits by a skilled service provider			Selected
At least four ANC visits by a skilled service provider	0		
Less than four ANC visits by a skilled service provider	1	Higher prevalence[8]	
Additional resting during pregnancy			Not selected
Took more rest	0		
Did not take more rest	1	Higher prevalence[8]	
Additional food consumption during pregnancy			Not selected
Consumed more food	0		
Did not consumed more food	1	Higher prevalence[7 8]	
Consumption of at least 100 IFA tablets during pregnancy			Not selected
Consumed at least 100 IFA tablets	0		
Did not consumed at least 100 IFA tablets	1	Higher prevalence[9]	
Received vitamin A capsule after last delivery			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	
Birth attendant/facility			Selected
Skilled	0		
Unskilled	1	Higher prevalence[10]	
Mother involved in income-generating activities			Selected
No	0		
Yes	1	Higher prevalence[6 13]	
Maternal BMI			Selected
BMI ≥18.5	0		
BMI <18.5	1	Higher prevalence[6 11]	
Maternal education			Selected
At least one-year formal education	0		
No schooling	1	Higher prevalence[6 11]	
Access of mass media			Selected
Access	0		
No access	1	Higher prevalence[12]	
Household food insecurity			Selected
Below severe	0		
Severe	1	Higher prevalence[8]	
Household monthly income ≥15000 BDT			Selected
≥15000 BDT	0		
<15000 BDT	1	Higher prevalence[11]	
Involved with aquaculture			Selected
Involved	0		
Did not involved	1	Higher prevalence[14]	
Hygienic latrine			Selected
Hygienic latrine	0		

Unhygienic latrine	1	Higher prevalence[6 11 15]	
Water and soap available in handwashing place			Selected
Available	0		
Unavailable	1	Higher prevalence[15]	
Household size			Selected
Below seven	0		
Seven or above	1	Higher prevalence[11]	
Household dietary diversity (HDDS)			Selected
HDDS ≥7	0		
HDDS <7	1	Higher prevalence[8]	
Sex of household head			Not selected
Female	0		
Male	1	Higher prevalence[8]	
Household head education			Not selected
At least one-year formal education	0		
No schooling	1	Higher prevalence[6]	
Religion			Not selected
Muslim	0		
Non-Muslim	1	Lower prevalence[6]	
Received any grant/allowance/stipend from the government			Not selected
Received	0		
Did not receive	1	Higher prevalence[16]	
Child's age			Selected
Age ≤18 months	0		
Age >18 months	1	Higher prevalence[8]	
Child's sex			
Female	0		
Male	1	Higher prevalence[8]	
Childhood illness in the last 15 days			Selected
No	0		
Yes	1	Higher prevalence[17]	
Minimum dietary diversity			Not selected
Received	0		
Did not receive	1	Higher prevalence[8 15]	
Early initiation of breastfeeding			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	
Received colostrum			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	

[1]Expected effects based on findings of the literature

Model evaluation: The predictive performance of the three statistical models was evaluated by computing model sensitivity and specificity, and calculating the area under the receiver operating curve (ROC) analysis. To ensure accurate results, the data was randomly split into a training set (75%) and a test set (25%) using a random-number seed 113843. The same training and test datasets were used for evaluating the performance of all algorithms to ensure consistency in the results. The sensitivity and specificity values, as well as the area under the ROC curve, were used to determine the overall accuracy of the algorithms in predicting childhood stunting.[26 27]

Patient and public involvement

Patients and public were not actively involved in formulating the research question and or protocol development, including the outcome measures. To expedite the field implementation, however, local elites e.g. teachers, religious persons, and local government council members were informed about the study.

Results

General characteristics: Out of 9600 cases, 9501 cases were found to be available. The refusal rate was around 1%. With respect to the outcome indicator, stunting in children aged 12-23 months, 52.7% of children were stunted at the baseline survey (intervention group: 52.6%; control group: 52.8%), whereas the proportion of children exhibiting stunting at endline was 50.0% (intervention: 49.9%; control: 50.1%; Figure 1). At both the baseline and endline surveys, there was no significant difference in proportion between intervention and control areas. The *difference-in-difference* in outcomes over time was also insignificant.

Figure 2 describes several other indicators related to maternal and child health, including the status of consuming a minimum acceptable diet (intervention: 35.2%; control: 14.9%), minimum dietary diversity (intervention: 42.8%; control: 20.4%), maternal decision-making (intervention: 45.0%; control: 31.0%), at least four maternal ANC visits by a skilled service provider (intervention: 36.1%; control: 17.7%), minimum dietary diversity for women (intervention: 52.6%; control: 33.5%), a household dietary diversity score of at least seven (intervention: 88.9%; control: 78.3%), and household food security status (intervention: 26.6%; control: 20.2%). Results from the endline survey showed that these indicators were significantly improved in the intervention group compared to the control group. However, the availability of hygienic latrines did not increase in the intervention group (intervention: 44.0%; control: 44.0%). Table 2 shows the households' socio-demographic characteristics, women's general characteristics, and children's characteristics at baseline and endline.

Table 2. General characteristics of the *Suchana* beneficiaries

Indicators, *n* (%)	Baseline *N*=3200	Endline *N*=6301	Total *N*=9501
At least four ANC visits by a skilled service provider			
Yes	408 (12.8)	1530 (24.3)	1938 (20.4)
No	2792 (87.2)	4771 (75.7)	7563 (79.6)
Delivery at skilled birth attendant/facility			
Yes	1000 (31.2)	2769 (44.0)	3769 (39.7)
No	2200 (68.8)	3532 (56.0)	5732 (60.3)
Access of mass media			
Access	563 (17.59)	1169 (18.55)	1732 (18.23)
No access	2637 (82.41)	5132 (81.45)	7769 (81.77)
Mother involved in income-generating activities			
No	3102 (96.9)	5665 (89.9)	8767 (92.2)
Yes	98 (3.1)	639 (10.1)	737 (7.8)
Maternal BMI			
BMI ≥18.5	1859 (58.1)	4073 (64.6)	5932 (62.4)
BMI <18.5	1341 (41.9)	2231 (35.4)	3572 (37.6)
Mother completed primary education			
Yes	1721 (53.8)	3808 (60.4)	5529 (58.2)
No	1479 (46.2)	2496 (39.6)	3975 (41.8)
Maternal age			
Age <30 years	2145 (67.0)	3559 (56.5)	5704 (60.0)
Age ≥30 years	1055 (33.0)	2745 (43.5)	3800 (40.0)
Type of delivery			
Normal	2879 (90.0)	5529 (87.8)	8408 (88.5)
Caesarean	321 (10.0)	772 (12.3)	1093 (11.5)
PNC			
No	2152 (67.3)	4128 (65.5)	6280 (66.1)
Yes	1048 (32.8)	2173 (34.5)	3221 (33.9)
Household severely food insecure			
Yes	912 (28.5)	1016 (16.1)	1928 (20.3)
No	2288 (71.5)	5285 (83.9)	7573 (79.7)
Household monthly income ≥15000 BDT			
Yes	424 (13.2)	1015 (16.1)	1439 (15.1)
No	2776 (86.8)	5289 (83.9)	8065 (84.9)
Household involved with aquaculture			
Yes	161 (5.0)	561 (8.9)	722 (7.6)
No	3039 (95.0)	5740 (91.1)	8779 (92.4)
Hygienic latrine			
Yes	1121 (35.0)	2782 (44.1)	3903 (41.1)
No	2079 (65.0)	3519 (55.9)	5598 (58.9)
Water and soap available in handwashing place			
Yes	862 (26.9)	3170 (50.3)	4032 (42.4)
No	2338 (73.1)	3131 (49.7)	5469 (57.6)
Household savings			
No	1080 (33.8)	2876 (45.6)	3956 (41.6)

	Yes	2120 (66.2)	3425 (54.4)	5545 (58.4)
Sex of household head				
	Female	110 (3.4)	501 (8.0)	611 (6.4)
	Male	3090 (96.6)	5799 (92.0)	8889 (93.6)
Source of drinking water				
	Tube well	2748 (85.9)	5713 (90.7)	8461 (89.0)
	Others	452 (14.1)	588 (9.3)	1040 (11.0)
Household dietary diversity score				
	HDDS ≥7	2182 (68.2)	5322 (84.5)	7504 (79.0)
	HDDS <7	1018 (31.8)	979 (15.5)	1997 (21.0)
Household monthly income (Thousand BDT)[1]		6.7 (5, 10)	7.5 (5.1, 10.8)	7.1 (5, 10.4)
Per capita income (Thousand)[1]		2.6 (1.8, 3.7)	2.9 (2, 4.1)	2.8 (2, 4)
Household size[1]		6.2±2.4	5.9±2.1	6±2.2
Child's age in months[2]		17.9±3.5	17.3±3.6	17.5±3.6
Length-for-age z-score[2]		-2.1±1.2	-2±1.1	-2±1.1
Weight-for-age z-score[2]		-1.7±1.1	-1.5±1.0	-1.5±1.0
Weight-for-length z-score[2]		-0.9±1.0	-0.7±0.9	-0.7±1.0
Child's age				
	Age <18 months	1745 (54.5)	3710 (58.9)	5455 (57.4)
	Age ≥18 months	1455 (45.5)	2594 (41.1)	4049 (42.6)
Child's sex				
	Female	1567 (49.0)	3044 (48.3)	4611 (48.5)
	Male	1633 (51.0)	3257 (51.7)	4890 (51.5)
Childhood illness in the last 15 days				
	Yes	2867 (89.6)	5763 (91.5)	8630 (90.8)
	No	333 (10.4)	538 (8.5)	871 (9.2)

[1]Median (IQR); [2]Mean ± SD

Associated factors: The study used two parametric predictive models to determine the correlates of childhood stunting. The results, presented in Table 3, showed the adjusted odds ratios (aOR) computed from multiple logistic regression and the adjusted coefficients computed from multiple probit regression. These results provide important insights into the factors that increase the odds of stunting in childhood, and can inform public health interventions aimed at reducing stunting and improving child health. The aORs provide a quantitative measure of the relationship between different factors and childhood stunting, adjusting for *Union* as cluster variable. Understanding the correlates of childhood stunting is critical for addressing this important public health issue and improving the health and well-being of children globally. The results of this study show that a number of maternal, household and children factors were correlated with an increased prevalence of stunting in children. Children of mothers who did not receive at least four ANC visits from a skilled service provider had 1.16 times higher odds of stunting (95% CI: 1.05, 1.30; p-value=0.005). Children of mothers who gave birth with an unskilled birth attendant or facility had

1.11 times higher odds of stunting (95% CI: 1.02, 1.20; p-value=0.012). The odds of stunting were 1.18 times higher in children whose mothers were involved in income-generating activities (95% CI: 1.02, 1.37; p-value=0.030), 1.23 times higher in children of underweight mothers (95% CI: 1.12, 1.36; p-value<0.001), and 1.31 times higher in children of low-educated mothers (95% CI: 1.20, 1.42; p-value<0.001). Furthermore, the lack of exposure to mass media was also found to be associated with stunting, with odds of 1.15 (95% CI: 1.02, 1.30; p-value=0.025) times higher. Children from households with severe food insecurity, lower-income households, households not involved in aquaculture, and households with low dietary diversity, were more likely to be stunted, with odds increasing by 1.12 (95% CI: 1.00, 1.24; p-value=0.041), 1.12 (95% CI: 1.01, 1.25; p-value=0.037), 1.19 (95% CI: 1.03, 1.38; p-value=0.018), and 1.17 (95% CI: 1.07, 1.29; p-value=0.001) times, respectively. The results also showed that the odds of stunting increased with increasing household size (95% CI: 1.11, 1.31; p-value<0.001), the absence of a hygienic latrine (95% CI: 1.10, 1.30; p-value<0.001), the absence of water and soap in the handwashing place (95% CI: 1.08, 1.30; p-value<0.001), increasing child age (95% CI: 1.39, 1.67; p-value<0.001), and being male (95% CI: 1.11, 1.34; p-value<0.001). The odds of stunting were also 1.20 times higher in children with acute illness (95% CI: 1.06, 1.36; p-value=0.003). The logistic and probit regression models were employed to predict stunting in a sample of 9501 individuals. Both models were found to be significant, with log-likelihoods of -6387.94 and -6388.02, respectively, and significant Wald chi-square statistics (p-value < 0.001). The correlations of childhood stunting, as determined by using a decision tree as a non-parametric predictive model, are also presented in Figure 3. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) are given in Supplementary Table 2a and 2b.

Table 3. Factors influencing stunting in children aged 12-23 months, computed using logistic and probit regression analyses

Indicators		Logistic		Probit	
		Adjusted OR (95% CI)	p-value	Adjusted Coef. (95% CI)	p-value
At least four ANC visits by a skilled service provider					
	Yes	Reference		Reference	
	No	1.16 (1.05, 1.30)	0.005	0.09 (0.03, 0.16)	0.005
Birth attendant/facility					
	Skilled	Reference		Reference	
	Unskilled	1.11 (1.02, 1.20)	0.012	0.06 (0.01, 0.11)	0.012

Mother involved in income-generating activities					
	No	Reference		Reference	
	Yes	1.18 (1.02, 1.37)	0.030	0.10 (0.01, 0.19)	0.030
Maternal BMI					
	BMI ≥18.5				
	BMI <18.5	1.23 (1.12, 1.36)	0.000	0.13 (0.07, 0.19)	0.000
Maternal education was primary completed					
	Yes	Reference		Reference	
	No	1.31 (1.20, 1.42)	0.000	0.17 (0.12, 0.22)	0.000
Access of mass media					
	Yes	Reference		Reference	
	No	1.15 (1.02, 1.30)	0.025	0.09 (0.01, 0.16)	0.025
Household food insecurity					
	Below severe				
	Severe	1.12 (1.00, 1.24)	0.041	0.07 (0.00, 0.13)	0.042
Household monthly income ≥15000 BDT					
	Yes	Reference		Reference	
	No	1.12 (1.01, 1.25)	0.037	0.07 (0.00, 0.14)	0.035
Involved with aquaculture					
	Yes	Reference		Reference	
	No	1.19 (1.03, 1.38)	0.018	0.11 (0.02, 0.20)	0.018
Household size					
	Below seven	Reference		Reference	
	Seven or above	1.20 (1.11, 1.31)	0.000	0.12 (0.06, 0.17)	0.000
Hygienic latrine					
	Yes	Reference		Reference	
	No	1.20 (1.10, 1.30)	0.000	0.11 (0.06, 0.16)	0.000
Water and soap available in handwashing place					
	Yes	Reference		Reference	
	No	1.19 (1.08, 1.30)	0.000	0.11 (0.05, 0.16)	0.000
Household dietary diversity					
	HDDS ≥7	Reference		Reference	
	HDDS <7	1.17 (1.07, 1.29)	0.001	0.10 (0.04, 0.16)	0.001
Child's age					
	Age ≤18 months	Reference		Reference	
	Age >18 months	1.52 (1.39, 1.67)	0.000	0.26 (0.2, 0.32)	0.000
Child's sex					
	Female	Reference		Reference	
	Male	1.22 (1.11, 1.34)	0.000	0.13 (0.07, 0.18)	0.000
Childhood illness in the last 15 days					
	No	Reference		Reference	
	Yes	1.20 (1.06, 1.36)	0.003	0.11 (0.04, 0.19)	0.003
Sample size and regression diagnostic values for logistic and probit regression analyses		n = 9501 Log-likelihood = -6387.94 Wald chi2(17) = 427.79 p-value<0.001 Pseudo R^2 = 0.0298		n = 9501 Log-likelihood = -6388.02 Wald chi2(17) = 441.18 p-value<0.001 Pseudo R^2 = 0.0298	

Unions were adjusted as clusters. Baseline and endline were adjusted as time variables

Predictive performance: Table 4 describes the model validation based on sensitivity, specificity, and whether the model was correctly classified for the overall dataset, as well as the training and test datasets. The sensitivity and specificity of the model were around 60% and 55%, respectively for all models. The correctly classified rate was 59%, and the area under the ROC curve was around 61%. We found that these values were approximately equal among the three datasets (main, training, and test datasets); however, the predictive performance of the model was low.

Table 4. Predictive performance of the model for stunting based on classification, sensitivity, and specificity in the full, training and test datasets with area under the receiver operating characteristic curve analysis

	Logistic regression	Probit regression	Decision tree
Full dataset			
Overall accuracy	58.46	58.38	56.51
Sensitivity	61.21	61.25	61.15
Specificity	55.61	55.41	51.70
Area under the curve	61.54	61.54	56.72
Training Dataset			
Overall accuracy	58.83	58.62	57.66
Sensitivity	61.59	61.70	63.93
Specificity	55.36	55.42	51.61
Area under the curve	61.37	61.37	58.44
Test Dataset			
Overall accuracy	58.11	58.19	56.67
Sensitivity	60.23	60.23	61.58
Specificity	55.90	56.07	51.94
Area under the curve	61.76	61.77	58.01

Discussion

In an effort to understand why the *Suchana* programme was not effective in reducing the prevalence of childhood stunting, this study analyzed data from both the baseline and endline surveys of the programme. The analysis aimed to identify the factors that were significantly correlated with stunting and to evaluate the model's predictive performance. After controlling for the *Union* as a cluster variable, the study found several indicators that were significantly related to stunting. These included the number of ANC visits by a skilled service provider, household dietary diversity, household food security, and household monthly income, which improved after the intervention. However, it was noted that the household food security status did not reach the target value of 50%, despite being an important factor associated with childhood stunting.[8 28 29] On the other hand, other outcome indicators of the *Suchana* programme, such as dietary diversity of children, maternal dietary diversity, and maternal empowerment, despite reaching their target values, were not found to be associated with stunting in this study.

The recent study found that while the *Suchana* programme showed improvement in certain programme indicators, it did not lead to a significant reduction in childhood stunting. Despite efforts to address key factors such as maternal nutrition and education, household food security, and hygiene practices, these factors remained largely unchanged. However, the study suggests that interventions aimed at adolescent mothers may be more effective in improving maternal nutrition and education, since these are age-dependent variables. Additionally, the results of the study were also impacted by natural disasters in 2017, including heavy rains and flooding in the Sylhet region, which resulted in widespread damage to agriculture, aquaculture, and homes in the study population.[30 31]

The study found a contradictory relationship between stunting and maternal involvement in income-generating activities, with higher stunting prevalence observed among children whose mothers were engaged in various earning activities. Although there was a slight increase in the proportion of mothers involved in income-generating activities after the intervention, the lack of childcare support for working mothers resulted in a marked rise in childhood stunting among low-income households. It is important to address this issue by providing adequate childcare support measures for working mothers from poor families, to ensure that the essential needs of the child are not impacted by the mother's employment status.[13] Another important finding based on the post-estimation findings as well as the value of the area under the ROC curve was that the predictive performance of the model was low. Thus, we need to identify other indicators from similar research contexts influencing childhood stunting that were not included in our model.

The literature suggests that environmental enteropathy may contribute to poor growth among children in rural Bangladesh and may represent an important factor affecting the study population in the *Suchana* programme.[32] Although it was not specifically assessed in this study, indicators such as unsanitary latrines, unimproved floors, lack of handwashing practices, and low education levels were available.[18 33] Improving Water, Sanitation and Hygiene (WaSH) variables, particularly latrine facilities and handwashing practices, may help reduce the burden of stunting in young children. One of the components of the intervention was poultry, but our qualitative findings revealed that many households shared living spaces with poultry, ducks, or other animals, which could increase the risk of infections with *Campylobacter* species, a leading food-borne pathogen.[18 34] Previous studies have shown a strong association between stunting and enteropathy among children who do not respond to nutritional interventions, and findings from rural Bangladesh have linked environmental conditions and stunting in children.[35-37] While assessing environmental enteropathy was beyond the scope of the *Suchana* evaluation, collecting data on indicators of enteropathy in the intervention and control areas could help evaluate the impact of appropriate interventions in the future. The failure to achieve the desired outcome may have been due to several factors, including food insecurity and a lack of aquaculture involvement due to natural disasters, poor WaSH status, a lack of focus on maternal education and nutrition, and a lack of focus on the risk of enteropathogen burden.

This study will aid programme managers in prioritizing their focus and designing effective interventions to reduce childhood stunting. Sustainable solutions should be based on the needs of the beneficiaries. Implementing short-term initiatives such as attendance at healthcare-led workshops and campaigns can increase ANC visits, skilled birth attendance, and handwashing practices. Establishing women's healthcare services that focus on maternal and child health and nutrition will also help reduce the incidence of stunting.[23] Improved access to media can help vulnerable communities benefit from government welfare programmes. Food security, income, sanitation, aquaculture, and illness are all time-sensitive factors. Increasing food production through self-production or purchasing can improve household food security and nutrition. However, household wealth and access to nearby markets can impact their ability to buy nutritious food. Climate change adaptation in agriculture is crucial to minimize current risks and prepare for future uncertainties. Using organic fertilizers instead of chemicals in agriculture has environmental benefits, reducing the need for pesticides and protecting human health and biodiversity. Aquaculture can provide a source of protein and improve nutrition, but establishing these facilities takes time. Improving sanitation requires improving socioeconomic status, which is also a time-intensive process. It takes time to improve stunting, as shown by national surveys such as BDHS and Food Security and National Surveillance Project (FSNSP).[5 38] To improve maternal nutrition, women need adequate food during adolescence and maternal education is a strong predictor of a child's nutritional status. Emphasizing the education of female children can break the cycle of poverty and stunting.[6 11] To reduce childhood stunting in developing countries, comprehensive interventions that include nutritional support, food security, maternal education, income-generating activities for women, and addressing domestic violence against women should be implemented.

Recommendation: The Suchana model offers a holistic and integrated approach to addressing food and nutrition security, recognizing undernutrition as a complex problem caused by multiple factors. The endline survey of Suchana showed significant improvement in programme indicators. The multi-sector approach of Suchana is a meaningful solution to addressing undernutrition. However, policy makers should consider implementing additional nutrition-sensitive and specific activities, such as promoting climate-resilient agriculture and increasing water and sanitation coverage. It is also important to have a sustainable mechanism for improving food security and to promote awareness of seasonal diseases associated with livestock and poultry. To further improve the programme, indicators such as child sex, maternal education, and nutrition could be adjusted during the design stage. The Suchana programme is one of the largest global nutrition interventions, leading to positive changes in critical indicators, with long-term benefits expected for the health and livelihoods of the beneficiaries.

Strength and limitation: The study had several strengths, including a large sample size, randomization, and appropriate sampling techniques. A dedicated quality control team was involved in checking the data, and the use of precise anthropometry instruments and separate training for the measurement team helped ensure accurate data collection. The study was also designed to avoid seasonality by conducting the baseline and endline surveys at the same time of the year. However, the study results may have been impacted by a lack of selection effect in the implementation of the programme, as well as by the short time horizon of the study. The short duration of the study may not have been enough to see a significant impact on stunting. Additionally, changes in the study population between the baseline and endline surveys could also

have contributed to the lack of differences observed in the results. Another limitation of this study is that we did not collect food intake data but only recall data from the previous 24 hours. These data may be subject to recall bias; thus, caution is necessary when drawing conclusions, especially for indicators such as dietary diversity, household food insecurity, domestic violence, and maternal healthcare.

Conclusion

Childhood stunting was heavily influenced by a number of factors, and majority of the factors were found in poor status in our study area. Despite the implementation of an intervention programme, the situation remained unchanged due to factors such as food insecurity, lack of involvement in aquaculture, poor access to WaSH facilities, and a lack of focus on maternal education and nutrition. The study did not include important indicators such as enteropathogen and environmental enteric dysfunction, which might have contributed to the failure to achieve the desired outcome. The results suggest that policy makers and programme planners should consider enhancing collaboration and coordination between nutrition-sensitive and specific activities to address nutritional deficiencies and family health programmes in vulnerable rural populations.

Acknowledgments: The study analyzed baseline survey data of *Suchana*; this intervention has been implemented by a consortium led by Save the Children, with support from the Foreign, Commonwealth and Development Office (FCDO) and European Union (EU). icddr,b acknowledges with gratitude the commitment of Save the Children, FCDO and EU to its research efforts. We also acknowledge with gratitude the commitment of the Government of the People's Republic of Bangladesh to icddr,b's research activities. We also acknowledge the following donors for providing unrestricted support to icddr,b's efforts and advancement of its strategic plan: Canada, Sweden and the United Kingdom. We gratefully acknowledge our core donors for their support and commitment to icddr,b's research efforts. We would like to acknowledge the invaluable contributions of Save the Children as lead agency, our technical partners Helen Keller International, World Fish, and International Development Enterprises, and the implementing partners Friends In Village Development Bangladesh (FIVDB), Rangpur Dinajpur Rural Services (RDRS), and the Center for Natural Resource Studies (CNRS) who played critical roles in generating and refining the data-collection tools. We would also like to acknowledge Tasnia Alam, Research Assistant and Md. Maniruzzaman, Assistant Professor, Khulna University, Khulna-9208, Bangladesh as the internal reviewers, and Andrea Devlin of Science Editing Experts for editing and linguistic revision of the manuscript.

Funding: (i) This study was made possible by the committed contribution of Foreign, Commonwealth and Development Office (Grant number: 204131-103), and (ii) icddr,b (N/A).

Conflicts of Interest: The authors declare no conflict of interest.

Author Contributions: TA and NC originated the idea for the study and led the protocol design. MAH conceptualized the manuscript. SMTA, SSR, MAH, NC, FDF, and TA contributed to the survey design. MAH performed statistical analysis and drafted the manuscript. NC and ASGF supervised the work, and critically reviewed and provided feedback for revising the manuscript. MAH, NC, MA, FDF, FN, BZW, TJS, ASGF, TA, and SSR contributed to the revision of the final draft for submission. All authors are responsible for the final content of the manuscript.

Ethics approval: This study was approved by the Research Review Committee and Ethical Review Committee, the two obligatory components of the Institutional Review Board (IRB) of icddr,b. Ethics Committee's approval ID# 00001822. Informed written consent was obtained from study participants.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

Reference

1. Bari A, Nazar M, Iftikhar A, et al. Comparison of Weight-for-Height Z-score and Mid-Upper Arm Circumference to Diagnose Moderate and Severe Acute Malnutrition in children aged 6-59 months. *Pakistan journal of medical sciences* 2019;35(2):337-41. doi: 10.12669/pjms.35.2.45 [published Online First: 2019/05/16]

2. Development Initiatives. 2018 Global Nutrition Report: Shining a light to spur action on nutrition. Bristol, UK: Development Initiatives, 2018.

3. United Nations Children's Fund (UNICEF), World Health Organization, International Bank for Reconstruction and Development/The World Bank. Levels and trends in child malnutrition: Key Findings of the 2020 Edition of the Joint Child Malnutrition Estimates. Geneva: World Health Organization; 2020. Licence: CC BY-NC-SA 3.0 IGO., 2020.

4. USAID. Bangladesh: Nutrition Profile, 2018.

5. National Institute of Population Research and Training (NIPORT), ICF. Bangladesh Demographic and Health Survey 2017-18: Key Indicators. NIPORT and ICF: Dhaka, Bangladesh and Rockville, Maryland, USA, 2019.

6. Kumar P, Rashmi R, Muhammad T, et al. Factors contributing to the reduction in childhood stunting in Bangladesh: a pooled data analysis from the Bangladesh demographic and health surveys of 2004 and 2017–18. *BMC public health* 2021;21(1):2101. doi: 10.1186/s12889-021-12178-6

7. Yaya S, Wang R, Tang S, et al. Intake of supplementary food during pregnancy and lactation and its association with child nutrition in Timor Leste. *PeerJ* 2018;6:e5935. doi: 10.7717/peerj.5935 [published Online First: 20181115]

8. Choudhury N, Raihan MJ, Sultana S, et al. Determinants of age-specific undernutrition in children aged less than 2 years-the Bangladesh context. *Maternal & child nutrition* 2017;13(3) [published Online First: 2016/10/19]

9. Nisar YB, Dibley MJ, Aguayo VM. Iron-Folic Acid Supplementation During Pregnancy Reduces the Risk of Stunting in Children Less Than 2 Years of Age: A Retrospective Cohort Study from Nepal. *Nutrients* 2016;8(2):67. doi: 10.3390/nu8020067 [published Online First: 20160127]

10. Li Z, Kim R, Vollmer S, et al. Factors Associated With Child Stunting, Wasting, and Underweight in 35 Low- and Middle-Income Countries. *JAMA Netw Open* 2020;3(4):e203386. doi: 10.1001/jamanetworkopen.2020.3386 [published Online First: 20200401]

11. Katoch OR. Determinants of malnutrition among children: A systematic review. *Nutrition* 2022;96:111565. doi: 10.1016/j.nut.2021.111565 [published Online First: 20211211]

12. Huo S, Wang K, Liu Z, et al. Influence of Maternal Exposure to Mass Media on Growth Stunting Among Children Under Five: Mediation Analysis Through the Water, Sanitation, and Hygiene Program. *JMIR Public Health Surveill* 2022;8(4):e33394. doi: 10.2196/33394 [published Online First: 20220406]

13. Win H, Shafique S, Mizan S, et al. Association between mother's work status and child stunting in urban slums: a cross-sectional assessment of 346 child-mother dyads in Dhaka, Bangladesh (2020). *Archives of Public Health* 2022;80(1):192. doi: 10.1186/s13690-022-00948-6

14. Iannotti LL, Blackmore I, Cohn R, et al. Aquatic Animal Foods for Nutrition Security and Child Health. *Food Nutr Bull* 2022;43(2):127-47. doi: 10.1177/03795721211061924 [published Online First: 20211214]

15. Prendergast AJ, Chasekwa B, Evans C, et al. Independent and combined effects of improved water, sanitation, and hygiene, and improved complementary feeding, on stunting and anaemia among HIV-exposed children in rural Zimbabwe: a cluster-randomised controlled trial. *The Lancet Child & adolescent health* 2019;3(2):77-90. doi: 10.1016/s2352-4642(18)30340-7 [published Online First: 20181218]

16. Anwar F, Khomsan A, Sukandar D, et al. High participation in the Posyandu nutrition program improved children nutritional status. *Nutr Res Pract* 2010;4(3):208-14. doi: 10.4162/nrp.2010.4.3.208 [published Online First: 20100628]

17. Orunmoluyi OS, Gayawan E, Manda S. Spatial Co-Morbidity of Childhood Acute Respiratory Infection, Diarrhoea and Stunting in Nigeria. *International journal of environmental research and public health* 2022;19(3) doi: 10.3390/ijerph19031838 [published Online First: 20220206]

18. Haque MA, Platts-Mills JA, Mduma E, et al. Determinants of Campylobacter infection and association with growth and enteric inflammation in children under 2 years of age in low-resource settings. *Scientific reports* 2019;9(1):17124. [published Online First: 2019/11/22]

19. National Institute of Population Research and Training - NIPORT/Bangladesh, Mitra and Associates, ICF International. Bangladesh Demographic and Health Survey 2014. NIPORT, Mitra and Associates, and ICF International: Dhaka, Bangladesh and Rockville, Maryland, USA, 2016.

20. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH). State of food security and nutrition in Bangladesh 2013. HKI and JPGSPH, 2014.

21. Yaya S, Bishwajit G, Ekholuenetale M, et al. Awareness and utilization of community clinic services among women in rural areas in Bangladesh: A cross-sectional study. *PLOS ONE* 2017;12(10):e0187303. doi: 10.1371/journal.pone.0187303

22. Choudhury N, Raihan MJ, Ahmed SMT, et al. The evaluation of Suchana, a large-scale development programme to prevent chronic undernutrition in north-eastern Bangladesh. *BMC public health* 2020;20(1):744. [published Online First: 2020/05/24]

23. Haque MA, Choudhury N, Ahmed SMT, et al. The large-scale community-based programme ‘Suchana’ improved maternal healthcare practices in north-eastern Bangladesh: Findings from a cluster randomized pre-post study. *Maternal & child nutrition* 2022;18(1):e13258.

585 24. Coates J, Swindale A, Bilinsky P. Household Food Insecurity Access Scale (HFIAS) for measurement of food access: indicator guide (v. 3). Washington, D.C.: Food and Nutrition Technical Assistance Project, Academy for Educational Development 2007.

588 25. Bursac Z, Gauss CH, Williams DK, et al. Purposeful selection of variables in logistic regression. *Source code for biology and medicine* 2008;3:17.

590 26. Tardini E, Zhang X, Canahuate G, et al. Optimal Treatment Selection in Sequential Systemic and Locoregional Therapy of Oropharyngeal Squamous Carcinomas: Deep Q-Learning With a Patient-Physician Digital Twin Dyad. *Journal of Medical Internet Research* 2022;24(4):e29455. doi: 10.2196/29455 [published Online First: 20220420]

594 27. Adamker G, Holzer T, Karakis I, et al. Prediction of Shigellosis outcomes in Israel using machine learning classifiers. *Epidemiology and Infection* 2018;146(11):1445-51. doi: 10.1017/s0950268818001498 [published Online First: 20180608]

597 28. Weatherspoon DD, Miller S, Ngabitsinze JC, et al. Stunting, food security, markets and food policy in Rwanda. *BMC public health* 2019;19(1):882. doi: 10.1186/s12889-019-7208-0 [published Online First: 2019/07/06]

600 29. Agho KE, Mukabutera C, Mukazi M, et al. Moderate and severe household food insecurity predicts stunting and severe stunting among Rwanda children aged 6-59 months residing in Gicumbi district. *Maternal & child nutrition* 2019;15(3):e12767.

603 30. Chowdhury D. Flood situation worsens in Sylhet. *The Daily Star* 2017.

604 31. ACAPS. ACAPS Briefing Note: Bangladesh - Floods in Moulvibazar and Sylhet (20 June 2018): reliefweb; 2018 [Available from: https://reliefweb.int/report/bangladesh/acaps-briefing-note-bangladesh-floods-moulvibazar-and-sylhet-20-june-20182023.

32. Lin A, Arnold BF, Afreen S, et al. Household environmental conditions are associated with enteropathy and impaired growth in rural Bangladesh. *American Journal of Tropical Medicine and Hygiene* 2013;89(1):130-37. doi: 10.4269/ajtmh.12-0629 [published Online First: 20130429]

33. Amour C, Gratz J, Mduma E, et al. Epidemiology and Impact of Campylobacter Infection in Children in 8 Low-Resource Settings: Results From the MAL-ED Study. *Clinical Infectious Diseases* 2016;63(9):1171-79. doi: 10.1093/cid/ciw542 [published Online First: 08/07]

34. Smith S, Meade J, Gibbons J, et al. The impact of environmental conditions on Campylobacter jejuni survival in broiler faeces and litter. *Infect Ecol Epidemiol* 2016;6:31685-85. doi: 10.3402/iee.v6.31685

35. Chen RY, Kung VL, Das S, et al. Duodenal Microbiota in Stunted Undernourished Children with Enteropathy. *New England Journal of Medicine* 2020;383(4):321-33. doi: 10.1056/NEJMoa1916004

36. George CM, Oldja L, Biswas SK, et al. Fecal Markers of Environmental Enteropathy are Associated with Animal Exposure and Caregiver Hygiene in Bangladesh. *American Journal of Tropical Medicine and Hygiene* 2015;93(2):269-75. doi: 10.4269/ajtmh.14-0694 [published Online First: 20150608]

37. Perin J, Burrowes V, Almeida M, et al. A Retrospective Case-Control Study of the Relationship between the Gut Microbiota, Enteropathy, and Child Growth. *American Journal of Tropical Medicine and Hygiene* 2020;103(1):520-27. doi: 10.4269/ajtmh.19-0761 [published Online First: 20200514]

38. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH). State of food security and nutrition in Bangladesh 2014. HKI and JPGSPH: Dhaka, BD, 2016.

Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline. The p-value of the *difference-in-difference* was estimated using interaction analysis in the multiple logistic regression model.

Figure 2. Results framework and *Suchana* log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

Figure 3. Factors influencing stunting in children aged 12-23 months, computed using decision tree analysis.

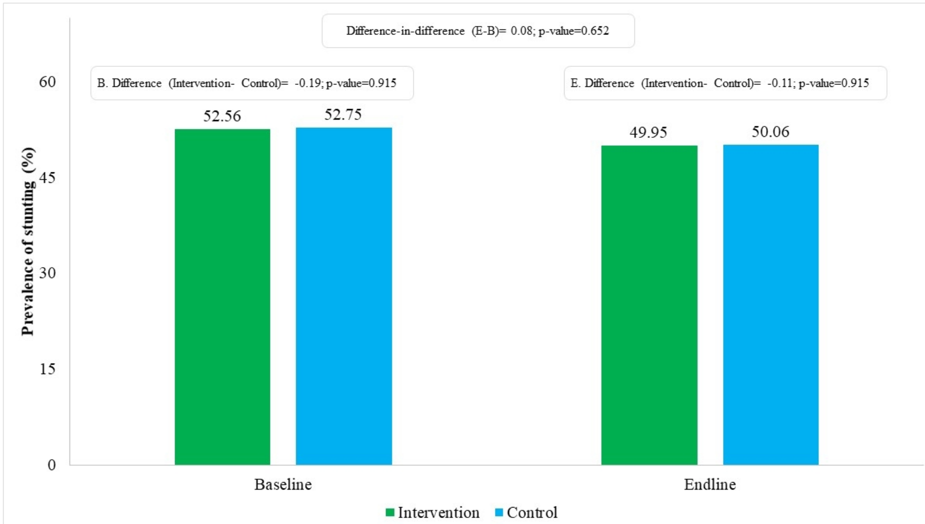


Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline. The p-value of the difference-in-difference was estimated using interaction analysis in the multiple logistic regression model.

338x190mm (96 x 96 DPI)

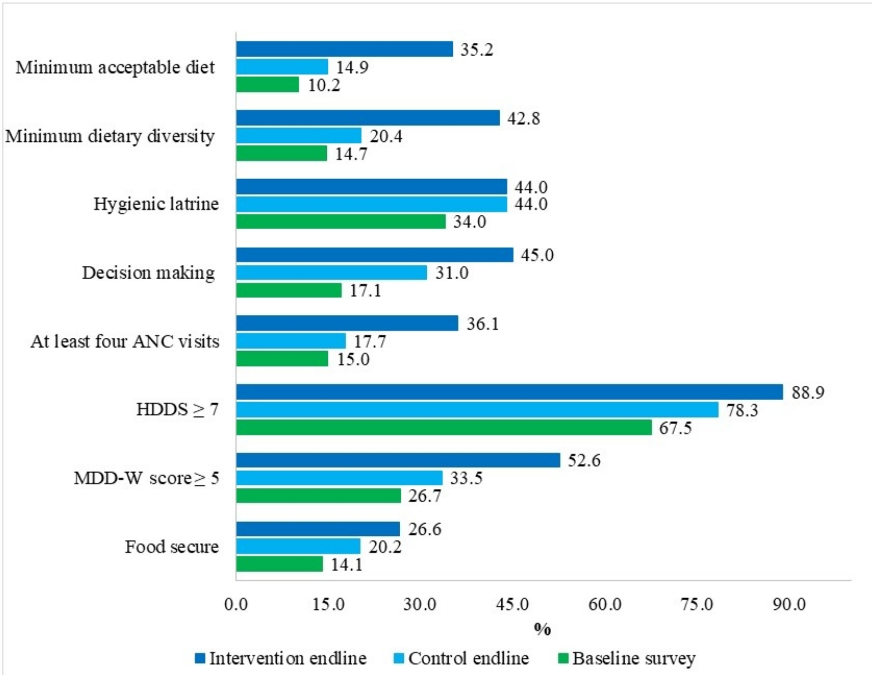


Figure 2. Results framework and Suchana log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women

254x190mm (96 x 96 DPI)

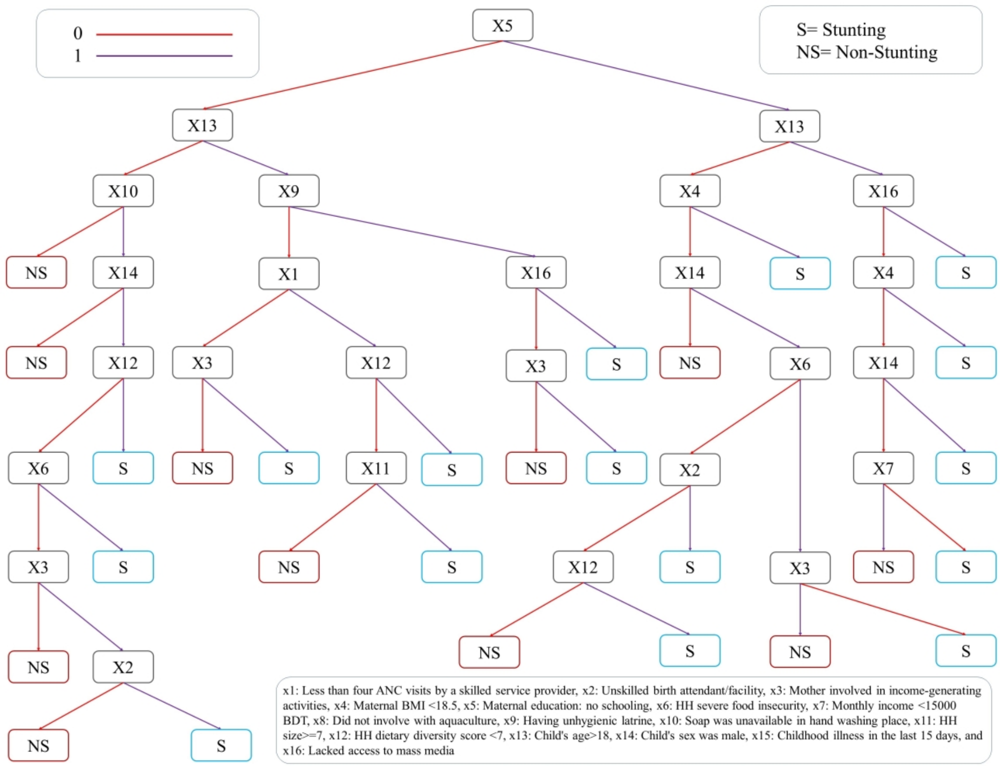


Figure 3. Factors influencing stunting in children aged 12-23 months, computed using decision tree analysis

325x254mm (300 x 300 DPI)

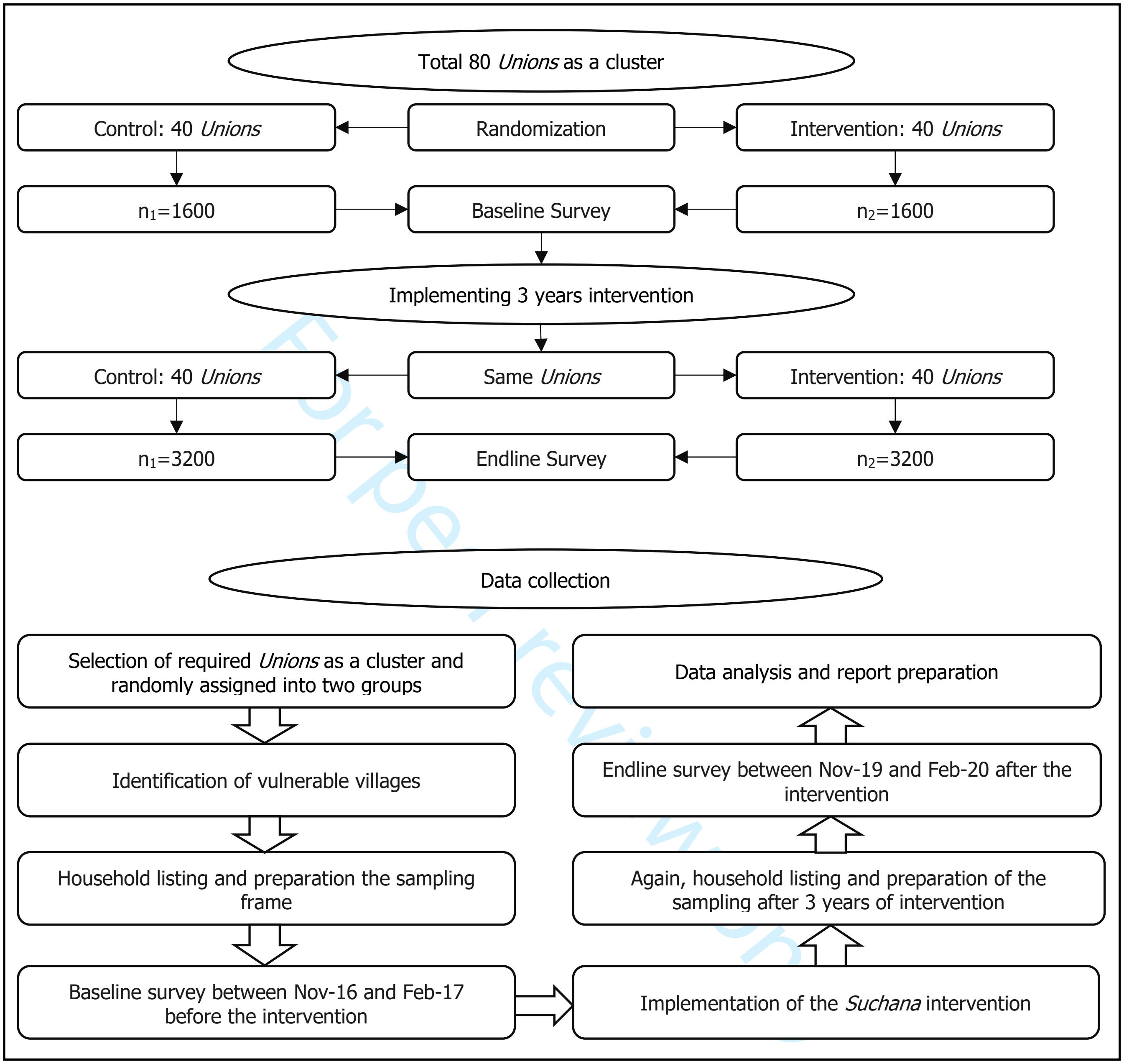
Appendix 1. Sample size calculation

```
clustersampsi, binomial samplesize p1(0.47) p2(0.41) k40) rho0.01)alpha(0.05) beta(0.8)
```

Output of the STATA command for sample size calculation

```
Sample size calculation to determine number of observations required per cluster, for a two-
sample comparison of proportions (using normal approximations) without continuity correction.

For the user specified parameters:
      p1: 0.4700
      p2: 0.4100
      significance level:  0.05
      power:  0.80
      number of clusters available:  40
      intra cluster correlation (ICC):  0.0100
clustersampsi estimated parameters:
      Firstly, assuming individual randomisation: sample size per arm: 1071
      Then, allowing for cluster randomisation: average cluster size required:  38
      sample size per arm:  1520
```



Supplementary Figure 1. The evaluation diagram of *Suchana* programme

Appendix 2. Data collection

The Suchana data collection software contained built-in validation rules. As the data were entered at the interviewer level and the records were uploaded to a server at the icddr,b using the built-in internet connectivity of the devices, maximum validation rules were set in the data system to prevent errors during data entry, which reduced the data entry burden. This allowed the data analysis team to review the

consistency of the data every day. Data were synchronized to the central server "Web Service" developed in Asp.Net based on the C# (C Sharp) code. Activities such as editing (after receiving any feedback from field staff members), updating, range checks, duplication checks, consistency checks, frequency checks and cross tabulation were regularly performed during the data entry period. In case of any unusual observations, the issues were discussed and resolved.

Appendix 3. Equation of logistic and probit regression

$$\text{logit}(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

$$\text{probit}(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

Where,

x1: Less than four ANC visits by a skilled service provider
x2: Unskilled birth attendant/facility
x3: Mother involved in income-generating activities
x4: Maternal BMI <18.5
x5: Maternal education: no schooling
x6: HH severe food insecurity
x7: Monthly income <15000 BDT
x8: Did not involve with aquaculture
x9: Having unhygienic latrine
x10: Soap was unavailable in hand washing place
x11: HH size≥7
x12: HH dietary diversity score <7
x13: Child's age>18
x14: Child's sex was male
x15: Childhood illness in the last 15 days
x16: Lacked access to mass media

and

$$\text{logit}(y) = \log[y/(1-y)]$$

Supplementary Table 1. *Suchana* inclusion criteria for registration of enrolling as vulnerable households

Vulnerable household verification questions	Inclusion criteria
Step 1 • Households currently participating/member of any livelihood, food security or asset transfer program	If "NO" go ahead for next questions
Step 2 • Ability to afford three (3) full meals per day for all family members round the year • Households monthly income BDT 7,500 or more • Household productive asset value worth BDT 15,000 or more (excluding land, pond and homestead) • Ownership of homestead land 10 decimals or more • Ownership of cultivable land 50 decimals or more (excluding homestead or pond)	If anyone is "NO" go ahead for next questions
Step 3 • Households have married women with in child bearing age (15 to 45 years) • Households have pregnant women (including abandoned or widowed woman) • Households have 0-23 months old children • Households have adolescent girls (15-19 years)	If anyone is 'Yes' go ahead for registration of enrolling as vulnerable Household
Sampling frame was prepared for collecting data from mother-child pair if the households had 0-23 months old children	

Supplementary Table 2a. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple logistic regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.07, 6.22)	0.006
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.55, 4.35)	0.012
Mother involved in income-generating activities			
No	54.55 (50.90, 58.19)	Reference	
Yes	50.59 (49.08, 52.11)	3.95 (0.40, 7.51)	0.029
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.41)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.40)	<0.001
HH food insecurity			
Below severe	53.03 (50.91, 55.15)	Reference	
Severe	50.36 (48.63, 52.09)	2.66 (0.11, 5.22)	0.041
HH monthly income ≥15000 BDT			
Yes	51.31 (49.79, 52.84)	Reference	
No	48.58 (45.86, 51.30)	2.73 (0.17, 5.30)	0.037
Involved with aquaculture			
Yes	51.22 (49.72, 52.72)	Reference	
No	46.99 (43.30, 50.69)	4.23 (0.73, 7.73)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.54 (46.74, 50.33)	4.10 (1.83, 6.38)	<0.001
HH size			
Below seven	53.86 (51.98, 55.74)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.92 (51.25, 56.60)	Reference	
HDDS <7	50.10 (48.70, 51.50)	3.83 (1.63, 6.02)	<0.001
Child's age			
Age ≤18 months	56.72 (54.77, 58.67)	Reference	
Age >18 months	46.59 (44.82, 48.35)	10.1 (7.94, 12.32)	<0.001
Child's sex			
Female	53.25 (51.17, 55.34)	Reference	
Male	48.40 (46.78, 50.03)	4.85 (2.59, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.77)	Reference	
Yes	50.49 (48.94, 52.05)	4.41 (1.48, 7.34)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.39, 50.88)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

Supplementary Table 2b. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple probit regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.08, 6.22)	0.007
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.54, 4.35)	0.011
Mother involved in income-generating activities			
No	54.55 (50.90, 58.16)	Reference	
Yes	50.59 (49.08, 52.11)	3.93 (0.39, 7.48)	0.024
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.40)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.41)	<0.001
HH food insecurity			
Below severe	53.01 (50.89, 55.12)	Reference	
Severe	50.37 (48.64, 52.10)	2.64 (0.09, 5.19)	0.042
HH monthly income ≥15000 BDT			
Yes	51.32 (49.79, 52.84)	Reference	
No	48.56 (45.84, 51.28)	2.75 (0.19, 5.32)	0.035
Involved with aquaculture			
Yes	51.22 (49.73, 52.71)	Reference	
No	46.99 (43.28, 50.69)	4.24 (0.73, 7.74)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.53 (46.74, 50.33)	4.11 (1.83, 6.39)	<0.001
HH size			
Below seven	53.86 (51.98, 55.73)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.90 (51.23, 56.57)	Reference	
HDDS <7	50.10 (48.71, 51.50)	3.79 (1.60, 5.98)	<0.001
Child's age			
Age ≤18 months	56.72 (54.76, 58.67)	Reference	
Age >18 months	46.59 (44.83, 48.35)	10.1 (7.93, 12.3)	<0.001
Child's sex			
Female	53.25 (51.17, 55.33)	Reference	
Male	48.41 (46.78, 50.03)	4.85 (2.60, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.75)	Reference	
Yes	50.50 (48.94, 52.05)	4.40 (1.47, 7.33)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.40, 50.86)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

STROBE Statement—Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1-2
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	1-2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-6
Objectives	3	State specific objectives, including any prespecified hypotheses	6
Methods			
Study design	4	Present key elements of study design early in the paper	6
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	6
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-7
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	*6-7*
Bias	9	Describe any efforts to address potential sources of bias	19
Study size	10	Explain how the study size was arrived at	7
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	8-9
		(*b*) Describe any methods used to examine subgroups and interactions	
		(*c*) Explain how missing data were addressed	
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	8-9
		(*e*) Describe any sensitivity analyses	
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	11
		(b) Give reasons for non-participation at each stage	
		(c) Consider use of a flow diagram	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	11
		(b) Indicate number of participants with missing data for each variable of interest	
Outcome data	15*	Report numbers of outcome events or summary measures	11
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	11-14

		(*b*) Report category boundaries when continuous variables were categorized	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	11-15
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
Discussion			
Key results	18	Summarise key results with reference to study objectives	16
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	19
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	16
Generalisability	21	Discuss the generalisability (external validity) of the study results	16-18
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	20

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

BMJ Open

A predictive modelling approach to illustrate factors correlating with stunting among children aged 12-23 months: a cluster randomized pre-post study

Journal:	*BMJ Open*
Manuscript ID	bmjopen-2022-067961.R3
Article Type:	Original research
Date Submitted by the Author:	07-Mar-2023
Complete List of Authors:	Haque, Md; ICDDRB Choudhury, Nuzhat; ICDDRB Wahid, Barbie Zaman; ICDDRB Ahmed, SM Tanvir ; Save the Children Bangladesh Farzana, Fahmida Dil; ICDDRB Ali, Mohammad; ICDDRB Naz, Farina; ICDDRB Siddiqua, Towfida Jahan ; Johns Hopkins University, Bangladesh Rahman, Shahed ; Save the Children Bangladesh Faruque, ASG; ICDDRB Ahmed, Tahmeed; ICDDRB
Primary Subject Heading:	Epidemiology
Secondary Subject Heading:	Public health
Keywords:	Nutrition < TROPICAL MEDICINE, EPIDEMIOLOGY, PUBLIC HEALTH

SCHOLARONE™
Manuscripts

A predictive modelling approach to illustrate factors correlating with stunting among children aged 12-23 months: a cluster randomized pre-post study

Md Ahshanul Haque[1*], Nuzhat Choudhury[1], Barbie Zaman Wahid[1], SM Tanvir Ahmed[2], Fahmida Dil Farzana[1], Mohammad Ali[1], Farina Naz[1], Towfida Jahan Siddiqua[1], Sheikh Shahed Rahman[2], ASG Faruque[1], Tahmeed Ahmed[1]

[1] Nutrition and Clinical Services Division, icddr,b, Dhaka, 1212, Bangladesh
[2] Child Poverty Sector, Save the Children Bangladesh, Dhaka, Bangladesh

*** Correspondence:** Md Ahshanul Haque, Assistant Scientist, Nutrition and Clinical Services Division, icddr,b, 68, Shaheed Tajuddin Ahmed Sarani, Mohakhali, Dhaka 1212, Bangladesh, Email: ahshanul.haque@icddrb.org

Word count: 4977

Abstract

Objective The aim of this study was to construct a predictive model in order to develop an intervention study to reduce the prevalence of stunting among children aged 12-23 months.

Design The study followed a cluster randomized pre-post design and measured the impacts on various indicators of livelihood, health, and nutrition. The study was based on a large dataset collected from two cross-sectional studies (baseline and endline).

Setting The study was conducted in the north-eastern region of Bangladesh under the Sylhet division, which is vulnerable to both natural disasters and poverty. The study specifically targeted children between the ages of 12 and 23 months.

Main outcome measures Childhood stunting, defined as a length-for-age z-score (LAZ)<-2, was the outcome variable in this study. Logistic and probit regression models and a decision tree were constructed to predict the factors associated with childhood stunting. The predictive performance

of the models was evaluated by computing the area under the receiver operating characteristic (ROC) curve analysis.

Results The baseline survey showed a prevalence of 52.7% stunting, while 50.0% were stunted at endline. Several factors were found to be associated with childhood stunting. The model's sensitivity was 61% and specificity was 56%, with a correctly classified rate of 59% and an area under the ROC curve of 0.615.

Conclusion The study showed that childhood stunting in the study area was largely influenced by factors such as maternal nutrition and education, food insecurity, and hygiene practices. Despite efforts to address these factors, they remain largely unchanged. The study suggests that a more effective approach may be developed in future to target adolescent mothers, as maternal nutrition and education are age-dependent variables. Policymakers and programme planners need to consider incorporating both nutrition-sensitive and specific activities and enhancing collaboration in their efforts to improve the health of vulnerable rural populations.

Study registration: RIDIE-STUDY-ID-5d5678361809b

Keywords: Childhood stunting, Chronic malnutrition, Global public health, Logistic regression, Probit regression, Decision tree

Strengths and limitations of this study

- The study used a combination of parametric and non-parametric predictive models to estimate the effect size of the independent variables and identify significant correlates of childhood stunting
- The study was designed to mitigate the potential impact of seasonal factors by conducting the baseline and endline surveys at the same time of the year
- A binary indicator of stunting based on a single LAZ cut-off point (<-2) may not provide a complete evaluation of the severity of malnutrition among children as it does not consider micronutrient deficiencies

- Use of recall data from the previous 24 hours for dietary diversity, household food insecurity, domestic violence, and maternal healthcare may be subject to recall bias
- Biological data has not been collected such as enteropathogen and environmental enteric dysfunction, which could have been related to childhood stunting

Introduction

Childhood stunting, which is defined as length-for-age z-score (LAZ)<-2, is a major concern for public health and has been widely used as an indicator of chronic malnutrition in children.[1, 2] Although childhood stunting scenarios have much improved globally, the prevalence of childhood stunting is still very high in low-resource settings, including countries such as Bangladesh. According to the 2018 Global Nutrition Report, 150.8 million children (22.2%) under five years-of-age are stunted globally, compared to 198.4 million (32.6%) and 165 million children in 2000 and 2011, respectively.[3, 4] Between 2000 and 2018, Asian countries have experienced a decrease in the rate of stunting among children under five from 38.1% to 23.2%. However, South Asia still has the highest prevalence of stunting in the region, with a rate of 38.9% in 2018.[3] In Bangladesh, about 5.5 million (36%) children under five were stunted in 2014,[5] however by 2018, childhood stunting has reduced to about 31%.[2] As the World Health Organization (WHO) considers a childhood stunting rate of 15% to be an emergency situation, the current prevalence of childhood stunting in Bangladesh reflects an alarming situation of chronic undernutrition.[6]

Literature suggests that children are at a higher prevalence of stunting if their mothers do not receive adequate antenatal care, fail to rest sufficiently, do not consume additional food, and neglect to take iron-folic acid (IFA) tablets during pregnancy.[7-9] Mass media exposure, receive a vitamin A capsule; have a skilled birth attendant; and have maternal nutritional status and maternal education, both of which are linked to childhood stunting.[6, 8, 10-12] Children in poor households in Bangladesh are more likely to experience stunted growth if their mothers are employed, as there are inadequate day-care centres available for the children, leading to insufficient breastfeeding.[13] Moreover, evidence suggests that a number of characteristics at the household level, which relate to both children and mothers, can influence childhood stunting. The characteristics of the household head, household food insecurity and lower dietary diversity, household lower-income, household involvement in several earning activities, availability of sanitation facility at home, hand-washing status, family size, religion, and receive several types of allowance from government are most often reported to be associated with stunting in the literature.[6, 8, 11, 14-16]

Based on child characteristics, several indicators are associated with stunting. This status is associated with two basic characteristics: a child's gender and age.[8] Children are commonly affected by the co-occurrence of illness in low- and middle-income countries, which is one of the most common causes of stunting.[17] Inadequate infant and young child feeding (IYCF) practices also reduce child growth.[8, 15] However, these findings are mostly based on nationally representative cross-sectional and cohort studies, or studies conducted in urban settings.[18, 19] Therefore, a knowledge gap exists on whether similar results would be obtained when nationwide data are compared with data for study populations from poor or very poor rural households in specific vulnerable regions.

Sylhet is one such vulnerable region of north-east Bangladesh, comprising diverse terrains such as plain land, hilly land, *Haor* (wetland), and flash flood-prone areas. This region is reported to perform poorly for all important maternal healthcare indicators,[20] despite the fact that Bangladesh has made substantial progress in improving the overall health of the population.[21] Moreover, the socio-economic profile of the inhabitants in Sylhet region includes both very rich and extremely poor people. This scenario may worsen without the implementation of appropriate strategies in the near future. Sylhet region is also performing poorly compared to the national averages for a number of health and nutritional indicators. Critical indicators such as the infant mortality rate and unemployment status of women are high.[19] In comparison to the overall situation of Bangladesh, where stunting among children under five has decreased, the Bangladesh Demographic and Health Survey (BDHS) 2014 indicates the prevalence of childhood stunting in Sylhet is astonishingly high, at 50%.[19] This alarming figure provided the rationale for implementation of a comprehensive intervention programme in this region. A large-scale nutrition programme, *Suchana: Ending the Cycle of Undernutrition in Bangladesh; a multi-sectoral nutrition programme,* was undertaken with the aim to prevent chronic malnutrition in Sylhet.

In general, *Suchana* nutrition interventions can be divided into two types: nutrition-sensitive and nutrition-specific.[22] The concept of nutrition-sensitive intervention refers to an intervention that benefits the beneficiaries in terms of food and nutrition security, and also influences the underlying determinants of nutrition. This type of intervention is largely delivered through the agricultural sector (homestead vegetable and fruit production, pro-poor nutrition-sensitive aquaculture), improved technology (mono-sex tilapia and carp-tilapia polyculture, subsistence fishing, fish drying), demonstrations (village model farms and demo ponds, livestock, food security, promotion of climate-smart technologies), and supported income-generating activities (skill development in business management, engagement with the private sector and other sectors). As nutrition-specific interventions were delivered through nutrition-sensitive interventions, their coverage, effectiveness, and scale can be increased. It can meet the targets by lowering them and implementing nutrition-specific interventions. A nutrition-specific intervention addresses the immediate cause of malnutrition. Direct determinants of nutrition are the focus of this intervention. There is a strong focus on nutrition-specific interventions in the health sector. Whether implemented alone or jointly, nutrition-specific interventions improve health outcomes. Some examples of nutrition-specific interventions are: counselling for mothers at the household level, community-based nutrition education for spouses and in-laws, growth monitoring and promotion sessions integrated with *Expanded Programme on Immunization* in communities, *Government of Bangladesh* health facilities equipped with *severe acute malnutrition* service delivery, and support for *National Nutrition Services* service delivery through community clinics, Union Health and Family Welfare Centers, and Upazila health complexes.

The primary objective of the *Suchana* programme was to reduce the prevalence of childhood stunting in the intervention areas. The secondary objectives were to assess the changes in *Suchana* beneficiaries' households, in terms of an increase and diversification of household income, food security status, optimal IYCF practices, haemoglobin status of children, the empowerment of women, and adolescents' nutritional knowledge and practices.[22]

The *Suchana* programme substantially improved nutritional behaviour, maternal healthcare practices, women's empowerment, household income, and household food security in the intervention area compared to the control area.[23] Contrary to predictions, however, *Suchana* did not result in any significant reduction in the prevalence of childhood stunting. Therefore, although most other factors related to childhood stunting improved, this raises the question of why the prevalence of stunting did not reduce after the intervention. An important observation from the *Suchana* survey was that the proportion of households in this study population using hygienic latrines was quite low. This factor was associated with stunting in children,[8] and did not significantly improve by endline in the intervention areas compared to the control areas.

In this study, we aimed to construct a predictive model to attempt to explain whether any improvements in associated factors may promote a significant reduction in stunting among children aged 12-23 months from poor and extremely poor households in the Sylhet region.

Methods

Study design and setting

The *Suchana* programme was implemented in 157 *Unions* over 20 sub-districts in the Sylhet region in the north-east of rural Bangladesh. The *Suchana* programme's protocol has been thoroughly explained elsewhere.[22] *Union*, the smallest local government and administrative entity in rural Bangladesh, was considered as a cluster and divided into four phases at random. Phase-1 was designated as the intervention group, while Phase-4 was the control group, and the other phases were treated as learning phases.[22] For implementation purposes, vulnerable villages were selected within Phase-1 and Phase-4 areas. The staff of the programme chose vulnerable villages in each *Union* based on their vulnerability (e.g., frequent floods or submerging, little or no intervention from other development programmes, poverty or household living circumstances, remoteness and accessibility issues, a high prevalence of superstitions and social taboos). After consultation with the local government representatives, elected officials, and local elites as well as field visits, this selection method was decided upon. The impacts of the intervention on livelihood, health, and nutrition were measured using a pre-post design. A large dataset was collected from two cross-sectional surveys (baseline and endline) under this study. The baseline survey was conducted in November 2016 and February 2017, followed by the endline survey in the same months three years later among the same population and different participants (Supplementary Figure 1).

Outcome variable

The outcome variable in this study was childhood stunting, which was defined as a length-for-age z-score (LAZ)<-2.[2]

Independent variables

Initially, a list of independent variables was finalized through results obtained from descriptive and bi-variate analyses, as well as a comprehensive literature review (Table 1). These included at least four antenatal care (ANC) visits by a skilled service provider, additional resting during pregnancy, additional food consumption during pregnancy, consumption of at least 100 IFA tablets during pregnancy, receiving vitamin A capsule after last delivery, birth attendant/facility, mother involved in income-generating activities, maternal BMI, maternal education, household food insecurity, household monthly income >15000 BDT, involved with aquaculture, hygienic latrine, water and soap available in handwashing place, household size, household dietary diversity, sex of household head, religion, received any grant/allowance/stipend from the government, access of mass media, child's age, child's sex, childhood illness in the last 15 days, minimum dietary diversity, early initiation of breastfeeding, and received colostrum. Household food insecurity access scale was measured using the Food and Nutrition Technical Assistance's Guideline, which categorizes household food insecurity into four levels: a) food secure, b) mildly food insecure, c) moderately food insecure, and d) severely food insecure.[24] In the analysis herein, this indicator was redefined as a binary indicator: severely food insecure or not severely food insecure.

Sample size

The sample size for this study was calculated with the STATA "*clustersampsi*" command module, considering the number of clusters in the surveys and considering the expected prevalence of childhood stunting in the control group (Supplemental Appendix 1). It was estimated that the expected prevalence of stunting was 47%, which was hypothesized to be reduced to 41% after three years of intervention. A sample size of 1520 per arm was calculated based on a 5% level of significance, 80% power, 40 clusters per arm, and an intra-cluster correlation coefficient (ICC) of 0.01. After rounding, the estimated sample size per arm was 1620, and the total sample size was 3200 at baseline, with an equal number of participants in the control and intervention groups. For evaluation purposes, the sample size at endline was doubled to ensure a stratified intervention component, resulting in a total sample size of 9600 mother-child pairs (baseline: 3200 and endline: 6400).[22]

Sampling

The baseline and endline surveys were conducted in a total of eight and twelve villages respectively, which were randomly selected from each *Union* using a list of vulnerable villages provided by Save the Children. The most vulnerable households were identified and verified using the inclusion criteria of the *Suchana* programme (Supplementary Table 1). These households were then given an identification number to prepare the sampling frame and required households were systematically selected for the surveys from the frame. The method of data collection is explained in detail in the Supplemental Appendix 2.

Statistical analysis

General characteristics: Stata-14 software (StataCorp LP, College Station, TX, USA) and R 4.2.2 (*rpart*)[25] were used to analyse the data. Bar diagram was used for data visualization. Descriptive statistics, such as frequency and proportions for categorical variables and mean and standard deviations for quantitative variables, were used to summarize the data at baseline and endline. Cross-tabulation was used to present that outcome variable segregated by intervention and control group at baseline survey as well as the endline survey. The *difference in difference* method was used to estimate the contrast of an intervention by comparing the difference in the outcomes between an intervention group and a control group before and after the intervention.[26]

Predictive model: Three statistical models were used as predictive models. Two parametric models, such as Logistic and Probit regression models, and Decision Tree as a non-parametric model. Logistic and Probit regression models were used as predictive models as well as classifier models. The models were also used to investigate which factors were significantly associated with childhood stunting, and estimate their effect size, in order to predict whether changes in behavioural practices might potentially help to achieve targeted reductions in stunting. Using those variables, a decision tree was applied, and the predictive performance was compared to other models.

For the parametric models, first, Chi-Square test was used to examine the bivariate associations between stunting and all possible explanatory variables. In the second step, variables with *p*-values <0.25 in the simple model were included in the multiple regression models.[27] In the final step, any independent variables thought to be likely predictors were added to the multiple regression model using the stepwise forward selection method. Some indicators, e.g., age, sex, and maternal nutritional status were added regardless of their *p*-value due to their scientific plausibility. The mathematical equation of logistic and probit regression models were given in the Supplemental Appendix 3. As a cluster variable, *Union* was used to adjust the standard errors. Furthermore, for the explanation of the regression model, a *p*-value <0.05 was considered as statistically significant, and the confidence interval (CI) of 95% was also reviewed. From the fitted model, the adjusted effect size (adjusted prevalence difference) against all predictors was estimated using the "*adjrr*" package in Stata. The list of independent variables with the value labels used in the model is given in Table 1.

Table 1. List of all independent variables

Indicators	Code	Stunting Status*	Selection in the model
At least four ANC visits by a skilled service provider			Selected
At least four ANC visits by a skilled service provider	0		
Less than four ANC visits by a skilled service provider	1	Higher prevalence[8]	
Additional resting during pregnancy			Not selected
Took more rest	0		
Did not take more rest	1	Higher prevalence[8]	
Additional food consumption during pregnancy			Not selected
Consumed more food	0		
Did not consumed more food	1	Higher prevalence[7, 8]	
Consumption of at least 100 IFA tablets during pregnancy			Not selected
Consumed at least 100 IFA tablets	0		
Did not consumed at least 100 IFA tablets	1	Higher prevalence[9]	
Received vitamin A capsule after last delivery			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	
Birth attendant/facility			Selected
Skilled	0		
Unskilled	1	Higher prevalence[10]	
Mother involved in income-generating activities			Selected
No	0		
Yes	1	Higher prevalence[6, 13]	
Maternal BMI			Selected
BMI ≥18.5	0		
BMI <18.5	1	Higher prevalence[6, 11]	

Maternal education				Selected
	At least one-year formal education	0		
	No schooling	1	Higher prevalence[6, 11]	
Access of mass media				Selected
	Access	0		
	No access	1	Higher prevalence[12]	
Household food insecurity				Selected
	Below severe	0		
	Severe	1	Higher prevalence[8]	
Household monthly income ≥15000 BDT				Selected
	≥15000 BDT	0		
	<15000 BDT	1	Higher prevalence[11]	
Involved with aquaculture				Selected
	Involved	0		
	Did not involved	1	Higher prevalence[14]	
Hygienic latrine				Selected
	Hygienic latrine	0		
	Unhygienic latrine	1	Higher prevalence[6, 11, 15]	
Water and soap available in handwashing place				Selected
	Available	0		
	Unavailable	1	Higher prevalence[15]	
Household size				Selected
	Below seven	0		
	Seven or above	1	Higher prevalence[11]	
Household dietary diversity (HDDS)				Selected
	HDDS ≥7	0		
	HDDS <7	1	Higher prevalence[8]	
Sex of household head				Not selected
	Female	0		
	Male	1	Higher prevalence[8]	
Household head education				Not selected
	At least one-year formal education	0		
	No schooling	1	Higher prevalence[6]	
Religion				Not selected
	Muslim	0		
	Non-Muslim	1	Lower prevalence[6]	
Received any grant/allowance/stipend from the government				Not selected
	Received	0		
	Did not receive	1	Higher prevalence[16]	
Child's age				Selected
	Age ≤18 months	0		
	Age >18 months	1	Higher prevalence[8]	
Child's sex				
	Female	0		
	Male	1	Higher prevalence[8]	
Childhood illness in the last 15 days				Selected
	No	0		
	Yes	1	Higher prevalence[17]	
Minimum dietary diversity				Not selected
	Received	0		
	Did not receive	1	Higher prevalence[8, 15]	
Early initiation of breastfeeding				Not selected
	Received	0		

Did not receive	1	Higher prevalence[8]	
Received colostrum			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	

[1]Expected effects based on findings of the literature

Model evaluation: The predictive performance of the three statistical models was evaluated by computing model sensitivity and specificity, and calculating the area under the receiver operating curve (ROC) analysis. To ensure accurate results, the data was randomly split into a training set (75%) and a test set (25%) using a random-number seed 113843. The same training and test datasets were used for evaluating the performance of all algorithms to ensure consistency in the results. The sensitivity and specificity values, as well as the area under the ROC curve, were used to determine the overall accuracy of the algorithms in predicting childhood stunting.[28, 29]

Patient and public involvement

Patients and public were not actively involved in formulating the research question and or protocol development, including the outcome measures. To expedite the field implementation, however, local elites e.g. teachers, religious persons, and local government council members were informed about the study.

Results

General characteristics: Out of 9600 cases, 9501 cases were found to be available. The refusal rate was around 1%. With respect to the outcome indicator, stunting in children aged 12-23 months, 52.7% of children were stunted at the baseline survey (intervention group: 52.6%; control group: 52.8%), whereas the proportion of children exhibiting stunting at endline was 50.0% (intervention: 49.9%; control: 50.1%; Figure 1). At both the baseline and endline surveys, there was no significant difference in proportion between intervention and control areas. The *difference-in-difference* in outcomes over time was also insignificant.

Figure 2 describes several other indicators related to maternal and child health, including the status of consuming a minimum acceptable diet (intervention: 35.2%; control: 14.9%), minimum dietary diversity (intervention: 42.8%; control: 20.4%), maternal decision-making (intervention: 45.0%; control: 31.0%), at least four maternal ANC visits by a skilled service provider (intervention:

36.1%; control: 17.7%), minimum dietary diversity for women (intervention: 52.6%; control: 33.5%), a household dietary diversity score of at least seven (intervention: 88.9%; control: 78.3%), and household food security status (intervention: 26.6%; control: 20.2%). Results from the endline survey showed that these indicators were significantly improved in the intervention group compared to the control group. However, the availability of hygienic latrines did not increase in the intervention group (intervention: 44.0%; control: 44.0%). Table 2 shows the households' socio-demographic characteristics, women's general characteristics, and children's characteristics at baseline and endline.

Table 2. General characteristics of the *Suchana* beneficiaries

Indicators, *n* (%)	**Baseline *N*=3200**	**Endline *N*=6301**	**Total *N*=9501**
At least four ANC visits by a skilled service provider			
Yes	408 (12.8)	1530 (24.3)	1938 (20.4)
No	2792 (87.2)	4771 (75.7)	7563 (79.6)
Delivery at skilled birth attendant/facility			
Yes	1000 (31.2)	2769 (44.0)	3769 (39.7)
No	2200 (68.8)	3532 (56.0)	5732 (60.3)
Access of mass media			
Access	563 (17.59)	1169 (18.55)	1732 (18.23)
No access	2637 (82.41)	5132 (81.45)	7769 (81.77)
Mother involved in income-generating activities			
No	3102 (96.9)	5665 (89.9)	8767 (92.2)
Yes	98 (3.1)	639 (10.1)	737 (7.8)
Maternal BMI			
BMI ≥18.5	1859 (58.1)	4073 (64.6)	5932 (62.4)
BMI <18.5	1341 (41.9)	2231 (35.4)	3572 (37.6)
Mother completed primary education			
Yes	1721 (53.8)	3808 (60.4)	5529 (58.2)
No	1479 (46.2)	2496 (39.6)	3975 (41.8)
Maternal age			
Age <30 years	2145 (67.0)	3559 (56.5)	5704 (60.0)
Age ≥30 years	1055 (33.0)	2745 (43.5)	3800 (40.0)
Type of delivery			
Normal	2879 (90.0)	5529 (87.8)	8408 (88.5)
Caesarean	321 (10.0)	772 (12.3)	1093 (11.5)
PNC			
No	2152 (67.3)	4128 (65.5)	6280 (66.1)
Yes	1048 (32.8)	2173 (34.5)	3221 (33.9)
Household severely food insecure			
Yes	912 (28.5)	1016 (16.1)	1928 (20.3)
No	2288 (71.5)	5285 (83.9)	7573 (79.7)
Household monthly income ≥15000 BDT			

	Yes	424 (13.2)	1015 (16.1)	1439 (15.1)
	No	2776 (86.8)	5289 (83.9)	8065 (84.9)
Household involved with aquaculture				
	Yes	161 (5.0)	561 (8.9)	722 (7.6)
	No	3039 (95.0)	5740 (91.1)	8779 (92.4)
Hygienic latrine				
	Yes	1121 (35.0)	2782 (44.1)	3903 (41.1)
	No	2079 (65.0)	3519 (55.9)	5598 (58.9)
Water and soap available in handwashing place				
	Yes	862 (26.9)	3170 (50.3)	4032 (42.4)
	No	2338 (73.1)	3131 (49.7)	5469 (57.6)
Household savings				
	No	1080 (33.8)	2876 (45.6)	3956 (41.6)
	Yes	2120 (66.2)	3425 (54.4)	5545 (58.4)
Sex of household head				
	Female	110 (3.4)	501 (8.0)	611 (6.4)
	Male	3090 (96.6)	5799 (92.0)	8889 (93.6)
Source of drinking water				
	Tube well	2748 (85.9)	5713 (90.7)	8461 (89.0)
	Others	452 (14.1)	588 (9.3)	1040 (11.0)
Household dietary diversity score				
	HDDS ≥7	2182 (68.2)	5322 (84.5)	7504 (79.0)
	HDDS <7	1018 (31.8)	979 (15.5)	1997 (21.0)
Household monthly income (Thousand BDT)[1]		6.7 (5, 10)	7.5 (5.1, 10.8)	7.1 (5, 10.4)
Per capita income (Thousand)[1]		2.6 (1.8, 3.7)	2.9 (2, 4.1)	2.8 (2, 4)
Household size[1]		6.2±2.4	5.9±2.1	6±2.2
Child's age in months[2]		17.9±3.5	17.3±3.6	17.5±3.6
Length-for-age z-score[2]		-2.1±1.2	-2±1.1	-2±1.1
Weight-for-age z-score[2]		-1.7±1.1	-1.5±1.0	-1.5±1.0
Weight-for-length z-score[2]		-0.9±1.0	-0.7±0.9	-0.7±1.0
Child's age				
	Age <18 months	1745 (54.5)	3710 (58.9)	5455 (57.4)
	Age ≥18 months	1455 (45.5)	2594 (41.1)	4049 (42.6)
Child's sex				
	Female	1567 (49.0)	3044 (48.3)	4611 (48.5)
	Male	1633 (51.0)	3257 (51.7)	4890 (51.5)
Childhood illness in the last 15 days				
	Yes	2867 (89.6)	5763 (91.5)	8630 (90.8)
	No	333 (10.4)	538 (8.5)	871 (9.2)

[1]Median (IQR); [2]Mean ± SD

Correlated factors: The study used two parametric predictive models to determine the correlates of childhood stunting. The results, presented in Table 3, showed the adjusted odds ratios (aOR) computed from multiple logistic regression and the adjusted coefficients computed from multiple probit regression. These results provide important insights into the factors that increase the odds of stunting in childhood, and can inform public health interventions aimed at reducing stunting and improving child health. The aORs provide a quantitative measure of the relationship between different factors and childhood stunting, adjusting for *Union* as cluster variable. Understanding the correlates of childhood stunting is critical for addressing this important public health issue and improving the health and well-being of children globally. The results of this study show that a number of maternal, household and children factors were correlated with an increased prevalence of stunting in children. Children of mothers who did not receive at least four ANC visits from a skilled service provider had 1.16 times higher odds of stunting (95% CI: 1.05, 1.30; p-value=0.005). Children of mothers who gave birth with an unskilled birth attendant or facility had 1.11 times higher odds of stunting (95% CI: 1.02, 1.20; p-value=0.012). The odds of stunting were 1.18 times higher in children whose mothers were involved in income-generating activities (95% CI: 1.02, 1.37; p-value=0.030), 1.23 times higher in children of underweight mothers (95% CI: 1.12, 1.36; p-value<0.001), and 1.31 times higher in children of low-educated mothers (95% CI: 1.20, 1.42; p-value<0.001). Furthermore, the lack of exposure to mass media was also found to be associated with stunting, with odds of 1.15 (95% CI: 1.02, 1.30; p-value=0.025) times higher. Children from households with severe food insecurity, lower-income households, households not involved in aquaculture, and households with low dietary diversity, were more likely to be stunted, with odds increasing by 1.12 (95% CI: 1.00, 1.24; p-value=0.041), 1.12 (95% CI: 1.01, 1.25; p-value=0.037), 1.19 (95% CI: 1.03, 1.38; p-value=0.018), and 1.17 (95% CI: 1.07, 1.29; p-value=0.001) times, respectively. The results also showed that the odds of stunting increased with increasing household size (95% CI: 1.11, 1.31; p-value<0.001), the absence of a hygienic latrine (95% CI: 1.10, 1.30; p-value<0.001), the absence of water and soap in the handwashing place (95% CI: 1.08, 1.30; p-value<0.001), increasing child age (95% CI: 1.39, 1.67; p-value<0.001), and being male (95% CI: 1.11, 1.34; p-value<0.001). The odds of stunting were also 1.20 times higher in children with acute illness (95% CI: 1.06, 1.36; p-value=0.003). The logistic and probit regression models were employed to predict stunting in a sample of 9501 individuals. Both models were found to be significant, with log-likelihoods of -6387.94 and -6388.02, respectively, and significant Wald chi-square statistics (p-value < 0.001). Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) are given in Supplementary Table 2a and 2b. The Factors correlating with childhood stunting, as determined by using a decision tree as a non-parametric predictive model, are also presented in Figure 3. The decision tree result suggests that maternal education was the most important variable in predicting childhood stunting, as it was the main root node. The other variables, such as maternal nutrition, hand washing indicators, and hygienic latrine, were also important, as they were next root node variables. This tree model can be used to predict the childhood stunting status with relative ease.

Table 3. Factors correlating with stunting in children aged 12-23 months, computed using logistic and probit regression analyses

Indicators	Logistic		Probit	
	Adjusted OR (95% CI)	p-value	Adjusted Coef. (95% CI)	p-value
At least four ANC visits by a skilled service provider				
Yes	Reference		Reference	
No	1.16 (1.05, 1.30)	0.005	0.09 (0.03, 0.16)	0.005
Birth attendant/facility				
Skilled	Reference		Reference	
Unskilled	1.11 (1.02, 1.20)	0.012	0.06 (0.01, 0.11)	0.012
Mother involved in income-generating activities				
No	Reference		Reference	
Yes	1.18 (1.02, 1.37)	0.030	0.10 (0.01, 0.19)	0.030
Maternal BMI				
BMI ≥18.5				
BMI <18.5	1.23 (1.12, 1.36)	0.000	0.13 (0.07, 0.19)	0.000
Maternal education was primary completed				
Yes	Reference		Reference	
No	1.31 (1.20, 1.42)	0.000	0.17 (0.12, 0.22)	0.000
Access of mass media				
Yes	Reference		Reference	
No	1.15 (1.02, 1.30)	0.025	0.09 (0.01, 0.16)	0.025
Household food insecurity				
Below severe				
Severe	1.12 (1.00, 1.24)	0.041	0.07 (0.00, 0.13)	0.042
Household monthly income ≥15000 BDT				
Yes	Reference		Reference	
No	1.12 (1.01, 1.25)	0.037	0.07 (0.00, 0.14)	0.035
Involved with aquaculture				
Yes	Reference		Reference	
No	1.19 (1.03, 1.38)	0.018	0.11 (0.02, 0.20)	0.018
Household size				
Below seven	Reference		Reference	
Seven or above	1.20 (1.11, 1.31)	0.000	0.12 (0.06, 0.17)	0.000
Hygienic latrine				
Yes	Reference		Reference	
No	1.20 (1.10, 1.30)	0.000	0.11 (0.06, 0.16)	0.000
Water and soap available in handwashing place				
Yes	Reference		Reference	
No	1.19 (1.08, 1.30)	0.000	0.11 (0.05, 0.16)	0.000
Household dietary diversity				
HDDS ≥7	Reference		Reference	
HDDS <7	1.17 (1.07, 1.29)	0.001	0.10 (0.04, 0.16)	0.001
Child's age				

Age ≤18 months	Reference		Reference	
Age >18 months	1.52 (1.39, 1.67)	0.000	0.26 (0.2, 0.32)	0.000
Child's sex				
Female	Reference		Reference	
Male	1.22 (1.11, 1.34)	0.000	0.13 (0.07, 0.18)	0.000
Childhood illness in the last 15 days				
No	Reference		Reference	
Yes	1.20 (1.06, 1.36)	0.003	0.11 (0.04, 0.19)	0.003
Sample size and regression diagnostic values for logistic and probit regression analyses	n = 9501 Log-likelihood = -6387.94 Wald chi2(17) = 427.79 p-value<0.001 Pseudo R^2 = 0.0298		n = 9501 Log-likelihood = -6388.02 Wald chi2(17) = 441.18 p-value<0.001 Pseudo R^2 = 0.0298	

Unions were adjusted as clusters. Baseline and endline were adjusted as time variables

Predictive performance: Table 4 describes the model validation based on sensitivity, specificity, and whether the model was correctly classified for the overall dataset, as well as the training and test datasets. The sensitivity and specificity of the model were around 60% and 55%, respectively for all models. The correctly classified rate was 59%, and the area under the ROC curve was around 61%. We found that these values were approximately equal among the three datasets (main, training, and test datasets); however, the predictive performance of the model was low.

Table 4. Predictive performance of the model for stunting based on classification, sensitivity, and specificity in the full, training and test datasets with area under the receiver operating characteristic curve analysis

	Logistic regression	Probit regression	Decision tree
Full dataset			
Overall accuracy	58.46	58.38	56.51
Sensitivity	61.21	61.25	61.15
Specificity	55.61	55.41	51.70
Area under the curve	61.54	61.54	56.72
Training Dataset			
Overall accuracy	58.83	58.62	57.66
Sensitivity	61.59	61.70	63.93
Specificity	55.36	55.42	51.61
Area under the curve	61.37	61.37	58.44
Test Dataset			
Overall accuracy	58.11	58.19	56.67
Sensitivity	60.23	60.23	61.58
Specificity	55.90	56.07	51.94

	Area under the curve	61.76	61.77	58.01

Discussion

In an effort to understand why the *Suchana* programme was not effective in reducing the prevalence of childhood stunting, this study analyzed data from both the baseline and endline surveys of the programme. The analysis aimed to identify the factors that were significantly correlated with stunting and to evaluate the model's predictive performance. After controlling for the *Union* as a cluster variable, the study found several indicators that were significantly related to stunting. These included the number of ANC visits by a skilled service provider, household dietary diversity, household food security, and household monthly income, all of which improved after the intervention. However, it was noted that the household food security status did not reach the target value of 50%, despite being an important factor associated with childhood stunting.[8, 30, 31] On the other hand, other outcome indicators of the *Suchana* programme, such as the dietary diversity of children, maternal dietary diversity, and maternal empowerment, despite reaching their target values, were not found to be associated with stunting in this study.

The study found that while the *Suchana* programme showed improvement in certain programme indicators, it did not lead to a significant reduction in childhood stunting. Despite efforts to address key factors such as maternal nutrition and education, household food security, and hygiene practices, these factors remained largely unchanged. However, the study suggests that interventions aimed at adolescent mothers may be more effective in improving maternal nutrition and education, since these are age-dependent variables. Additionally, the results of the study were also impacted by natural disasters in 2017, including heavy rains and flooding in the Sylhet region, which resulted in widespread damage to agriculture, aquaculture, and homes in the study population.[32, 33]

The study found a contradictory relationship between stunting and maternal involvement in income-generating activities, with a higher prevalence of stunting observed among children whose mothers were engaged in various earning activities. Although there was a slight increase in the proportion of mothers involved in income-generating activities after the intervention, the lack of childcare support for working mothers resulted in a marked rise in childhood stunting among low-income households. It is important to address this issue by providing adequate childcare support measures for working mothers from poor families to ensure that the child's essential needs are not impacted by the mother's employment status.[13] Additionally, efforts should be made to increase awareness among working mothers regarding the importance of child health and nutrition. This can be achieved through targeted education and outreach programmes that provide information on proper child feeding practices, hygiene, and health-seeking behaviours.

The literature suggests that environmental enteropathy may contribute to poor growth among children in rural Bangladesh and may represent an important factor affecting the study population in the *Suchana* programme.[34] Although it was not specifically assessed in this study, indicators such as unsanitary latrines, unimproved floors, a lack of handwashing practices, and low education levels were available.[18, 35] Improving Water, Sanitation and Hygiene (WaSH) variables, particularly latrine facilities and handwashing practices, may help reduce the burden of stunting in young children. One of the components of the intervention was poultry, but our qualitative findings revealed that many households shared living spaces with poultry, ducks, or other animals, which could increase the risk of infections with *Campylobacter* species, a leading food-borne pathogen.[18, 36] Previous studies have shown a strong association between stunting and enteropathy among children who do not respond to nutritional interventions, and findings from rural Bangladesh have linked environmental conditions and stunting in children.[37-39] While assessing environmental enteropathy was beyond the scope of the *Suchana* evaluation, collecting data on indicators of enteropathy in the intervention and control areas could help evaluate the impact of appropriate interventions in the future. The failure to achieve the desired outcome may have been due to several factors, including food insecurity and a lack of aquaculture involvement due to natural disasters, poor WaSH status, a lack of focus on maternal education and nutrition, and a lack of focus on the risk of enteropathogen burden.

Another important finding based on the post-estimation findings as well as the value of the area under the ROC curve was that the predictive performance of the model was low. Thus, we need to identify other indicators from similar research contexts that influence childhood stunting but were not included in our model. Future research in the field of childhood stunting should give priority to the development of more suitable methods for monitoring and identifying effective interventions. It is also essential to collect data that considers biological and environmental factors related to childhood stunting, following the literature. By considering these diverse factors, we can improve the accuracy and predictive performance of statistical models. This, in turn, can help draw more reliable conclusions about the effectiveness of interventions aimed at reducing childhood stunting in similar contexts. Additionally, evaluating the model on an independent dataset or conducting external validation could help to determine the generalizability of the model to new data.

This study will aid programme managers in prioritizing their focus and designing effective interventions to reduce childhood stunting. Sustainable solutions should be based on the needs of the beneficiaries. Implementing short-term initiatives such as attendance at healthcare-led workshops and campaigns can increase ANC visits, skilled birth attendance, and handwashing practices. Establishing women's healthcare services that focus on maternal and child health and nutrition will also help reduce the incidence of stunting.[23] Improved access to media can help vulnerable communities benefit from government welfare programmes. Food security, income, sanitation, aquaculture, and illness are all time-sensitive factors. Increasing food production through self-production or purchasing can improve household food security and nutrition. However, household wealth and access to nearby markets can impact their ability to buy nutritious food. Climate change adaptation in agriculture is crucial to minimize current risks and prepare for future uncertainties. Using organic fertilizers instead of chemicals in agriculture has environmental benefits, reducing the need for pesticides and protecting human health and biodiversity. Aquaculture can provide a source of protein and improve nutrition, but establishing these facilities takes time. Improving sanitation requires improving socioeconomic status, which is also a time-intensive process. It takes time to improve stunting, as shown by national surveys such as the BDHS and the Food Security and National Surveillance Project (FSNSP).[2, 40] Improving maternal nutrition and education is crucial for promoting the optimal growth and development of children. Adequate food, good environmental conditions, and access to schooling facilities during adolescence are necessary for women to maintain their own health and to positively impact the health of their children. Emphasizing the education of female children can break the cycle of poverty and stunting, as it can lead to improved knowledge and decision-making skills related to nutrition and health.[6, 11] To reduce childhood stunting in developing countries, comprehensive interventions that include nutritional support, food security, maternal education, income-generating activities for women with childcare support, and addressing domestic violence against women should be implemented. These interventions should be tailored to the specific needs and cultural context of the community in which they are implemented, and community participation and engagement are essential for their success. By addressing the underlying factors contributing to childhood stunting, we can make significant progress towards reducing its prevalence and improving the health and well-being of children in developing countries. Furthermore, continued monitoring and evaluation of these interventions is essential to ensure their effectiveness and to identify areas for improvement.

Recommendation: The *Suchana* model offers a holistic and integrated approach to addressing food and nutrition security, recognizing undernutrition as a complex problem caused by multiple factors. The endline survey of *Suchana* showed significant improvement in programme indicators. The multi-sector approach of *Suchana* is a meaningful solution to addressing undernutrition. However, policy makers should consider implementing additional nutrition-sensitive and specific activities, such as promoting climate-resilient agriculture and increasing water and sanitation coverage. It is also important to have a sustainable mechanism for improving food security and to promote awareness of seasonal diseases associated with livestock and poultry. To further improve the programme, indicators such as child sex, maternal education, and nutrition could be adjusted during the design stage. The *Suchana* programme is one of the largest global nutrition interventions, leading to positive changes in critical indicators, with long-term benefits expected for the health and livelihoods of the beneficiaries.

Strength and limitation: The study had several strengths, including a large sample size, randomization, and appropriate sampling techniques. A dedicated quality control team was involved in checking the data, and the use of precise anthropometry instruments and separate training for the measurement team helped ensure accurate data collection. The study was also designed to avoid seasonality by conducting the baseline and endline surveys at the same time of the year. However, the study results may have been impacted by a lack of selection effect in the implementation of the programme, as well as by the short time horizon of the study. The short duration of the study may not have been enough to see a significant impact on stunting. Additionally, changes in the study population between the baseline and endline surveys could also have contributed to the lack of differences observed in the results. Another limitation of this study is that we did not collect food intake data but only recall data from the previous 24 hours. These data may be subject to recall bias; thus, caution is necessary when drawing conclusions, especially for indicators such as dietary diversity, household food insecurity, domestic violence, and maternal healthcare. Finally, using a binary indicator of stunting based on a single LAZ cut-off point, which was defined as <-2, may not provide a comprehensive assessment of the severity of malnutrition among children, as it fails to account for micronutrient deficiencies

Conclusion

Childhood stunting was heavily influenced by a number of factors, and majority of the factors were found in poor status in our study area. Despite the implementation of an intervention programme, the situation remained unchanged due to factors such as food insecurity, lack of involvement in aquaculture, poor access to WaSH facilities, and a lack of focus on maternal education and nutrition. The study did not include important indicators such as enteropathogen and environmental enteric dysfunction, which might have contributed to the failure to achieve the desired outcome. The results suggest that policy makers and programme planners should consider enhancing collaboration and coordination between nutrition-sensitive and specific activities to address nutritional deficiencies and family health programmes in vulnerable rural populations.

Acknowledgments: The study analyzed baseline survey data of *Suchana*; this intervention has been implemented by a consortium led by Save the Children, with support from the Foreign, Commonwealth and Development Office (FCDO) and European Union (EU). icddr,b acknowledges with gratitude the commitment of Save the Children, FCDO and EU to its research efforts. We also acknowledge with gratitude the commitment of the Government of the People's Republic of Bangladesh to icddr,b's research activities. We also acknowledge the following donors for providing unrestricted support to icddr,b's efforts and advancement of its strategic plan: Canada, Sweden and the United Kingdom. We gratefully acknowledge our core donors for their support and commitment to icddr,b's research efforts. We would like to acknowledge the invaluable contributions of Save the Children as lead agency, our technical partners Helen Keller International, World Fish, and International Development Enterprises, and the implementing partners Friends In Village Development Bangladesh (FIVDB), Rangpur Dinajpur Rural Services (RDRS), and the Center for Natural Resource Studies (CNRS) who played critical roles in generating and refining the data-collection tools. We would also like to acknowledge Tasnia Alam, Research Assistant and Md. Maniruzzaman, Assistant Professor, Khulna University, Khulna-9208, Bangladesh as the internal reviewers, and Andrea Devlin of Science Editing Experts for editing and linguistic revision of the manuscript.

Funding: (i) This study was made possible by the committed contribution of Foreign, Commonwealth and Development Office (Grant number: 204131-103), and (ii) icddr,b (N/A).

Conflicts of Interest: The authors declare no conflict of interest.

Author Contributions: TA and NC originated the idea for the study and led the protocol design. MAH conceptualized the manuscript. SMTA, SSR, MAH, NC, FDF, and TA contributed to the survey design. MAH performed statistical analysis and drafted the manuscript. NC and ASGF supervised the work, and critically reviewed and provided feedback for revising the manuscript. MAH, NC, MA, FDF, FN, BZW, TJS, ASGF, TA, and SSR contributed to the revision of the final draft for submission. All authors are responsible for the final content of the manuscript.

Ethics approval: This study was approved by the Research Review Committee and Ethical Review Committee, the two obligatory components of the Institutional Review Board (IRB) of icddr,b. Ethics Committee's approval ID# 00001822. Informed written consent was obtained from study participants.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

Reference

1. Bari, A., et al., *Comparison of Weight-for-Height Z-score and Mid-Upper Arm Circumference to Diagnose Moderate and Severe Acute Malnutrition in children aged 6-59 months.* Pakistan Journal of Medical Sciences, 2019. **35**(2): p. 337-341.

2. National Institute of Population Research and Training (NIPORT) and ICF, *Bangladesh Demographic and Health Survey 2017-18: Key Indicators*. 2019, Dhaka, Bangladesh and Rockville, Maryland, USA: NIPORT and ICF.

3. Development Initiatives, *2018 Global Nutrition Report: Shining a light to spur action on nutrition*. 2018: Bristol, UK: Development Initiatives.

4. United Nations Children's Fund (UNICEF), World Health Organization, and International Bank for Reconstruction and Development/The World Bank, *Levels and trends in child malnutrition: Key Findings of the 2020 Edition of the Joint Child Malnutrition Estimates*. 2020: Geneva: World Health Organization; 2020. Licence: CC BY-NC-SA 3.0 IGO.

5. USAID, *Bangladesh: Nutrition Profile*. 2018.

6. Kumar, P., et al., *Factors contributing to the reduction in childhood stunting in Bangladesh: a pooled data analysis from the Bangladesh demographic and health surveys of 2004 and 2017–18.* BMC Public Health, 2021. **21**(1): p. 2101.

7. Yaya, S., et al., *Intake of supplementary food during pregnancy and lactation and its association with child nutrition in Timor Leste.* PeerJ, 2018. **6**: p. e5935.

8. Choudhury, N., et al., *Determinants of age-specific undernutrition in children aged less than 2 years-the Bangladesh context.* Maternal & Child Nutrition, 2017. **13**(3).

9. Nisar, Y.B., M.J. Dibley, and V.M. Aguayo, *Iron-Folic Acid Supplementation During Pregnancy Reduces the Risk of Stunting in Children Less Than 2 Years of Age: A Retrospective Cohort Study from Nepal.* Nutrients, 2016. **8**(2): p. 67.

10. Li, Z., et al., *Factors Associated With Child Stunting, Wasting, and Underweight in 35 Low- and Middle-Income Countries.* JAMA Network Open, 2020. **3**(4): p. e203386.

11. Katoch, O.R., *Determinants of malnutrition among children: A systematic review.* Nutrition, 2022. **96**: p. 111565.

12. Huo, S., et al., *Influence of Maternal Exposure to Mass Media on Growth Stunting Among Children Under Five: Mediation Analysis Through the Water, Sanitation, and Hygiene Program.* JMIR Public Health and Surveillance, 2022. **8**(4): p. e33394.

13. Win, H., et al., *Association between mother's work status and child stunting in urban slums: a cross-sectional assessment of 346 child-mother dyads in Dhaka, Bangladesh (2020).* Archives of Public Health, 2022. **80**(1): p. 192.

14. Iannotti, L.L., et al., *Aquatic Animal Foods for Nutrition Security and Child Health.* Food and Nutrition Bulletin, 2022. **43**(2): p. 127-147.

15. Prendergast, A.J., et al., *Independent and combined effects of improved water, sanitation, and hygiene, and improved complementary feeding, on stunting and anaemia among HIV-exposed children in rural Zimbabwe: a cluster-randomised controlled trial.* The Lancet Child & Adolescent Health, 2019. **3**(2): p. 77-90.

16. Anwar, F., et al., *High participation in the Posyandu nutrition program improved children nutritional status.* Nutrition Research and Practice, 2010. **4**(3): p. 208-14.

17. Orunmoluyi, O.S., E. Gayawan, and S. Manda, *Spatial Co-Morbidity of Childhood Acute Respiratory Infection, Diarrhoea and Stunting in Nigeria.* International Journal of Environmental Research and Public Health, 2022. **19**(3).

18. Haque, M.A., et al., *Determinants of Campylobacter infection and association with growth and enteric inflammation in children under 2 years of age in low-resource settings.* Scientific Reports, 2019. **9**(1): p. 17124.

19. National Institute of Population Research and Training - NIPORT/Bangladesh, Mitra and Associates, and ICF International, *Bangladesh Demographic and Health Survey 2014*. 2016, Dhaka, Bangladesh and Rockville, Maryland, USA: NIPORT, Mitra and Associates, and ICF International.

20. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH), *State of food security and nutrition in Bangladesh 2013*. 2014: HKI and JPGSPH.

21. Yaya, S., et al., *Awareness and utilization of community clinic services among women in rural areas in Bangladesh: A cross-sectional study.* PLOS ONE, 2017. **12**(10): p. e0187303.

22. Choudhury, N., et al., *The evaluation of Suchana, a large-scale development programme to prevent chronic undernutrition in north-eastern Bangladesh.* BMC Public Health, 2020. **20**(1): p. 744.

23. Haque, M.A., et al., *The large-scale community-based programme 'Suchana' improved maternal healthcare practices in north-eastern Bangladesh: Findings from a cluster randomized pre-post study.* Maternal & Child Nutrition, 2022. **18**(1): p. e13258.

24. Coates, J., A. Swindale, and P. Bilinsky, *Household Food Insecurity Access Scale (HFIAS) for measurement of food access: indicator guide (v. 3)*. 2007, Washington, D.C.: Food and Nutrition Technical Assistance Project, Academy for Educational Development.

25. Therneau, T., B. Atkinson, and B. Ripley. *rpart: Recursive partitioning and regression trees*. R package version 2022 [cited 2023; Available from: https://cran.r-project.org/package=rpart.

26. Villa, J.M., *Simplifying the estimation of difference-in-differences treatment effects.* The Stata Journal, 2016: p. 52-71.

27. Bursac, Z., et al., *Purposeful selection of variables in logistic regression.* Source Code for Biology and Medicine, 2008. **3**: p. 17.

28. Tardini, E., et al., *Optimal Treatment Selection in Sequential Systemic and Locoregional Therapy of Oropharyngeal Squamous Carcinomas: Deep Q-Learning With a Patient-Physician Digital Twin Dyad.* Journal of Medical Internet Research, 2022. **24**(4): p. e29455.

29. Adamker, G., et al., *Prediction of Shigellosis outcomes in Israel using machine learning classifiers.* Epidemiology and Infection, 2018. **146**(11): p. 1445-1451.

30. Weatherspoon, D.D., et al., *Stunting, food security, markets and food policy in Rwanda.* BMC Public Health, 2019. **19**(1): p. 882.

31. Agho, K.E., et al., *Moderate and severe household food insecurity predicts stunting and severe stunting among Rwanda children aged 6-59 months residing in Gicumbi district.* Maternal & Child Nutrition, 2019. **15**(3): p. e12767.

32. Chowdhury, D., *Flood situation worsens in Sylhet*, in *The Daily Star*. 2017: Dhaka.

33. ACAPS. *ACAPS Briefing Note: Bangladesh - Floods in Moulvibazar and Sylhet (20 June 2018)*. 2018 [cited 2023; Available from: https://reliefweb.int/report/bangladesh/acaps-briefing-note-bangladesh-floods-moulvibazar-and-sylhet-20-june-2018.

34. Lin, A., et al., *Household environmental conditions are associated with enteropathy and impaired growth in rural Bangladesh.* American Journal of Tropical Medicine and Hygiene, 2013. **89**(1): p. 130-137.

35. Amour, C., et al., *Epidemiology and Impact of Campylobacter Infection in Children in 8 Low-Resource Settings: Results From the MAL-ED Study.* Clinical Infectious Diseases, 2016. **63**(9): p. 1171-1179.

36. Smith, S., et al., *The impact of environmental conditions on Campylobacter jejuni survival in broiler faeces and litter.* Infection Ecology & Epidemiology, 2016. **6**: p. 31685-31685.

37. Chen, R.Y., et al., *Duodenal Microbiota in Stunted Undernourished Children with Enteropathy.* The New England Journal of Medicine, 2020. **383**(4): p. 321-333.

38. George, C.M., et al., *Fecal Markers of Environmental Enteropathy are Associated with Animal Exposure and Caregiver Hygiene in Bangladesh.* American Journal of Tropical Medicine and Hygiene, 2015. **93**(2): p. 269-75.

39. Perin, J., et al., *A Retrospective Case-Control Study of the Relationship between the Gut Microbiota, Enteropathy, and Child Growth.* American Journal of Tropical Medicine and Hygiene, 2020. **103**(1): p. 520-527.

40. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH), *State of food security and nutrition in Bangladesh 2014*. 2016, Dhaka, BD: HKI and JPGSPH.

Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline. The p-value of the *difference-in-difference* was estimated using interaction analysis in the multiple logistic regression model.

Figure 2. Results framework and *Suchana* log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

Figure 3. Factors correlating with stunting in children aged 12-23 months, computed using decision tree analysis. (X_1: Less than four ANC visits by a skilled service provider, X_2: Unskilled birth attendant/facility, X_3: Mother involved in income-generating activities, X_4: Maternal BMI <18.5, X_5: Maternal education: no schooling, X_6: Household severe food insecurity, X_7: Monthly income <15000 BDT, X_8: Did not involve with aquaculture, X_9: Having unhygienic latrine, X_{10}: Soap was unavailable in hand washing place, X_{11}: HH size≥7, X_{12}: HH dietary diversity score <7, X_{13}: Child's age>18, X_{14}: Child's sex was male, X_{15}: Childhood illness in the last 15 days, and X_{16}: Lacked access to mass media)

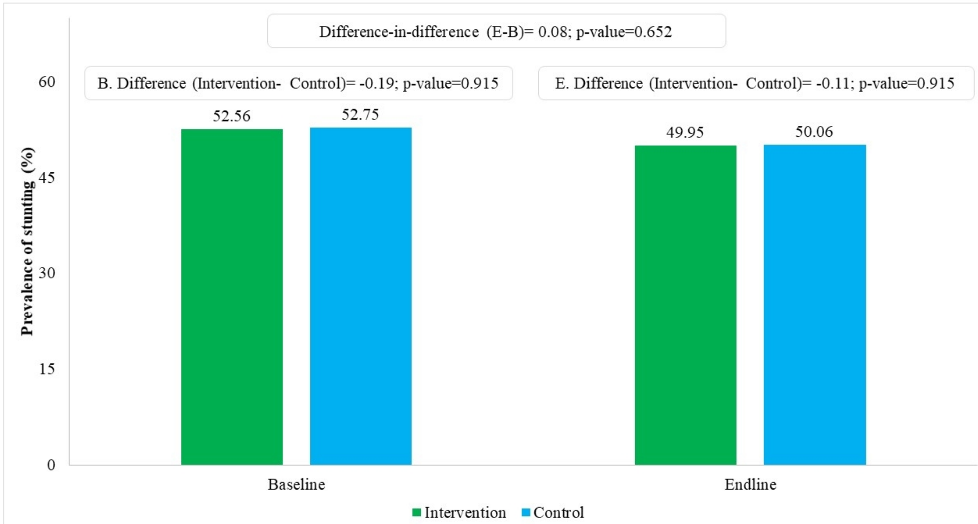


Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline. The p-value of the difference-in-difference was estimated using interaction analysis in the multiple logistic regression model.

108x60mm (300 x 300 DPI)

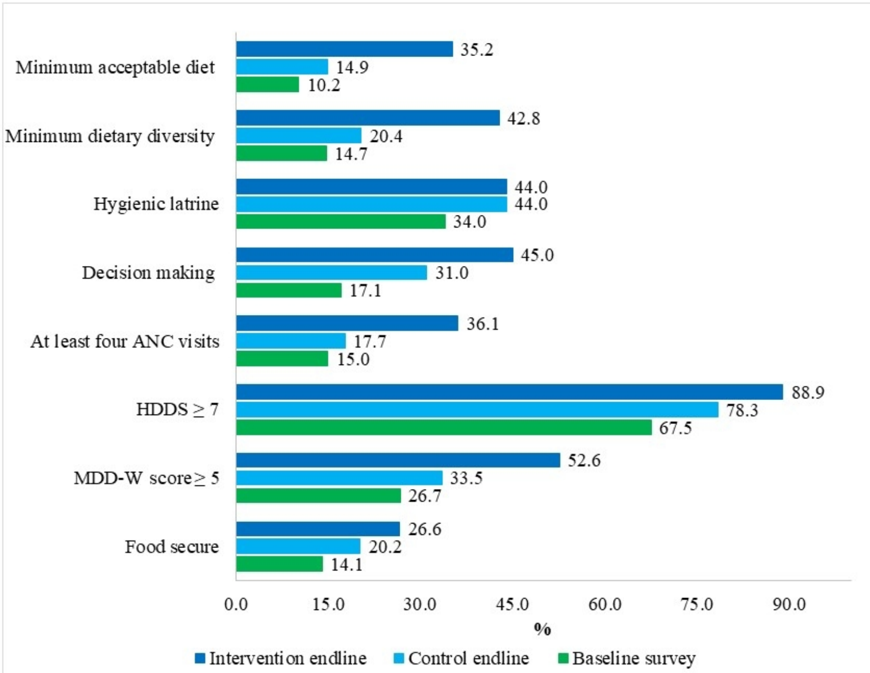


Figure 2. Results framework and Suchana log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

254x190mm (96 x 96 DPI)

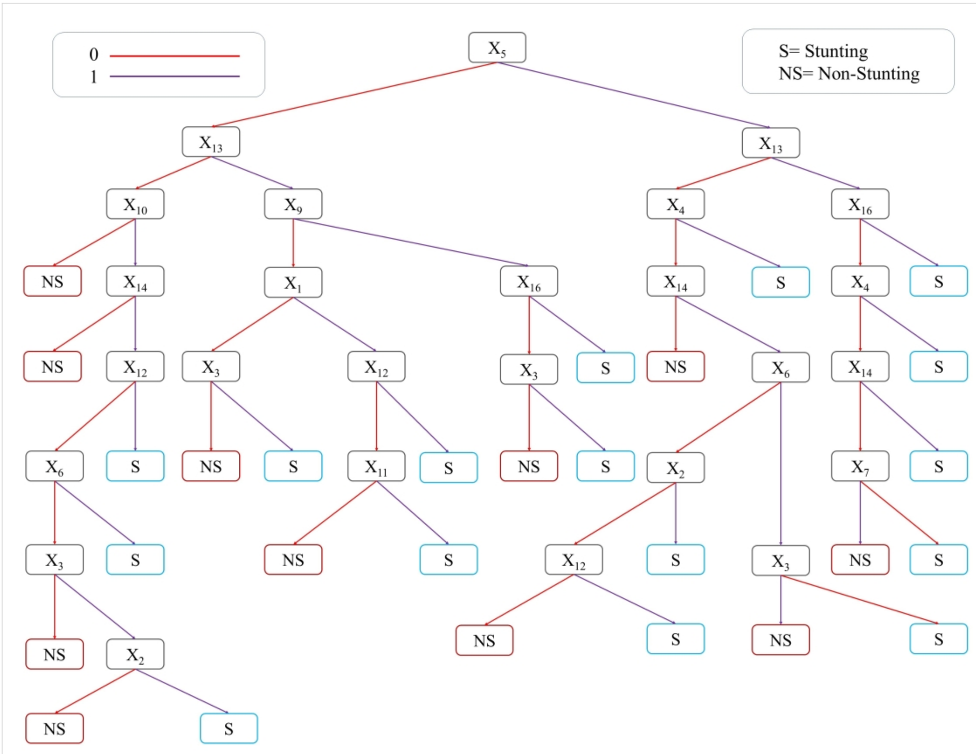


Figure 3. Factors correlating with stunting in children aged 12-23 months, computed using decision tree analysis. (X1: Less than four ANC visits by a skilled service provider, X2: Unskilled birth attendant/facility, X3: Mother involved in income-generating activities, X4: Maternal BMI <18.5, X5: Maternal education: no schooling, X6: Household severe food insecurity, X7: Monthly income <15000 BDT, X8: Did not involve with aquaculture, X9: Having unhygienic latrine, X10: Soap was unavailable in hand washing place, X11: HH size>7, X12: HH dietary diversity score <7, X13: Child's age>18, X14: Child's sex was male, X15: Childhood illness in the last 15 days, and X16: Lacked access to mass media)

325x254mm (300 x 300 DPI)

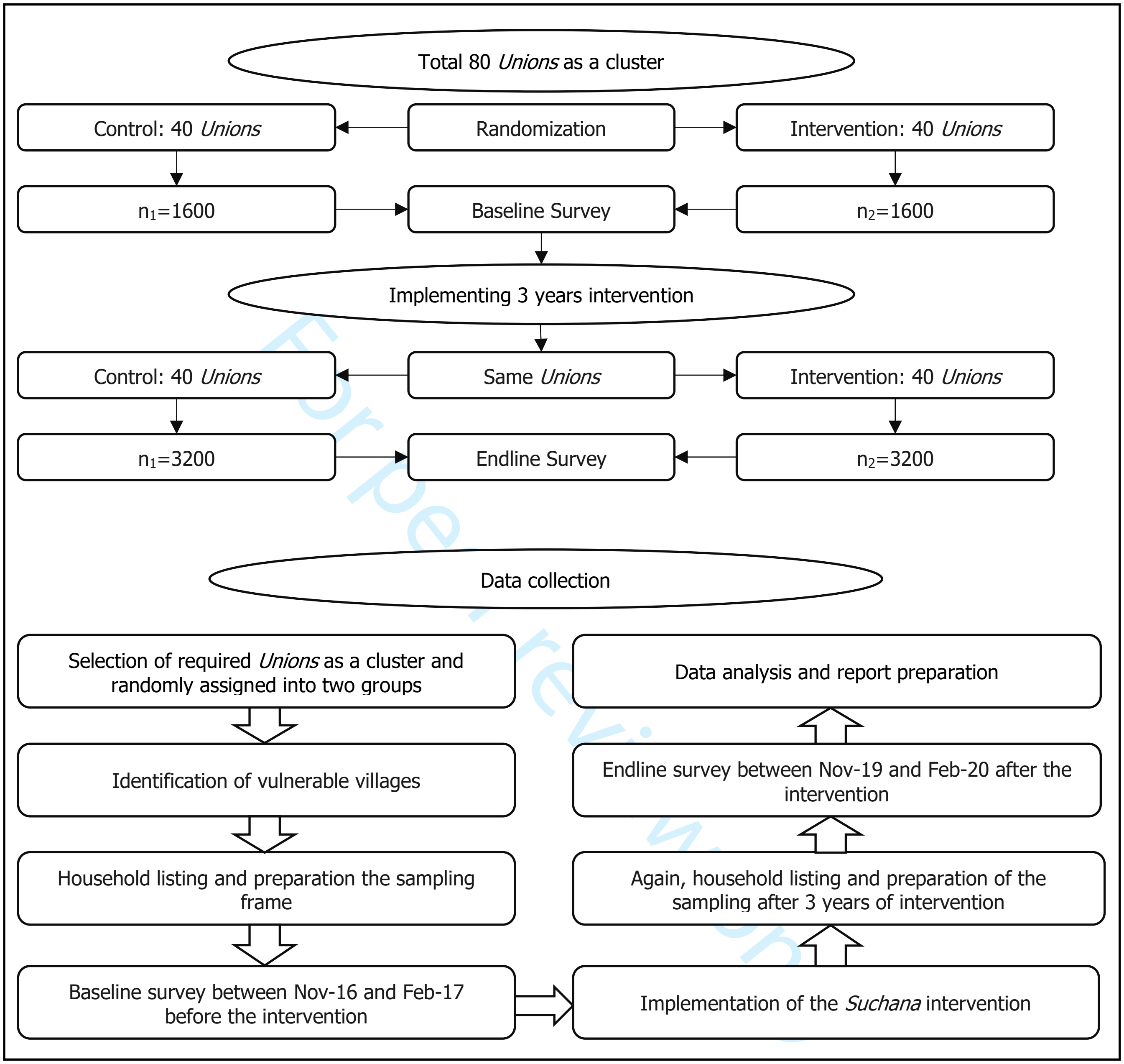
Appendix 1. Sample size calculation

```
clustersampsi, binomial samplesize p1(0.47) p2(0.41) k40) rho0.01)alpha(0.05) beta(0.8)
```

Output of the STATA command for sample size calculation

```
Sample size calculation to determine number of observations required per cluster, for a two-
sample comparison of proportions (using normal approximations) without continuity correction.

For the user specified parameters:
      p1: 0.4700
      p2: 0.4100
      significance level:  0.05
      power:  0.80
      number of clusters available:  40
      intra cluster correlation (ICC):  0.0100
clustersampsi estimated parameters:
      Firstly, assuming individual randomisation: sample size per arm: 1071
      Then, allowing for cluster randomisation: average cluster size required:  38
      sample size per arm:   1520
```



Supplementary Figure 1. The evaluation diagram of *Suchana* programme

Appendix 2. Data collection

The Suchana data collection software contained built-in validation rules. As the data were entered at the interviewer level and the records were uploaded to a server at the icddr,b using the built-in internet connectivity of the devices, maximum validation rules were set in the data system to prevent errors during data entry, which reduced the data entry burden. This allowed the data analysis team to review the

consistency of the data every day. Data were synchronized to the central server "Web Service" developed in Asp.Net based on the C# (C Sharp) code. Activities such as editing (after receiving any feedback from field staff members), updating, range checks, duplication checks, consistency checks, frequency checks and cross tabulation were regularly performed during the data entry period. In case of any unusual observations, the issues were discussed and resolved.

Appendix 3. Equation of logistic and probit regression

$$logit(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

$$probit(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

Where,

x1: Less than four ANC visits by a skilled service provider
x2: Unskilled birth attendant/facility
x3: Mother involved in income-generating activities
x4: Maternal BMI <18.5
x5: Maternal education: no schooling
x6: HH severe food insecurity
x7: Monthly income <15000 BDT
x8: Did not involve with aquaculture
x9: Having unhygienic latrine
x10: Soap was unavailable in hand washing place
x11: HH size$\geq$7
x12: HH dietary diversity score <7
x13: Child's age>18
x14: Child's sex was male
x15: Childhood illness in the last 15 days
x16: Lacked access to mass media

and

$$logit(y) = log[y/(1-y)]$$

Supplementary Table 1. *Suchana* inclusion criteria for registration of enrolling as vulnerable households

Vulnerable household verification questions	Inclusion criteria
Step 1 • Households currently participating/member of any livelihood, food security or asset transfer program	If "NO" go ahead for next questions
Step 2 • Ability to afford three (3) full meals per day for all family members round the year • Households monthly income BDT 7,500 or more • Household productive asset value worth BDT 15,000 or more (excluding land, pond and homestead) • Ownership of homestead land 10 decimals or more • Ownership of cultivable land 50 decimals or more (excluding homestead or pond)	If anyone is "NO" go ahead for next questions
Step 3 • Households have married women with in child bearing age (15 to 45 years) • Households have pregnant women (including abandoned or widowed woman) • Households have 0-23 months old children • Households have adolescent girls (15-19 years)	If anyone is 'Yes' go ahead for registration of enrolling as vulnerable Household
Sampling frame was prepared for collecting data from mother-child pair if the households had 0-23 months old children	

Supplementary Table 2a. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple logistic regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.07, 6.22)	0.006
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.55, 4.35)	0.012
Mother involved in income-generating activities			
No	54.55 (50.90, 58.19)	Reference	
Yes	50.59 (49.08, 52.11)	3.95 (0.40, 7.51)	0.029
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.41)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.40)	<0.001
HH food insecurity			
Below severe	53.03 (50.91, 55.15)	Reference	
Severe	50.36 (48.63, 52.09)	2.66 (0.11, 5.22)	0.041
HH monthly income ≥15000 BDT			
Yes	51.31 (49.79, 52.84)	Reference	
No	48.58 (45.86, 51.30)	2.73 (0.17, 5.30)	0.037
Involved with aquaculture			
Yes	51.22 (49.72, 52.72)	Reference	
No	46.99 (43.30, 50.69)	4.23 (0.73, 7.73)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.54 (46.74, 50.33)	4.10 (1.83, 6.38)	<0.001
HH size			
Below seven	53.86 (51.98, 55.74)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.92 (51.25, 56.60)	Reference	
HDDS <7	50.10 (48.70, 51.50)	3.83 (1.63, 6.02)	<0.001
Child's age			
Age ≤18 months	56.72 (54.77, 58.67)	Reference	
Age >18 months	46.59 (44.82, 48.35)	10.1 (7.94, 12.32)	<0.001
Child's sex			
Female	53.25 (51.17, 55.34)	Reference	
Male	48.40 (46.78, 50.03)	4.85 (2.59, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.77)	Reference	
Yes	50.49 (48.94, 52.05)	4.41 (1.48, 7.34)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.39, 50.88)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

Supplementary Table 2b. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple probit regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.08, 6.22)	0.007
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.54, 4.35)	0.011
Mother involved in income-generating activities			
No	54.55 (50.90, 58.16)	Reference	
Yes	50.59 (49.08, 52.11)	3.93 (0.39, 7.48)	0.024
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.40)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.41)	<0.001
HH food insecurity			
Below severe	53.01 (50.89, 55.12)	Reference	
Severe	50.37 (48.64, 52.10)	2.64 (0.09, 5.19)	0.042
HH monthly income ≥15000 BDT			
Yes	51.32 (49.79, 52.84)	Reference	
No	48.56 (45.84, 51.28)	2.75 (0.19, 5.32)	0.035
Involved with aquaculture			
Yes	51.22 (49.73, 52.71)	Reference	
No	46.99 (43.28, 50.69)	4.24 (0.73, 7.74)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.53 (46.74, 50.33)	4.11 (1.83, 6.39)	<0.001
HH size			
Below seven	53.86 (51.98, 55.73)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.90 (51.23, 56.57)	Reference	
HDDS <7	50.10 (48.71, 51.50)	3.79 (1.60, 5.98)	<0.001
Child's age			
Age ≤18 months	56.72 (54.76, 58.67)	Reference	
Age >18 months	46.59 (44.83, 48.35)	10.1 (7.93, 12.3)	<0.001
Child's sex			
Female	53.25 (51.17, 55.33)	Reference	
Male	48.41 (46.78, 50.03)	4.85 (2.60, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.75)	Reference	
Yes	50.50 (48.94, 52.05)	4.40 (1.47, 7.33)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.40, 50.86)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

STROBE Statement—Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1-2
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	1-2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-6
Objectives	3	State specific objectives, including any prespecified hypotheses	6
Methods			
Study design	4	Present key elements of study design early in the paper	6
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	6
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-7
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	*6-7*
Bias	9	Describe any efforts to address potential sources of bias	20
Study size	10	Explain how the study size was arrived at	7
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	8-9
		(*b*) Describe any methods used to examine subgroups and interactions	
		(*c*) Explain how missing data were addressed	
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	8-9
		(*e*) Describe any sensitivity analyses	
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	11
		(b) Give reasons for non-participation at each stage	
		(c) Consider use of a flow diagram	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	11
		(b) Indicate number of participants with missing data for each variable of interest	
Outcome data	15*	Report numbers of outcome events or summary measures	11
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	11-14

		(*b*) Report category boundaries when continuous variables were categorized	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	11-15
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
Discussion			
Key results	18	Summarise key results with reference to study objectives	17
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	20
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	17
Generalisability	21	Discuss the generalisability (external validity) of the study results	17-18
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	22

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

BMJ Open

A predictive modelling approach to illustrate factors correlating with stunting among children aged 12-23 months: a cluster randomized pre-post study

Journal:	*BMJ Open*
Manuscript ID	bmjopen-2022-067961.R4
Article Type:	Original research
Date Submitted by the Author:	30-Mar-2023
Complete List of Authors:	Haque, Md; ICDDRB Choudhury, Nuzhat; ICDDRB Wahid, Barbie Zaman; ICDDRB Ahmed, SM Tanvir ; Save the Children Bangladesh Farzana, Fahmida Dil; ICDDRB Ali, Mohammad; ICDDRB Naz, Farina; ICDDRB Siddiqua, Towfida Jahan ; Johns Hopkins University, Bangladesh Rahman, Shahed ; Save the Children Bangladesh Faruque, ASG; ICDDRB Ahmed, Tahmeed; ICDDRB
Primary Subject Heading:	Epidemiology
Secondary Subject Heading:	Public health
Keywords:	Nutrition < TROPICAL MEDICINE, EPIDEMIOLOGY, PUBLIC HEALTH

SCHOLARONE™
Manuscripts

A predictive modelling approach to illustrate factors correlating with stunting among children aged 12-23 months: a cluster randomized pre-post study

Md Ahshanul Haque[1*], Nuzhat Choudhury[1], Barbie Zaman Wahid[1], SM Tanvir Ahmed[2], Fahmida Dil Farzana[1], Mohammad Ali[1], Farina Naz[1], Towfida Jahan Siddiqua[1], Sheikh Shahed Rahman[2], ASG Faruque[1], Tahmeed Ahmed[1]

[1] Nutrition and Clinical Services Division, icddr,b, Dhaka, 1212, Bangladesh
[2] Child Poverty Sector, Save the Children Bangladesh, Dhaka, Bangladesh

*** Correspondence:** Md Ahshanul Haque, Assistant Scientist, Nutrition and Clinical Services Division, icddr,b, 68, Shaheed Tajuddin Ahmed Sarani, Mohakhali, Dhaka 1212, Bangladesh, Email: ahshanul.haque@icddrb.org

Word count: 4977

Abstract

Objective The aim of this study was to construct a predictive model in order to develop an intervention study to reduce the prevalence of stunting among children aged 12-23 months.

Design The study followed a cluster randomized pre-post design and measured the impacts on various indicators of livelihood, health, and nutrition. The study was based on a large dataset collected from two cross-sectional studies (baseline and endline).

Setting The study was conducted in the north-eastern region of Bangladesh under the Sylhet division, which is vulnerable to both natural disasters and poverty. The study specifically targeted children between the ages of 12 and 23 months.

Main outcome measures Childhood stunting, defined as a length-for-age z-score (LAZ)<-2, was the outcome variable in this study. Logistic and probit regression models and a decision tree were constructed to predict the factors associated with childhood stunting. The predictive performance

of the models was evaluated by computing the area under the receiver operating characteristic (ROC) curve analysis.

Results The baseline survey showed a prevalence of 52.7% stunting, while 50.0% were stunted at endline. Several factors were found to be associated with childhood stunting. The model's sensitivity was 61% and specificity was 56%, with a correctly classified rate of 59% and an area under the ROC curve of 0.615.

Conclusion The study found that childhood stunting in the study area was correlated with several factors, including maternal nutrition and education, food insecurity, and hygiene practices. Despite efforts to address these factors, they remain largely unchanged. The study suggests that a more effective approach may be developed in future to target adolescent mothers, as maternal nutrition and education are age-dependent variables. Policymakers and programme planners need to consider incorporating both nutrition-sensitive and specific activities and enhancing collaboration in their efforts to improve the health of vulnerable rural populations.

Study registration: RIDIE-STUDY-ID-5d5678361809b

Keywords: Childhood stunting, Chronic malnutrition, Global public health, Logistic regression, Probit regression, Decision tree

Strengths and limitations of this study

- The study used a combination of parametric and non-parametric predictive models to estimate the effect size of the independent variables and identify significant correlates of childhood stunting
- The study was designed to mitigate the potential impact of seasonal factors by conducting the baseline and endline surveys at the same time of the year
- A binary indicator of stunting based on a single LAZ cut-off point (<-2) may not provide a complete evaluation of the severity of malnutrition among children as it does not consider micronutrient deficiencies

- Use of recall data from the previous 24 hours for dietary diversity, household food insecurity, domestic violence, and maternal healthcare may be subject to recall bias
- Biological data has not been collected such as enteropathogen and environmental enteric dysfunction, which could have been related to childhood stunting

Introduction

Childhood stunting, which is defined as length-for-age z-score (LAZ)<-2, is a major concern for public health and has been widely used as an indicator of chronic malnutrition in children.[1 2] Although childhood stunting scenarios have much improved globally, the prevalence of childhood stunting is still very high in low-resource settings, including countries such as Bangladesh. According to the 2018 Global Nutrition Report, 150.8 million children (22.2%) under five years-of-age are stunted globally, compared to 198.4 million (32.6%) and 165 million children in 2000 and 2011, respectively.[3 4] Between 2000 and 2018, Asian countries have experienced a decrease in the rate of stunting among children under five from 38.1% to 23.2%. However, South Asia still has the highest prevalence of stunting in the region, with a rate of 38.9% in 2018.[3] In Bangladesh, about 5.5 million (36%) children under five were stunted in 2014,[5] however by 2018, childhood stunting has reduced to about 31%.[2] As the World Health Organization (WHO) considers a childhood stunting rate of 15% to be an emergency situation, the current prevalence of childhood stunting in Bangladesh reflects an alarming situation of chronic undernutrition.[6]

Literature suggests that children are at a higher prevalence of stunting if their mothers do not receive adequate antenatal care, fail to rest sufficiently, do not consume additional food, and neglect to take iron-folic acid (IFA) tablets during pregnancy.[7-9] Additionally, maternal and child health are correlated with mass media exposure, receiving a vitamin A capsule, having a skilled birth attendant, and maternal education.[6 8 10-12] Children in poor households in Bangladesh are more likely to experience stunted growth if their mothers are employed, as there are inadequate day-care centres available for the children, leading to insufficient breastfeeding.[13] Moreover, evidence suggests that a number of characteristics at the household level, which relate to both children and mothers, can influence childhood stunting. The characteristics of the household head, household food insecurity and lower dietary diversity, household lower-income, household involvement in several earning activities, availability of sanitation facility at home, hand-washing status, family size, religion, and receive several types of allowance from government are most often reported to be associated with stunting in the literature.[6 8 11 14-16]

Based on child characteristics, several indicators are associated with stunting. This status is associated with two basic characteristics: a child's gender and age.[8] Children are commonly affected by the co-occurrence of illness in low- and middle-income countries, which is one of the most common causes of stunting.[17] Inadequate infant and young child feeding (IYCF) practices also reduce child growth.[8 15] However, these findings are mostly based on nationally representative cross-sectional and cohort studies, or studies conducted in urban settings.[18 19] Therefore, a knowledge gap exists on whether similar results would be obtained when nationwide data are compared with data for study populations from poor or very poor rural households in specific vulnerable regions.

Sylhet is one such vulnerable region of north-east Bangladesh, comprising diverse terrains such as plain land, hilly land, *Haor* (wetland), and flash flood-prone areas. This region is reported to perform poorly for all important maternal healthcare indicators,[20] despite the fact that Bangladesh has made substantial progress in improving the overall health of the population.[21] Moreover, the socio-economic profile of the inhabitants in Sylhet region includes both very rich and extremely poor people. This scenario may worsen without the implementation of appropriate strategies in the near future. Sylhet region is also performing poorly compared to the national averages for a number of health and nutritional indicators. Critical indicators such as the infant mortality rate and unemployment status of women are high.[19] In comparison to the overall situation of Bangladesh, where stunting among children under five has decreased, the Bangladesh Demographic and Health Survey (BDHS) 2014 indicates the prevalence of childhood stunting in Sylhet is astonishingly high, at 50%.[19] This alarming figure provided the rationale for implementation of a comprehensive intervention programme in this region. A large-scale nutrition programme, *Suchana: Ending the Cycle of Undernutrition in Bangladesh; a multi-sectoral nutrition programme,* was undertaken with the aim to prevent chronic malnutrition in Sylhet.

In general, *Suchana* nutrition interventions can be divided into two types: nutrition-sensitive and nutrition-specific.[22] The concept of nutrition-sensitive intervention refers to an intervention that benefits the beneficiaries in terms of food and nutrition security, and also influences the underlying determinants of nutrition. This type of intervention is largely delivered through the agricultural sector (homestead vegetable and fruit production, pro-poor nutrition-sensitive aquaculture), improved technology (mono-sex tilapia and carp-tilapia polyculture, subsistence fishing, fish drying), demonstrations (village model farms and demo ponds, livestock, food security, promotion of climate-smart technologies), and supported income-generating activities (skill development in business management, engagement with the private sector and other sectors). As nutrition-specific interventions were delivered through nutrition-sensitive interventions, their coverage, effectiveness, and scale can be increased. It can meet the targets by lowering them and implementing nutrition-specific interventions. A nutrition-specific intervention addresses the immediate cause of malnutrition. Direct determinants of nutrition are the focus of this intervention. There is a strong focus on nutrition-specific interventions in the health sector. Whether implemented alone or jointly, nutrition-specific interventions improve health outcomes. Some examples of nutrition-specific interventions are: counselling for mothers at the household level, community-based nutrition education for spouses and in-laws, growth monitoring and promotion sessions integrated with *Expanded Programme on Immunization* in communities, *Government of Bangladesh* health facilities equipped with *severe acute malnutrition* service delivery, and support for *National Nutrition Services* service delivery through community clinics, Union Health and Family Welfare Centers, and Upazila health complexes.

The primary objective of the *Suchana* programme was to reduce the prevalence of childhood stunting in the intervention areas. The secondary objectives were to assess the changes in *Suchana* beneficiaries' households, in terms of an increase and diversification of household income, food security status, optimal IYCF practices, haemoglobin status of children, the empowerment of women, and adolescents' nutritional knowledge and practices.[22]

The *Suchana* programme substantially improved nutritional behaviour, maternal healthcare practices, women's empowerment, household income, and household food security in the intervention area compared to the control area.[23] Contrary to predictions, however, *Suchana* did not result in any significant reduction in the prevalence of childhood stunting. Therefore, although most other factors related to childhood stunting improved, this raises the question of why the prevalence of stunting did not reduce after the intervention. An important observation from the *Suchana* survey was that the proportion of households in this study population using hygienic latrines was quite low. This factor was associated with stunting in children,[8] and did not significantly improve by endline in the intervention areas compared to the control areas.

In this study, we aimed to construct a predictive model to attempt to explain whether any improvements in associated factors may promote a significant reduction in stunting among children aged 12-23 months from poor and extremely poor households in the Sylhet region.

Methods

Study design and setting

The *Suchana* programme was implemented in 157 *Unions* over 20 sub-districts in the Sylhet region in the north-east of rural Bangladesh. The *Suchana* programme's protocol has been thoroughly explained elsewhere.[22] *Union*, the smallest local government and administrative entity in rural Bangladesh, was considered as a cluster and divided into four phases at random. Phase-1 was designated as the intervention group, while Phase-4 was the control group, and the other phases were treated as learning phases.[22] For implementation purposes, vulnerable villages were selected within Phase-1 and Phase-4 areas. The staff of the programme chose vulnerable villages in each *Union* based on their vulnerability (e.g., frequent floods or submerging, little or no intervention from other development programmes, poverty or household living circumstances, remoteness and accessibility issues, a high prevalence of superstitions and social taboos). After consultation with the local government representatives, elected officials, and local elites as well as field visits, this selection method was decided upon. The impacts of the intervention on livelihood, health, and nutrition were measured using a pre-post design. A large dataset was collected from two cross-sectional surveys (baseline and endline) under this study. The baseline survey was conducted in November 2016 and February 2017, followed by the endline survey in the same months three years later among the same population and different participants (Supplementary Figure 1).

Outcome variable

The outcome variable in this study was childhood stunting, which was defined as a length-for-age z-score (LAZ)<-2.[2]

Independent variables

Initially, a list of independent variables was finalized through results obtained from descriptive and bi-variate analyses, as well as a comprehensive literature review (Table 1). These included at least four antenatal care (ANC) visits by a skilled service provider, additional resting during pregnancy, additional food consumption during pregnancy, consumption of at least 100 IFA tablets during pregnancy, receiving vitamin A capsule after last delivery, birth attendant/facility, mother involved in income-generating activities, maternal BMI, maternal education, household food insecurity, household monthly income >15000 BDT, involved with aquaculture, hygienic latrine, water and soap available in handwashing place, household size, household dietary diversity, sex of household head, religion, received any grant/allowance/stipend from the government, access of mass media, child's age, child's sex, childhood illness in the last 15 days, minimum dietary diversity, early initiation of breastfeeding, and received colostrum. Household food insecurity access scale was measured using the Food and Nutrition Technical Assistance's Guideline, which categorizes household food insecurity into four levels: a) food secure, b) mildly food insecure, c) moderately food insecure, and d) severely food insecure.[24] In the analysis herein, this indicator was redefined as a binary indicator: severely food insecure or not severely food insecure.

Sample size

The sample size for this study was calculated with the STATA "*clustersampsi*" command module, considering the number of clusters in the surveys and considering the expected prevalence of childhood stunting in the control group (Supplemental Appendix 1). It was estimated that the expected prevalence of stunting was 47%, which was hypothesized to be reduced to 41% after three years of intervention. A sample size of 1520 per arm was calculated based on a 5% level of significance, 80% power, 40 clusters per arm, and an intra-cluster correlation coefficient (ICC) of 0.01. After rounding, the estimated sample size per arm was 1620, and the total sample size was 3200 at baseline, with an equal number of participants in the control and intervention groups. For evaluation purposes, the sample size at endline was doubled to ensure a stratified intervention component, resulting in a total sample size of 9600 mother-child pairs (baseline: 3200 and endline: 6400).[22]

Sampling

The baseline and endline surveys were conducted in a total of eight and twelve villages respectively, which were randomly selected from each *Union* using a list of vulnerable villages provided by Save the Children. The most vulnerable households were identified and verified using the inclusion criteria of the *Suchana* programme (Supplementary Table 1). These households were then given an identification number to prepare the sampling frame and required households were systematically selected for the surveys from the frame. The method of data collection is explained in detail in the Supplemental Appendix 2.

Statistical analysis

General characteristics: Stata-14 software (StataCorp LP, College Station, TX, USA) and R 4.2.2 (*rpart*)[25] were used to analyse the data. Bar diagram was used for data visualization. Descriptive statistics, such as frequency and proportions for categorical variables and mean and standard deviations for quantitative variables, were used to summarize the data at baseline and endline. Cross-tabulation was used to present that outcome variable segregated by intervention and control group at baseline survey as well as the endline survey. The *difference in difference* method was used to estimate the contrast of an intervention by comparing the difference in the outcomes between an intervention group and a control group before and after the intervention.[26]

Predictive model: Three statistical models were used as predictive models. Two parametric models, such as Logistic and Probit regression models, and Decision Tree as a non-parametric model. Logistic and Probit regression models were used as predictive models as well as classifier models. The models were also used to investigate which factors were significantly associated with childhood stunting, and estimate their effect size, in order to predict whether changes in behavioural practices might potentially help to achieve targeted reductions in stunting. Using those variables, a decision tree was applied, and the predictive performance was compared to other models.

For the parametric models, first, Chi-Square test was used to examine the bivariate associations between stunting and all possible explanatory variables. In the second step, variables with *p*-values <0.25 in the simple model were included in the multiple regression models.[27] In the final step, any independent variables thought to be likely predictors were added to the multiple regression model using the stepwise forward selection method. Some indicators, e.g., age, sex, and maternal nutritional status were added regardless of their *p*-value due to their scientific plausibility. The mathematical equation of logistic and probit regression models were given in the Supplemental Appendix 3. As a cluster variable, *Union* was used to adjust the standard errors. Furthermore, for the explanation of the regression model, a *p*-value <0.05 was considered as statistically significant, and the confidence interval (CI) of 95% was also reviewed. From the fitted model, the adjusted effect size (adjusted prevalence difference) against all predictors was estimated using the "*adjrr*" package in Stata. The list of independent variables with the value labels used in the model is given in Table 1.

Table 1. List of all independent variables

Indicators	Code	Stunting Status*	Selection in the model
At least four ANC visits by a skilled service provider			Selected
At least four ANC visits by a skilled service provider	0		
Less than four ANC visits by a skilled service provider	1	Higher prevalence[8]	
Additional resting during pregnancy			Not selected
Took more rest	0		
Did not take more rest	1	Higher prevalence[8]	
Additional food consumption during pregnancy			Not selected
Consumed more food	0		
Did not consumed more food	1	Higher prevalence[7 8]	
Consumption of at least 100 IFA tablets during pregnancy			Not selected
Consumed at least 100 IFA tablets	0		
Did not consumed at least 100 IFA tablets	1	Higher prevalence[9]	
Received vitamin A capsule after last delivery			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	
Birth attendant/facility			Selected
Skilled	0		
Unskilled	1	Higher prevalence[10]	
Mother involved in income-generating activities			Selected
No	0		
Yes	1	Higher prevalence[6 13]	
Maternal BMI			Selected
BMI ≥18.5	0		
BMI <18.5	1	Higher prevalence[6 11]	
Maternal education			Selected

At least one-year formal education	0		
No schooling	1	Higher prevalence[6 11]	
Access of mass media			Selected
Access	0		
No access	1	Higher prevalence[12]	
Household food insecurity			Selected
Below severe	0		
Severe	1	Higher prevalence[8]	
Household monthly income ≥15000 BDT			Selected
≥15000 BDT	0		
<15000 BDT	1	Higher prevalence[11]	
Involved with aquaculture			Selected
Involved	0		
Did not involved	1	Higher prevalence[14]	
Hygienic latrine			Selected
Hygienic latrine	0		
Unhygienic latrine	1	Higher prevalence[6 11 15]	
Water and soap available in handwashing place			Selected
Available	0		
Unavailable	1	Higher prevalence[15]	
Household size			Selected
Below seven	0		
Seven or above	1	Higher prevalence[11]	
Household dietary diversity (HDDS)			Selected
HDDS ≥7	0		
HDDS <7	1	Higher prevalence[8]	
Sex of household head			Not selected
Female	0		
Male	1	Higher prevalence[8]	
Household head education			Not selected
At least one-year formal education	0		
No schooling	1	Higher prevalence[6]	
Religion			Not selected
Muslim	0		
Non-Muslim	1	Lower prevalence[6]	
Received any grant/allowance/stipend from the government			Not selected
Received	0		
Did not receive	1	Higher prevalence[16]	
Child's age			Selected
Age ≤18 months	0		
Age >18 months	1	Higher prevalence[8]	
Child's sex			
Female	0		
Male	1	Higher prevalence[8]	
Childhood illness in the last 15 days			Selected
No	0		
Yes	1	Higher prevalence[17]	
Minimum dietary diversity			Not selected
Received	0		
Did not receive	1	Higher prevalence[8 15]	
Early initiation of breastfeeding			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	

Received colostrum			
Received	0		Not selected
Did not receive	1	Higher prevalence[8]	

[1]Expected effects based on findings of the literature

Model evaluation: The predictive performance of the three statistical models was evaluated by computing model sensitivity and specificity, and calculating the area under the receiver operating curve (ROC) analysis. To ensure accurate results, the data was randomly split into a training set (75%) and a test set (25%) using a random-number seed 113843. The same training and test datasets were used for evaluating the performance of all algorithms to ensure consistency in the results. The sensitivity and specificity values, as well as the area under the ROC curve, were used to determine the overall accuracy of the algorithms in predicting childhood stunting.[28 29]

Patient and public involvement

Patients and public were not actively involved in formulating the research question and or protocol development, including the outcome measures. To expedite the field implementation, however, local elites e.g. teachers, religious persons, and local government council members were informed about the study.

Results

General characteristics: Out of 9600 cases, 9501 cases were found to be available. The refusal rate was around 1%. With respect to the outcome indicator, stunting in children aged 12-23 months, 52.7% of children were stunted at the baseline survey (intervention group: 52.6%; control group: 52.8%), whereas the proportion of children exhibiting stunting at endline was 50.0% (intervention: 49.9%; control: 50.1%; Figure 1). At both the baseline and endline surveys, there was no significant difference in proportion between intervention and control areas. The *difference-in-difference* in outcomes over time was also insignificant.

Figure 2 describes several other indicators related to maternal and child health, including the status of consuming a minimum acceptable diet (intervention: 35.2%; control: 14.9%), minimum dietary diversity (intervention: 42.8%; control: 20.4%), maternal decision-making (intervention: 45.0%; control: 31.0%), at least four maternal ANC visits by a skilled service provider (intervention: 36.1%; control: 17.7%), minimum dietary diversity for women (intervention: 52.6%; control:

33.5%), a household dietary diversity score of at least seven (intervention: 88.9%; control: 78.3%), and household food security status (intervention: 26.6%; control: 20.2%). Results from the endline survey showed that these indicators were significantly improved in the intervention group compared to the control group. However, the availability of hygienic latrines did not increase in the intervention group (intervention: 44.0%; control: 44.0%). Table 2 shows the households' socio-demographic characteristics, women's general characteristics, and children's characteristics at baseline and endline.

Table 2. General characteristics of the *Suchana* beneficiaries

Indicators, *n* (%)	**Baseline *N*=3200**	**Endline *N*=6301**	**Total *N*=9501**
At least four ANC visits by a skilled service provider			
Yes	408 (12.8)	1530 (24.3)	1938 (20.4)
No	2792 (87.2)	4771 (75.7)	7563 (79.6)
Delivery at skilled birth attendant/facility			
Yes	1000 (31.2)	2769 (44.0)	3769 (39.7)
No	2200 (68.8)	3532 (56.0)	5732 (60.3)
Access of mass media			
Access	563 (17.59)	1169 (18.55)	1732 (18.23)
No access	2637 (82.41)	5132 (81.45)	7769 (81.77)
Mother involved in income-generating activities			
No	3102 (96.9)	5665 (89.9)	8767 (92.2)
Yes	98 (3.1)	639 (10.1)	737 (7.8)
Maternal BMI			
BMI ≥18.5	1859 (58.1)	4073 (64.6)	5932 (62.4)
BMI <18.5	1341 (41.9)	2231 (35.4)	3572 (37.6)
Mother completed primary education			
Yes	1721 (53.8)	3808 (60.4)	5529 (58.2)
No	1479 (46.2)	2496 (39.6)	3975 (41.8)
Maternal age			
Age <30 years	2145 (67.0)	3559 (56.5)	5704 (60.0)
Age ≥30 years	1055 (33.0)	2745 (43.5)	3800 (40.0)
Type of delivery			
Normal	2879 (90.0)	5529 (87.8)	8408 (88.5)
Caesarean	321 (10.0)	772 (12.3)	1093 (11.5)
PNC			
No	2152 (67.3)	4128 (65.5)	6280 (66.1)
Yes	1048 (32.8)	2173 (34.5)	3221 (33.9)
Household severely food insecure			
Yes	912 (28.5)	1016 (16.1)	1928 (20.3)
No	2288 (71.5)	5285 (83.9)	7573 (79.7)
Household monthly income ≥15000 BDT			
Yes	424 (13.2)	1015 (16.1)	1439 (15.1)
No	2776 (86.8)	5289 (83.9)	8065 (84.9)

Household involved with aquaculture			
Yes	161 (5.0)	561 (8.9)	722 (7.6)
No	3039 (95.0)	5740 (91.1)	8779 (92.4)
Hygienic latrine			
Yes	1121 (35.0)	2782 (44.1)	3903 (41.1)
No	2079 (65.0)	3519 (55.9)	5598 (58.9)
Water and soap available in handwashing place			
Yes	862 (26.9)	3170 (50.3)	4032 (42.4)
No	2338 (73.1)	3131 (49.7)	5469 (57.6)
Household savings			
No	1080 (33.8)	2876 (45.6)	3956 (41.6)
Yes	2120 (66.2)	3425 (54.4)	5545 (58.4)
Sex of household head			
Female	110 (3.4)	501 (8.0)	611 (6.4)
Male	3090 (96.6)	5799 (92.0)	8889 (93.6)
Source of drinking water			
Tube well	2748 (85.9)	5713 (90.7)	8461 (89.0)
Others	452 (14.1)	588 (9.3)	1040 (11.0)
Household dietary diversity score			
HDDS ≥7	2182 (68.2)	5322 (84.5)	7504 (79.0)
HDDS <7	1018 (31.8)	979 (15.5)	1997 (21.0)
Household monthly income (Thousand BDT)[1]	6.7 (5, 10)	7.5 (5.1, 10.8)	7.1 (5, 10.4)
Per capita income (Thousand)[1]	2.6 (1.8, 3.7)	2.9 (2, 4.1)	2.8 (2, 4)
Household size[1]	6.2±2.4	5.9±2.1	6±2.2
Child's age in months[2]	17.9±3.5	17.3±3.6	17.5±3.6
Length-for-age z-score[2]	-2.1±1.2	-2±1.1	-2±1.1
Weight-for-age z-score[2]	-1.7±1.1	-1.5±1.0	-1.5±1.0
Weight-for-length z-score[2]	-0.9±1.0	-0.7±0.9	-0.7±1.0
Child's age			
Age <18 months	1745 (54.5)	3710 (58.9)	5455 (57.4)
Age ≥18 months	1455 (45.5)	2594 (41.1)	4049 (42.6)
Child's sex			
Female	1567 (49.0)	3044 (48.3)	4611 (48.5)
Male	1633 (51.0)	3257 (51.7)	4890 (51.5)
Childhood illness in the last 15 days			
Yes	2867 (89.6)	5763 (91.5)	8630 (90.8)
No	333 (10.4)	538 (8.5)	871 (9.2)

[1]Median (IQR); [2]Mean ± SD

Correlated factors: The study used two parametric predictive models to determine the correlates of childhood stunting. The results, presented in Table 3, showed the adjusted odds ratios (aOR) computed from multiple logistic regression and the adjusted coefficients computed from multiple probit regression. These results provide important insights into the factors that increase the odds of stunting in childhood, and can inform public health interventions aimed at reducing stunting and improving child health. The aORs provide a quantitative measure of the relationship between different factors and childhood stunting, adjusting for *Union* as cluster variable. Understanding the correlates of childhood stunting is critical for addressing this important public health issue and improving the health and well-being of children globally. The results of this study show that a number of maternal, household and children factors were correlated with an increased prevalence of stunting in children. Children of mothers who did not receive at least four ANC visits from a skilled service provider had 1.16 times higher odds of stunting (95% CI: 1.05, 1.30; p-value=0.005). Children of mothers who gave birth with an unskilled birth attendant or facility had 1.11 times higher odds of stunting (95% CI: 1.02, 1.20; p-value=0.012). The odds of stunting were 1.18 times higher in children whose mothers were involved in income-generating activities (95% CI: 1.02, 1.37; p-value=0.030), 1.23 times higher in children of underweight mothers (95% CI: 1.12, 1.36; p-value<0.001), and 1.31 times higher in children of low-educated mothers (95% CI: 1.20, 1.42; p-value<0.001). Furthermore, the lack of exposure to mass media was also found to be associated with stunting, with odds of 1.15 (95% CI: 1.02, 1.30; p-value=0.025) times higher. Children from households with severe food insecurity, lower-income households, households not involved in aquaculture, and households with low dietary diversity, were more likely to be stunted, with odds increasing by 1.12 (95% CI: 1.00, 1.24; p-value=0.041), 1.12 (95% CI: 1.01, 1.25; p-value=0.037), 1.19 (95% CI: 1.03, 1.38; p-value=0.018), and 1.17 (95% CI: 1.07, 1.29; p-value=0.001) times, respectively. The results also showed that the odds of stunting increased with increasing household size (95% CI: 1.11, 1.31; p-value<0.001), the absence of a hygienic latrine (95% CI: 1.10, 1.30; p-value<0.001), the absence of water and soap in the handwashing place (95% CI: 1.08, 1.30; p-value<0.001), increasing child age (95% CI: 1.39, 1.67; p-value<0.001), and being male (95% CI: 1.11, 1.34; p-value<0.001). The odds of stunting were also 1.20 times higher in children with acute illness (95% CI: 1.06, 1.36; p-value=0.003). The logistic and probit regression models were employed to predict stunting in a sample of 9501 individuals. Both models were found to be significant, with log-likelihoods of -6387.94 and -6388.02, respectively, and significant Wald chi-square statistics (p-value < 0.001). Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) are given in Supplementary Table 2a and 2b. The Factors correlating with childhood stunting, as determined by using a decision tree as a non-parametric predictive model, are also presented in Figure 3. The decision tree result suggests that maternal education was the most important variable in predicting childhood stunting, as it was the main root node. The other variables, such as maternal nutrition, hand washing indicators, and hygienic latrine, were also important, as they were next root node variables. This tree model can be used to predict the childhood stunting status with relative ease.

Table 3. Factors correlating with stunting in children aged 12-23 months, computed using logistic and probit regression analyses

Indicators		Logistic		Probit	
		Adjusted OR (95% CI)	p-value	Adjusted Coef. (95% CI)	p-value
At least four ANC visits by a skilled service provider					
	Yes	Reference		Reference	
	No	1.16 (1.05, 1.30)	0.005	0.09 (0.03, 0.16)	0.005
Birth attendant/facility					
	Skilled	Reference		Reference	
	Unskilled	1.11 (1.02, 1.20)	0.012	0.06 (0.01, 0.11)	0.012
Mother involved in income-generating activities					
	No	Reference		Reference	
	Yes	1.18 (1.02, 1.37)	0.030	0.10 (0.01, 0.19)	0.030
Maternal BMI					
	BMI ≥18.5				
	BMI <18.5	1.23 (1.12, 1.36)	0.000	0.13 (0.07, 0.19)	0.000
Maternal education was primary completed					
	Yes	Reference		Reference	
	No	1.31 (1.20, 1.42)	0.000	0.17 (0.12, 0.22)	0.000
Access of mass media					
	Yes	Reference		Reference	
	No	1.15 (1.02, 1.30)	0.025	0.09 (0.01, 0.16)	0.025
Household food insecurity					
	Below severe				
	Severe	1.12 (1.00, 1.24)	0.041	0.07 (0.00, 0.13)	0.042
Household monthly income ≥15000 BDT					
	Yes	Reference		Reference	
	No	1.12 (1.01, 1.25)	0.037	0.07 (0.00, 0.14)	0.035
Involved with aquaculture					
	Yes	Reference		Reference	
	No	1.19 (1.03, 1.38)	0.018	0.11 (0.02, 0.20)	0.018
Household size					
	Below seven	Reference		Reference	
	Seven or above	1.20 (1.11, 1.31)	0.000	0.12 (0.06, 0.17)	0.000
Hygienic latrine					
	Yes	Reference		Reference	
	No	1.20 (1.10, 1.30)	0.000	0.11 (0.06, 0.16)	0.000
Water and soap available in handwashing place					
	Yes	Reference		Reference	
	No	1.19 (1.08, 1.30)	0.000	0.11 (0.05, 0.16)	0.000
Household dietary diversity					
	HDDS ≥7	Reference		Reference	
	HDDS <7	1.17 (1.07, 1.29)	0.001	0.10 (0.04, 0.16)	0.001
Child's age					
	Age ≤18 months	Reference		Reference	
	Age >18 months	1.52 (1.39, 1.67)	0.000	0.26 (0.2, 0.32)	0.000

Child's sex				
Female	Reference		Reference	
Male	1.22 (1.11, 1.34)	0.000	0.13 (0.07, 0.18)	0.000
Childhood illness in the last 15 days				
No	Reference		Reference	
Yes	1.20 (1.06, 1.36)	0.003	0.11 (0.04, 0.19)	0.003
Sample size and regression diagnostic values for logistic and probit regression analyses	n = 9501 Log-likelihood = -6387.94 Wald chi2(17) = 427.79 p-value<0.001 Pseudo R^2 = 0.0298		n = 9501 Log-likelihood = -6388.02 Wald chi2(17) = 441.18 p-value<0.001 Pseudo R^2 = 0.0298	

Unions were adjusted as clusters. Baseline and endline were adjusted as time variables

Predictive performance: Table 4 describes the model validation based on sensitivity, specificity, and whether the model was correctly classified for the overall dataset, as well as the training and test datasets. The sensitivity and specificity of the model were around 60% and 55%, respectively for all models. The correctly classified rate was 59%, and the area under the ROC curve was around 61%. We found that these values were approximately equal among the three datasets (main, training, and test datasets); however, the predictive performance of the model was low.

Table 4. Predictive performance of the model for stunting based on classification, sensitivity, and specificity in the full, training and test datasets with area under the receiver operating characteristic curve analysis

	Logistic regression	Probit regression	Decision tree
Full dataset			
Overall accuracy	58.46	58.38	56.51
Sensitivity	61.21	61.25	61.15
Specificity	55.61	55.41	51.70
Area under the curve	61.54	61.54	56.72
Training Dataset			
Overall accuracy	58.83	58.62	57.66
Sensitivity	61.59	61.70	63.93
Specificity	55.36	55.42	51.61
Area under the curve	61.37	61.37	58.44
Test Dataset			
Overall accuracy	58.11	58.19	56.67
Sensitivity	60.23	60.23	61.58
Specificity	55.90	56.07	51.94
Area under the curve	61.76	61.77	58.01

Discussion

In an effort to understand why the *Suchana* programme was not effective in reducing the prevalence of childhood stunting, this study analyzed data from both the baseline and endline surveys of the programme. The analysis aimed to identify the factors that were significantly correlated with stunting and to evaluate the model's predictive performance. After controlling for the *Union* as a cluster variable, the study found several indicators that were significantly related to stunting. These included the number of ANC visits by a skilled service provider, household dietary diversity, household food security, and household monthly income, all of which improved after the intervention. However, it was noted that the household food security status did not reach the target value of 50%, despite being an important factor associated with childhood stunting.[8 30 31] On the other hand, other outcome indicators of the *Suchana* programme, such as the dietary diversity of children, maternal dietary diversity, and maternal empowerment, despite reaching their target values, were not found to be associated with stunting in this study.

The study found that while the *Suchana* programme showed improvement in certain programme indicators, it did not lead to a significant reduction in childhood stunting. Despite efforts to address key factors such as maternal nutrition and education, household food security, and hygiene practices, these factors remained largely unchanged. However, the study suggests that interventions aimed at adolescent mothers may be more effective in improving maternal nutrition and education, since these are age-dependent variables. Additionally, the results of the study were also impacted by natural disasters in 2017, including heavy rains and flooding in the Sylhet region, which resulted in widespread damage to agriculture, aquaculture, and homes in the study population.[32 33]

The study found a contradictory relationship between stunting and maternal involvement in income-generating activities, with a higher prevalence of stunting observed among children whose mothers were engaged in various earning activities. Although there was a slight increase in the proportion of mothers involved in income-generating activities after the intervention, the lack of childcare support for working mothers resulted in a marked rise in childhood stunting among low-income households. It is important to address this issue by providing adequate childcare support measures for working mothers from poor families to ensure that the child's essential needs are not impacted by the mother's employment status.[13] Additionally, efforts should be made to increase awareness among working mothers regarding the importance of child health and nutrition. This can be achieved through targeted education and outreach programmes that provide information on proper child feeding practices, hygiene, and health-seeking behaviours.

The literature suggests that environmental enteropathy may contribute to poor growth among children in rural Bangladesh and may represent an important factor affecting the study population in the *Suchana* programme.[34] Although it was not specifically assessed in this study, indicators such as unsanitary latrines, unimproved floors, a lack of handwashing practices, and low education levels were available.[18 35] Improving Water, Sanitation and Hygiene (WaSH) variables, particularly latrine facilities and handwashing practices, may help reduce the burden of stunting in young children. One of the components of the intervention was poultry, but our qualitative findings revealed that many households shared living spaces with poultry, ducks, or other animals, which could increase the risk of infections with *Campylobacter* species, a leading food-borne pathogen.[18 36] Previous studies have shown a strong association between stunting and enteropathy among children who do not respond to nutritional interventions, and findings from rural Bangladesh have linked environmental conditions and stunting in children.[37-39] While assessing environmental enteropathy was beyond the scope of the *Suchana* evaluation, collecting data on indicators of enteropathy in the intervention and control areas could help evaluate the impact of appropriate interventions in the future. The failure to achieve the desired outcome may have been due to several factors, including food insecurity and a lack of aquaculture involvement due to natural disasters, poor WaSH status, a lack of focus on maternal education and nutrition, and a lack of focus on the risk of enteropathogen burden.

Another important finding based on the post-estimation findings as well as the value of the area under the ROC curve was that the predictive performance of the model was low. Thus, we need to identify other indicators from similar research contexts that influence childhood stunting but were not included in our model. Future research in the field of childhood stunting should give priority to the development of more suitable methods for monitoring and identifying effective interventions. It is also essential to collect data that considers biological and environmental factors related to childhood stunting, following the literature. By considering these diverse factors, we can improve the accuracy and predictive performance of statistical models. This, in turn, can help draw more reliable conclusions about the effectiveness of interventions aimed at reducing childhood stunting in similar contexts. Additionally, evaluating the model on an independent dataset or conducting external validation could help to determine the generalizability of the model to new data.

This study will aid programme managers in prioritizing their focus and designing effective interventions to reduce childhood stunting. Sustainable solutions should be based on the needs of the beneficiaries. Implementing short-term initiatives such as attendance at healthcare-led workshops and campaigns can increase ANC visits, skilled birth attendance, and handwashing practices. Establishing women's healthcare services that focus on maternal and child health and nutrition will also help reduce the incidence of stunting.[23] Improved access to media can help vulnerable communities benefit from government welfare programmes. Food security, income, sanitation, aquaculture, and illness are all time-sensitive factors. Increasing food production through self-production or purchasing can improve household food security and nutrition. However, household wealth and access to nearby markets can impact their ability to buy nutritious food. Climate change adaptation in agriculture is crucial to minimize current risks and prepare for future uncertainties. Using organic fertilizers instead of chemicals in agriculture has environmental benefits, reducing the need for pesticides and protecting human health and biodiversity. Aquaculture can provide a source of protein and improve nutrition, but establishing these facilities takes time. Improving sanitation requires improving socioeconomic status, which is also a time-intensive process. It takes time to improve stunting, as shown by national surveys such as the BDHS and the Food Security and National Surveillance Project (FSNSP).[2 40] Improving maternal nutrition and education is crucial for promoting the optimal growth and development of children. Adequate food, good environmental conditions, and access to schooling facilities during adolescence are necessary for women to maintain their own health and to positively impact the health of their children. Emphasizing the education of female children can break the cycle of poverty and stunting, as it can lead to improved knowledge and decision-making skills related to nutrition and health.[6 11] To reduce childhood stunting in developing countries, comprehensive interventions that include nutritional support, food security, maternal education, income-generating activities for women with childcare support, and addressing domestic violence against women should be implemented. These interventions should be tailored to the specific needs and cultural context of the community in which they are implemented, and community participation and engagement are essential for their success. By addressing the underlying factors contributing to childhood stunting, we can make significant progress towards reducing its prevalence and improving the health and well-being of children in developing countries. Furthermore, continued monitoring and evaluation of these interventions is essential to ensure their effectiveness and to identify areas for improvement.

Recommendation: The *Suchana* model offers a holistic and integrated approach to addressing food and nutrition security, recognizing undernutrition as a complex problem caused by multiple factors. The endline survey of *Suchana* showed significant improvement in programme indicators. The multi-sector approach of *Suchana* is a meaningful solution to addressing undernutrition. However, policy makers should consider implementing additional nutrition-sensitive and specific activities, such as promoting climate-resilient agriculture and increasing water and sanitation coverage. It is also important to have a sustainable mechanism for improving food security and to promote awareness of seasonal diseases associated with livestock and poultry. To further improve the programme, indicators such as child sex, maternal education, and nutrition could be adjusted during the design stage. The *Suchana* programme is one of the largest global nutrition interventions, leading to positive changes in critical indicators, with long-term benefits expected for the health and livelihoods of the beneficiaries.

Strength and limitation: The study had several strengths, including a large sample size, randomization, and appropriate sampling techniques. A dedicated quality control team was involved in checking the data, and the use of precise anthropometry instruments and separate training for the measurement team helped ensure accurate data collection. The study was also designed to avoid seasonality by conducting the baseline and endline surveys at the same time of the year. However, the study results may have been impacted by a lack of selection effect in the implementation of the programme, as well as by the short time horizon of the study. The short duration of the study may not have been enough to see a significant impact on stunting. Additionally, changes in the study population between the baseline and endline surveys could also

have contributed to the lack of differences observed in the results. Another limitation of this study is that we did not collect food intake data but only recall data from the previous 24 hours. These data may be subject to recall bias; thus, caution is necessary when drawing conclusions, especially for indicators such as dietary diversity, household food insecurity, domestic violence, and maternal healthcare. Finally, using a binary indicator of stunting based on a single LAZ cut-off point, which was defined as <-2, may not provide a comprehensive assessment of the severity of malnutrition among children, as it fails to account for micronutrient deficiencies

Conclusion

Childhood stunting was heavily influenced by a number of factors, and majority of the factors were found in poor status in our study area. Despite the implementation of an intervention programme, the situation remained unchanged due to factors such as food insecurity, lack of involvement in aquaculture, poor access to WaSH facilities, and a lack of focus on maternal education and nutrition. The study did not include important indicators such as enteropathogen and environmental enteric dysfunction, which might have contributed to the failure to achieve the desired outcome. The results suggest that policy makers and programme planners should consider enhancing collaboration and coordination between nutrition-sensitive and specific activities to address nutritional deficiencies and family health programmes in vulnerable rural populations.

Acknowledgments: The study analyzed baseline survey data of *Suchana*; this intervention has been implemented by a consortium led by Save the Children, with support from the Foreign, Commonwealth and Development Office (FCDO) and European Union (EU). icddr,b acknowledges with gratitude the commitment of Save the Children, FCDO and EU to its research efforts. We also acknowledge with gratitude the commitment of the Government of the People's Republic of Bangladesh to icddr,b's research activities. We also acknowledge the following donors for providing unrestricted support to icddr,b's efforts and advancement of its strategic plan: Canada, Sweden and the United Kingdom. We gratefully acknowledge our core donors for their support and commitment to icddr,b's research efforts. We would like to acknowledge the invaluable contributions of Save the Children as lead agency, our technical partners Helen Keller International, World Fish, and International Development Enterprises, and the implementing partners Friends In Village Development Bangladesh (FIVDB), Rangpur Dinajpur Rural Services (RDRS), and the Center for Natural Resource Studies (CNRS) who played critical roles in generating and refining the data-collection tools. We would also like to acknowledge Tasnia Alam, Research Assistant and Md. Maniruzzaman, Assistant Professor, Khulna University, Khulna-9208, Bangladesh as the internal reviewers, and Andrea Devlin of Science Editing Experts for editing and linguistic revision of the manuscript.

Funding: (i) This study was made possible by the committed contribution of Foreign, Commonwealth and Development Office (Grant number: 204131-103), and (ii) icddr,b (N/A).

Conflicts of Interest: The authors declare no conflict of interest.

Author Contributions: TA and NC originated the idea for the study and led the protocol design. MAH conceptualized the manuscript. SMTA, SSR, MAH, NC, FDF, and TA contributed to the survey design. MAH performed statistical analysis and drafted the manuscript. NC and ASGF supervised the work, and critically reviewed and provided feedback for revising the manuscript. MAH, NC, MA, FDF, FN, BZW, TJS, ASGF, TA, and SSR contributed to the revision of the final draft for submission. All authors are responsible for the final content of the manuscript.

Ethics approval: This study was approved by the Research Review Committee and Ethical Review Committee, the two obligatory components of the Institutional Review Board (IRB) of icddr,b. Ethics Committee's approval ID# 00001822. Informed written consent was obtained from study participants.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

Reference

1. Bari A, Nazar M, Iftikhar A, et al. Comparison of Weight-for-Height Z-score and Mid-Upper Arm Circumference to Diagnose Moderate and Severe Acute Malnutrition in children aged 6-59 months. *Pakistan journal of medical sciences* 2019;35(2):337-41. doi: 10.12669/pjms.35.2.45 [published Online First: 2019/05/16]

2. National Institute of Population Research and Training (NIPORT), ICF. Bangladesh Demographic and Health Survey 2017-18: Key Indicators. NIPORT and ICF: Dhaka, Bangladesh and Rockville, Maryland, USA, 2019.

3. Development Initiatives. 2018 Global Nutrition Report: Shining a light to spur action on nutrition. Bristol, UK: Development Initiatives, 2018.

4. United Nations Children's Fund (UNICEF), World Health Organization, International Bank for Reconstruction and Development/The World Bank. Levels and trends in child malnutrition: Key Findings of the 2020 Edition of the Joint Child Malnutrition Estimates. Geneva: World Health Organization; 2020. Licence: CC BY-NC-SA 3.0 IGO., 2020.

5. USAID. Bangladesh: Nutrition Profile, 2018.

6. Kumar P, Rashmi R, Muhammad T, et al. Factors contributing to the reduction in childhood stunting in Bangladesh: a pooled data analysis from the Bangladesh demographic and health surveys of 2004 and 2017–18. *BMC public health* 2021;21(1):2101. doi: 10.1186/s12889-021-12178-6

7. Yaya S, Wang R, Tang S, et al. Intake of supplementary food during pregnancy and lactation and its association with child nutrition in Timor Leste. *PeerJ* 2018;6:e5935. doi: 10.7717/peerj.5935 [published Online First: 20181115]

8. Choudhury N, Raihan MJ, Sultana S, et al. Determinants of age-specific undernutrition in children aged less than 2 years-the Bangladesh context. *Maternal & child nutrition* 2017;13(3) [published Online First: 2016/10/19]

9. Nisar YB, Dibley MJ, Aguayo VM. Iron-Folic Acid Supplementation During Pregnancy Reduces the Risk of Stunting in Children Less Than 2 Years of Age: A Retrospective Cohort Study from Nepal. *Nutrients* 2016;8(2):67. doi: 10.3390/nu8020067 [published Online First: 20160127]

10. Li Z, Kim R, Vollmer S, et al. Factors Associated With Child Stunting, Wasting, and Underweight in 35 Low- and Middle-Income Countries. *JAMA Network Open* 2020;3(4):e203386. doi: 10.1001/jamanetworkopen.2020.3386 [published Online First: 20200401]

11. Katoch OR. Determinants of malnutrition among children: A systematic review. *Nutrition* 2022;96:111565. doi: 10.1016/j.nut.2021.111565 [published Online First: 20211211]

12. Huo S, Wang K, Liu Z, et al. Influence of Maternal Exposure to Mass Media on Growth Stunting Among Children Under Five: Mediation Analysis Through the Water, Sanitation, and Hygiene Program. *JMIR Public Health and Surveillance* 2022;8(4):e33394. doi: 10.2196/33394 [published Online First: 20220406]

13. Win H, Shafique S, Mizan S, et al. Association between mother's work status and child stunting in urban slums: a cross-sectional assessment of 346 child-mother dyads in Dhaka, Bangladesh (2020). *Archives of Public Health* 2022;80(1):192. doi: 10.1186/s13690-022-00948-6

14. Iannotti LL, Blackmore I, Cohn R, et al. Aquatic Animal Foods for Nutrition Security and Child Health. *Food and Nutrition Bulletin* 2022;43(2):127-47. doi: 10.1177/03795721211061924 [published Online First: 20211214]

15. Prendergast AJ, Chasekwa B, Evans C, et al. Independent and combined effects of improved water, sanitation, and hygiene, and improved complementary feeding, on stunting and anaemia among HIV-exposed children in rural Zimbabwe: a cluster-randomised controlled trial. *The Lancet Child & Adolescent Health* 2019;3(2):77-90. doi: 10.1016/s2352-4642(18)30340-7 [published Online First: 20181218]

16. Anwar F, Khomsan A, Sukandar D, et al. High participation in the Posyandu nutrition program improved children nutritional status. *Nutrition Research and Practice* 2010;4(3):208-14. doi: 10.4162/nrp.2010.4.3.208 [published Online First: 20100628]

17. Orunmoluyi OS, Gayawan E, Manda S. Spatial Co-Morbidity of Childhood Acute Respiratory Infection, Diarrhoea and Stunting in Nigeria. *International journal of environmental research and public health* 2022;19(3) doi: 10.3390/ijerph19031838 [published Online First: 20220206]

18. Haque MA, Platts-Mills JA, Mduma E, et al. Determinants of Campylobacter infection and association with growth and enteric inflammation in children under 2 years of age in low-resource settings. *Scientific reports* 2019;9(1):17124. [published Online First: 2019/11/22]

19. National Institute of Population Research and Training - NIPORT/Bangladesh, Mitra and Associates, ICF International. Bangladesh Demographic and Health Survey 2014. NIPORT, Mitra and Associates, and ICF International: Dhaka, Bangladesh and Rockville, Maryland, USA, 2016.

20. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH). State of food security and nutrition in Bangladesh 2013. HKI and JPGSPH, 2014.

21. Yaya S, Bishwajit G, Ekholuenetale M, et al. Awareness and utilization of community clinic services among women in rural areas in Bangladesh: A cross-sectional study. *PLOS ONE* 2017;12(10):e0187303. doi: 10.1371/journal.pone.0187303

22. Choudhury N, Raihan MJ, Ahmed SMT, et al. The evaluation of Suchana, a large-scale development programme to prevent chronic undernutrition in north-eastern Bangladesh. *BMC public health* 2020;20(1):744. [published Online First: 2020/05/24]

23. Haque MA, Choudhury N, Ahmed SMT, et al. The large-scale community-based programme ‘Suchana’ improved maternal healthcare practices in north-eastern Bangladesh: Findings from a cluster randomized pre-post study. *Maternal & child nutrition* 2022;18(1):e13258.

24. Coates J, Swindale A, Bilinsky P. Household Food Insecurity Access Scale (HFIAS) for measurement of food access: indicator guide (v. 3). Washington, D.C.: Food and Nutrition Technical Assistance Project, Academy for Educational Development 2007.

25. Therneau T, Atkinson B, Ripley B. rpart: Recursive partitioning and regression trees 2022 [Available from: https://cran.r-project.org/package=rpart2023.

26. Villa JM. Simplifying the estimation of difference-in-differences treatment effects. *The Stata Journal* 2016:52-71.

27. Bursac Z, Gauss CH, Williams DK, et al. Purposeful selection of variables in logistic regression. *Source code for biology and medicine* 2008;3:17.

28. Tardini E, Zhang X, Canahuate G, et al. Optimal Treatment Selection in Sequential Systemic and Locoregional Therapy of Oropharyngeal Squamous Carcinomas: Deep Q-Learning With a Patient-Physician Digital Twin Dyad. *Journal of Medical Internet Research* 2022;24(4):e29455. doi: 10.2196/29455 [published Online First: 20220420]

29. Adamker G, Holzer T, Karakis I, et al. Prediction of Shigellosis outcomes in Israel using machine learning classifiers. *Epidemiology and Infection* 2018;146(11):1445-51. doi: 10.1017/s0950268818001498 [published Online First: 20180608]

30. Weatherspoon DD, Miller S, Ngabitsinze JC, et al. Stunting, food security, markets and food policy in Rwanda. *BMC public health* 2019;19(1):882. doi: 10.1186/s12889-019-7208-0 [published Online First: 2019/07/06]

31. Agho KE, Mukabutera C, Mukazi M, et al. Moderate and severe household food insecurity predicts stunting and severe stunting among Rwanda children aged 6-59 months residing in Gicumbi district. *Maternal & child nutrition* 2019;15(3):e12767.

32. Chowdhury D. Flood situation worsens in Sylhet. *The Daily Star* 2017.

33. ACAPS. ACAPS Briefing Note: Bangladesh - Floods in Moulvibazar and Sylhet (20 June 2018): reliefweb; 2018 [Available from: https://reliefweb.int/report/bangladesh/acaps-briefing-note-bangladesh-floods-moulvibazar-and-sylhet-20-june-20182023.

34. Lin A, Arnold BF, Afreen S, et al. Household environmental conditions are associated with enteropathy and impaired growth in rural Bangladesh. *American Journal of Tropical Medicine and Hygiene* 2013;89(1):130-37. doi: 10.4269/ajtmh.12-0629 [published Online First: 20130429]

35. Amour C, Gratz J, Mduma E, et al. Epidemiology and Impact of Campylobacter Infection in Children in 8 Low-Resource Settings: Results From the MAL-ED Study. *Clinical Infectious Diseases* 2016;63(9):1171-79. doi: 10.1093/cid/ciw542 [published Online First: 08/07]

36. Smith S, Meade J, Gibbons J, et al. The impact of environmental conditions on Campylobacter jejuni survival in broiler faeces and litter. *Infect Ecol Epidemiol* 2016;6:31685-85. doi: 10.3402/iee.v6.31685

37. Chen RY, Kung VL, Das S, et al. Duodenal Microbiota in Stunted Undernourished Children with Enteropathy. *The New England Journal of Medicine* 2020;383(4):321-33. doi: 10.1056/NEJMoa1916004

38. George CM, Oldja L, Biswas SK, et al. Fecal Markers of Environmental Enteropathy are Associated with Animal Exposure and Caregiver Hygiene in Bangladesh. *American Journal of Tropical Medicine and Hygiene* 2015;93(2):269-75. doi: 10.4269/ajtmh.14-0694 [published Online First: 20150608]

39. Perin J, Burrowes V, Almeida M, et al. A Retrospective Case-Control Study of the Relationship between the Gut Microbiota, Enteropathy, and Child Growth. *American Journal of Tropical Medicine and Hygiene* 2020;103(1):520-27. doi: 10.4269/ajtmh.19-0761 [published Online First: 20200514]

40. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH). State of food security and nutrition in Bangladesh 2014. HKI and JPGSPH: Dhaka, BD, 2016.

Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline. The p-value of the *difference-in-difference* was estimated using interaction analysis in the multiple logistic regression model.

Figure 2. Results framework and *Suchana* log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

Figure 3. Factors correlating with stunting in children aged 12-23 months, computed using decision tree analysis. (X_1: Less than four ANC visits by a skilled service provider, X_2: Unskilled birth attendant/facility, X_3: Mother involved in income-generating activities, X_4: Maternal BMI <18.5, X_5: Maternal education: no schooling, X_6: Household severe food insecurity, X_7: Monthly income <15000 BDT, X_8: Did not involve with aquaculture, X_9: Having unhygienic latrine, X_{10}: Soap was unavailable in hand washing place, X_{11}: HH size≥7, X_{12}: HH dietary diversity score <7, X_{13}: Child's age>18, X_{14}: Child's sex was male, X_{15}: Childhood illness in the last 15 days, and X_{16}: Lacked access to mass media)

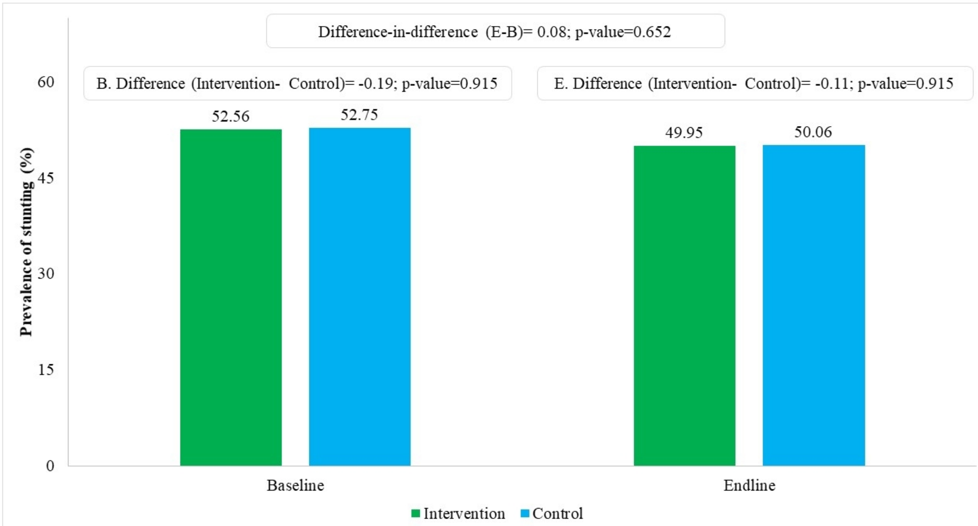


Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline. The p-value of the difference-in-difference was estimated using interaction analysis in the multiple logistic regression model.

108x60mm (300 x 300 DPI)

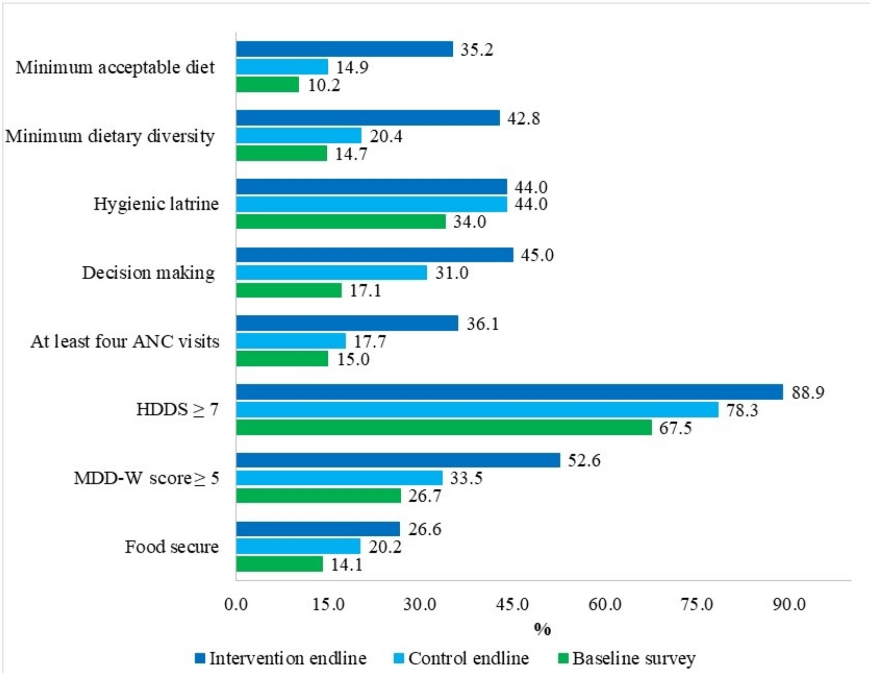


Figure 2. Results framework and Suchana log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

254x190mm (96 x 96 DPI)

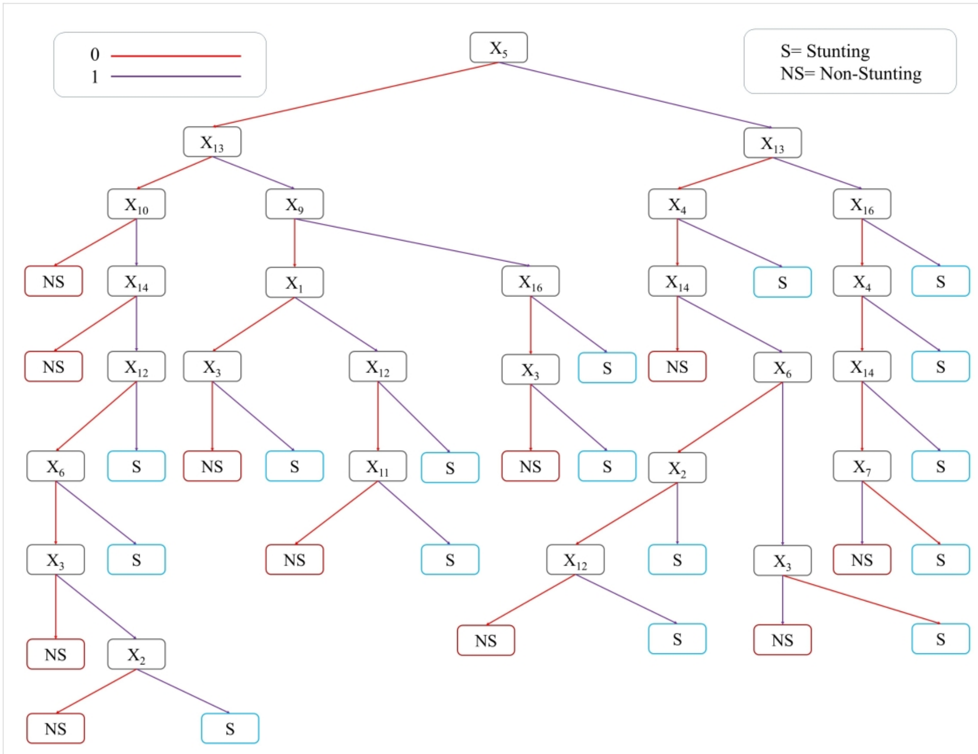


Figure 3. Factors correlating with stunting in children aged 12-23 months, computed using decision tree analysis. (X1: Less than four ANC visits by a skilled service provider, X2: Unskilled birth attendant/facility, X3: Mother involved in income-generating activities, X4: Maternal BMI <18.5, X5: Maternal education: no schooling, X6: Household severe food insecurity, X7: Monthly income <15000 BDT, X8: Did not involve with aquaculture, X9: Having unhygienic latrine, X10: Soap was unavailable in hand washing place, X11: HH size>7, X12: HH dietary diversity score <7, X13: Child's age>18, X14: Child's sex was male, X15: Childhood illness in the last 15 days, and X16: Lacked access to mass media)

325x254mm (300 x 300 DPI)

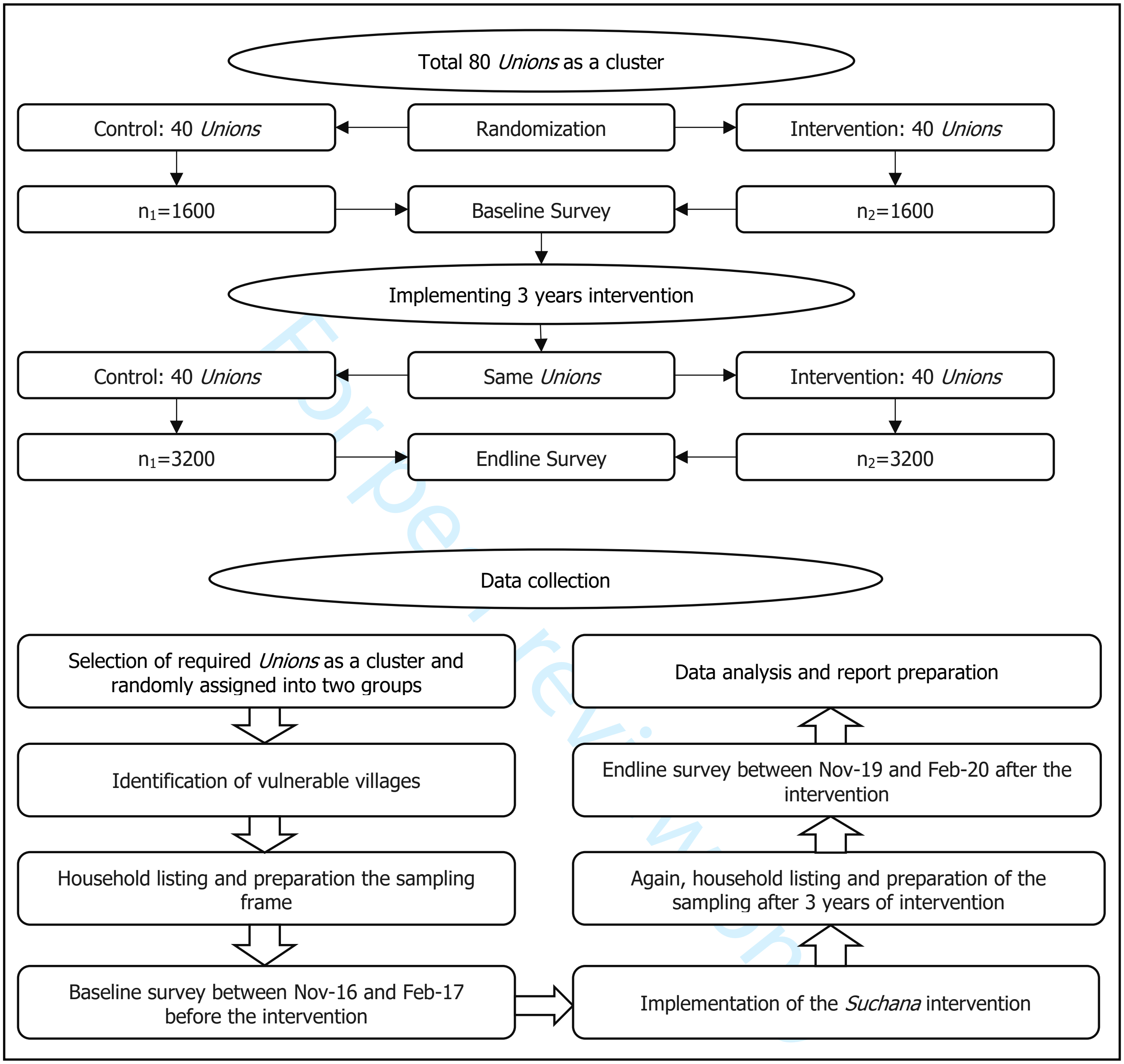
Appendix 1. Sample size calculation

```
clustersampsi, binomial samplesize p1(0.47) p2(0.41) k40) rho0.01)alpha(0.05) beta(0.8)
```

Output of the STATA command for sample size calculation

```
Sample size calculation to determine number of observations required per cluster, for a two-
sample comparison of proportions (using normal approximations) without continuity correction.

For the user specified parameters:
      p1: 0.4700
      p2: 0.4100
      significance level:  0.05
      power:  0.80
      number of clusters available:  40
      intra cluster correlation (ICC):  0.0100
clustersampsi estimated parameters:
      Firstly, assuming individual randomisation: sample size per arm: 1071
      Then, allowing for cluster randomisation: average cluster size required:  38
      sample size per arm:  1520
```



Supplementary Figure 1. The evaluation diagram of *Suchana* programme

Appendix 2. Data collection

The Suchana data collection software contained built-in validation rules. As the data were entered at the interviewer level and the records were uploaded to a server at the icddr,b using the built-in internet connectivity of the devices, maximum validation rules were set in the data system to prevent errors during data entry, which reduced the data entry burden. This allowed the data analysis team to review the

consistency of the data every day. Data were synchronized to the central server "Web Service" developed in Asp.Net based on the C# (C Sharp) code. Activities such as editing (after receiving any feedback from field staff members), updating, range checks, duplication checks, consistency checks, frequency checks and cross tabulation were regularly performed during the data entry period. In case of any unusual observations, the issues were discussed and resolved.

Appendix 3. Equation of logistic and probit regression

$$\text{logit}(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

$$\text{probit}(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

Where,

x1: Less than four ANC visits by a skilled service provider
x2: Unskilled birth attendant/facility
x3: Mother involved in income-generating activities
x4: Maternal BMI <18.5
x5: Maternal education: no schooling
x6: HH severe food insecurity
x7: Monthly income <15000 BDT
x8: Did not involve with aquaculture
x9: Having unhygienic latrine
x10: Soap was unavailable in hand washing place
x11: HH size≥7
x12: HH dietary diversity score <7
x13: Child's age>18
x14: Child's sex was male
x15: Childhood illness in the last 15 days
x16: Lacked access to mass media

and

$$\text{logit}(y) = \log[y/(1-y)]$$

Supplementary Table 1. *Suchana* inclusion criteria for registration of enrolling as vulnerable households

Vulnerable household verification questions	Inclusion criteria
Step 1 • Households currently participating/member of any livelihood, food security or asset transfer program	If "NO" go ahead for next questions
Step 2 • Ability to afford three (3) full meals per day for all family members round the year • Households monthly income BDT 7,500 or more • Household productive asset value worth BDT 15,000 or more (excluding land, pond and homestead) • Ownership of homestead land 10 decimals or more • Ownership of cultivable land 50 decimals or more (excluding homestead or pond)	If anyone is "NO" go ahead for next questions
Step 3 • Households have married women with in child bearing age (15 to 45 years) • Households have pregnant women (including abandoned or widowed woman) • Households have 0-23 months old children • Households have adolescent girls (15-19 years)	If anyone is 'Yes' go ahead for registration of enrolling as vulnerable Household
Sampling frame was prepared for collecting data from mother-child pair if the households had 0-23 months old children	

Supplementary Table 2a. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple logistic regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.07, 6.22)	0.006
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.55, 4.35)	0.012
Mother involved in income-generating activities			
No	54.55 (50.90, 58.19)	Reference	
Yes	50.59 (49.08, 52.11)	3.95 (0.40, 7.51)	0.029
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.41)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.40)	<0.001
HH food insecurity			
Below severe	53.03 (50.91, 55.15)	Reference	
Severe	50.36 (48.63, 52.09)	2.66 (0.11, 5.22)	0.041
HH monthly income ≥15000 BDT			
Yes	51.31 (49.79, 52.84)	Reference	
No	48.58 (45.86, 51.30)	2.73 (0.17, 5.30)	0.037
Involved with aquaculture			
Yes	51.22 (49.72, 52.72)	Reference	
No	46.99 (43.30, 50.69)	4.23 (0.73, 7.73)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.54 (46.74, 50.33)	4.10 (1.83, 6.38)	<0.001
HH size			
Below seven	53.86 (51.98, 55.74)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.92 (51.25, 56.60)	Reference	
HDDS <7	50.10 (48.70, 51.50)	3.83 (1.63, 6.02)	<0.001
Child's age			
Age ≤18 months	56.72 (54.77, 58.67)	Reference	
Age >18 months	46.59 (44.82, 48.35)	10.1 (7.94, 12.32)	<0.001
Child's sex			
Female	53.25 (51.17, 55.34)	Reference	
Male	48.40 (46.78, 50.03)	4.85 (2.59, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.77)	Reference	
Yes	50.49 (48.94, 52.05)	4.41 (1.48, 7.34)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.39, 50.88)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

Supplementary Table 2b. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple probit regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.08, 6.22)	0.007
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.54, 4.35)	0.011
Mother involved in income-generating activities			
No	54.55 (50.90, 58.16)	Reference	
Yes	50.59 (49.08, 52.11)	3.93 (0.39, 7.48)	0.024
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.40)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.41)	<0.001
HH food insecurity			
Below severe	53.01 (50.89, 55.12)	Reference	
Severe	50.37 (48.64, 52.10)	2.64 (0.09, 5.19)	0.042
HH monthly income ≥15000 BDT			
Yes	51.32 (49.79, 52.84)	Reference	
No	48.56 (45.84, 51.28)	2.75 (0.19, 5.32)	0.035
Involved with aquaculture			
Yes	51.22 (49.73, 52.71)	Reference	
No	46.99 (43.28, 50.69)	4.24 (0.73, 7.74)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.53 (46.74, 50.33)	4.11 (1.83, 6.39)	<0.001
HH size			
Below seven	53.86 (51.98, 55.73)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.90 (51.23, 56.57)	Reference	
HDDS <7	50.10 (48.71, 51.50)	3.79 (1.60, 5.98)	<0.001
Child's age			
Age ≤18 months	56.72 (54.76, 58.67)	Reference	
Age >18 months	46.59 (44.83, 48.35)	10.1 (7.93, 12.3)	<0.001
Child's sex			
Female	53.25 (51.17, 55.33)	Reference	
Male	48.41 (46.78, 50.03)	4.85 (2.60, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.75)	Reference	
Yes	50.50 (48.94, 52.05)	4.40 (1.47, 7.33)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.40, 50.86)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

STROBE Statement—Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1-2
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	1-2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-6
Objectives	3	State specific objectives, including any prespecified hypotheses	6
Methods			
Study design	4	Present key elements of study design early in the paper	6
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	6
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-7
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	*6-7*
Bias	9	Describe any efforts to address potential sources of bias	20
Study size	10	Explain how the study size was arrived at	7
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	8-9
		(*b*) Describe any methods used to examine subgroups and interactions	
		(*c*) Explain how missing data were addressed	
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	8-9
		(*e*) Describe any sensitivity analyses	
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	11
		(b) Give reasons for non-participation at each stage	
		(c) Consider use of a flow diagram	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	11
		(b) Indicate number of participants with missing data for each variable of interest	
Outcome data	15*	Report numbers of outcome events or summary measures	11
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	11-14

		(*b*) Report category boundaries when continuous variables were categorized	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	11-15
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
Discussion			
Key results	18	Summarise key results with reference to study objectives	17
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	20
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	17
Generalisability	21	Discuss the generalisability (external validity) of the study results	17-18
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	22

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

BMJ Open

A predictive modelling approach to illustrate factors correlating with stunting among children aged 12-23 months: a cluster randomized pre-post study

Journal:	*BMJ Open*
Manuscript ID	bmjopen-2022-067961.R5
Article Type:	Original research
Date Submitted by the Author:	30-Mar-2023
Complete List of Authors:	Haque, Md; ICDDRB Choudhury, Nuzhat; ICDDRB Wahid, Barbie Zaman; ICDDRB Ahmed, SM Tanvir ; Save the Children Bangladesh Farzana, Fahmida Dil; ICDDRB Ali, Mohammad; ICDDRB Naz, Farina; ICDDRB Siddiqua, Towfida Jahan ; Johns Hopkins University, Bangladesh Rahman, Shahed ; Save the Children Bangladesh Faruque, ASG; ICDDRB Ahmed, Tahmeed; ICDDRB
Primary Subject Heading:	Epidemiology
Secondary Subject Heading:	Public health
Keywords:	Nutrition < TROPICAL MEDICINE, EPIDEMIOLOGY, PUBLIC HEALTH

SCHOLARONE™ Manuscripts

I, the Submitting Author has the right to grant and does grant on behalf of all authors of the Work (as defined in the below author licence), an exclusive licence and/or a non-exclusive licence for contributions from authors who are: i) UK Crown employees; ii) where BMJ has agreed a CC-BY licence shall apply, and/or iii) in accordance with the terms applicable for US Federal Government officers or employees acting as part of their official duties; on a worldwide, perpetual, irrevocable, royalty-free basis to BMJ Publishing Group Ltd ("BMJ") its licensees and where the relevant Journal is co-owned by BMJ to the co-owners of the Journal, to publish the Work in this journal and any other BMJ products and to exploit all rights, as set out in our licence.

The Submitting Author accepts and understands that any supply made under these terms is made by BMJ to the Submitting Author unless you are acting as an employee on behalf of your employer or a postgraduate student of an affiliated institution which is paying any applicable article publishing charge ("APC") for Open Access articles. Where the Submitting Author wishes to make the Work available on an Open Access basis (and intends to pay the relevant APC), the terms of reuse of such Open Access shall be governed by a Creative Commons licence – details of these licences and which Creative Commons licence will apply to this Work are set out in our licence referred to above.

Other than as permitted in any relevant BMJ Author's Self Archiving Policies, I confirm this Work has not been accepted for publication elsewhere, is not being considered for publication elsewhere and does not duplicate material already published. I confirm all authors consent to publication of this Work and authorise the granting of this licence.

A predictive modelling approach to illustrate factors correlating with stunting among children aged 12-23 months: a cluster randomized pre-post study

Md Ahshanul Haque[1*], Nuzhat Choudhury[1], Barbie Zaman Wahid[1], SM Tanvir Ahmed[2], Fahmida Dil Farzana[1], Mohammad Ali[1], Farina Naz[1], Towfida Jahan Siddiqua[1], Sheikh Shahed Rahman[2], ASG Faruque[1], Tahmeed Ahmed[1]

[1] Nutrition and Clinical Services Division, icddr,b, Dhaka, 1212, Bangladesh
[2] Child Poverty Sector, Save the Children Bangladesh, Dhaka, Bangladesh

*** Correspondence:** Md Ahshanul Haque, Assistant Scientist, Nutrition and Clinical Services Division, icddr,b, 68, Shaheed Tajuddin Ahmed Sarani, Mohakhali, Dhaka 1212, Bangladesh, Email: ahshanul.haque@icddrb.org

Word count: 4977

Abstract

Objective The aim of this study was to construct a predictive model in order to develop an intervention study to reduce the prevalence of stunting among children aged 12-23 months.

Design The study followed a cluster randomized pre-post design and measured the impacts on various indicators of livelihood, health, and nutrition. The study was based on a large dataset collected from two cross-sectional studies (baseline and endline).

Setting The study was conducted in the north-eastern region of Bangladesh under the Sylhet division, which is vulnerable to both natural disasters and poverty. The study specifically targeted children between the ages of 12 and 23 months.

Main outcome measures Childhood stunting, defined as a length-for-age z-score (LAZ)<-2, was the outcome variable in this study. Logistic and probit regression models and a decision tree were constructed to predict the factors associated with childhood stunting. The predictive performance

of the models was evaluated by computing the area under the receiver operating characteristic (ROC) curve analysis.

Results The baseline survey showed a prevalence of 52.7% stunting, while 50.0% were stunted at endline. Several factors were found to be associated with childhood stunting. The model's sensitivity was 61% and specificity was 56%, with a correctly classified rate of 59% and an area under the ROC curve of 0.615.

Conclusion The study found that childhood stunting in the study area was correlated with several factors, including maternal nutrition and education, food insecurity, and hygiene practices. Despite efforts to address these factors, they remain largely unchanged. The study suggests that a more effective approach may be developed in future to target adolescent mothers, as maternal nutrition and education are age-dependent variables. Policymakers and programme planners need to consider incorporating both nutrition-sensitive and specific activities and enhancing collaboration in their efforts to improve the health of vulnerable rural populations.

Study registration: RIDIE-STUDY-ID-5d5678361809b

Keywords: Childhood stunting, Chronic malnutrition, Global public health, Logistic regression, Probit regression, Decision tree

Strengths and limitations of this study

- The study used a combination of parametric and non-parametric predictive models to estimate the effect size of the independent variables and identify significant correlates of childhood stunting
- The study was designed to mitigate the potential impact of seasonal factors by conducting the baseline and endline surveys at the same time of the year
- A binary indicator of stunting based on a single LAZ cut-off point (<-2) may not provide a complete evaluation of the severity of malnutrition among children as it does not consider micronutrient deficiencies

- Use of recall data from the previous 24 hours for dietary diversity, household food insecurity, domestic violence, and maternal healthcare may be subject to recall bias
- Biological data has not been collected such as enteropathogen and environmental enteric dysfunction, which could have been related to childhood stunting

Introduction

Childhood stunting, which is defined as length-for-age z-score (LAZ)<-2, is a major concern for public health and has been widely used as an indicator of chronic malnutrition in children.[1 2] Although childhood stunting scenarios have much improved globally, the prevalence of childhood stunting is still very high in low-resource settings, including countries such as Bangladesh. According to the 2018 Global Nutrition Report, 150.8 million children (22.2%) under five years-of-age are stunted globally, compared to 198.4 million (32.6%) and 165 million children in 2000 and 2011, respectively.[3 4] Between 2000 and 2018, Asian countries have experienced a decrease in the rate of stunting among children under five from 38.1% to 23.2%. However, South Asia still has the highest prevalence of stunting in the region, with a rate of 38.9% in 2018.[3] In Bangladesh, about 5.5 million (36%) children under five were stunted in 2014,[5] however by 2018, childhood stunting has reduced to about 31%.[2] As the World Health Organization (WHO) considers a childhood stunting rate of 15% to be an emergency situation, the current prevalence of childhood stunting in Bangladesh reflects an alarming situation of chronic undernutrition.[6]

Literature suggests that children are at a higher prevalence of stunting if their mothers do not receive adequate antenatal care, fail to rest sufficiently, do not consume additional food, and neglect to take iron-folic acid (IFA) tablets during pregnancy.[7-9] Additionally, maternal and child health are correlated with mass media exposure, receiving a vitamin A capsule, having a skilled birth attendant, and maternal education.[6 8 10-12] Children in poor households in Bangladesh are more likely to experience stunted growth if their mothers are employed, as there are inadequate day-care centres available for the children, leading to insufficient breastfeeding.[13] Moreover, evidence suggests that a number of characteristics at the household level, which relate to both children and mothers, can influence childhood stunting. The characteristics of the household head, household food insecurity and lower dietary diversity, household lower-income, household involvement in several earning activities, availability of sanitation facility at home, hand-washing status, family size, religion, and receive several types of allowance from government are most often reported to be associated with stunting in the literature.[6 8 11 14-16]

Based on child characteristics, several indicators are associated with stunting. This status is associated with two basic characteristics: a child's gender and age.[8] Children are commonly affected by the co-occurrence of illness in low- and middle-income countries, which is one of the most common causes of stunting.[17] Inadequate infant and young child feeding (IYCF) practices also reduce child growth.[8 15] However, these findings are mostly based on nationally representative cross-sectional and cohort studies, or studies conducted in urban settings.[18 19] Therefore, a knowledge gap exists on whether similar results would be obtained when nationwide data are compared with data for study populations from poor or very poor rural households in specific vulnerable regions.

Sylhet is one such vulnerable region of north-east Bangladesh, comprising diverse terrains such as plain land, hilly land, *Haor* (wetland), and flash flood-prone areas. This region is reported to perform poorly for all important maternal healthcare indicators,[20] despite the fact that Bangladesh has made substantial progress in improving the overall health of the population.[21] Moreover, the socio-economic profile of the inhabitants in Sylhet region includes both very rich and extremely poor people. This scenario may worsen without the implementation of appropriate strategies in the near future. Sylhet region is also performing poorly compared to the national averages for a number of health and nutritional indicators. Critical indicators such as the infant mortality rate and unemployment status of women are high.[19] In comparison to the overall situation of Bangladesh, where stunting among children under five has decreased, the Bangladesh Demographic and Health Survey (BDHS) 2014 indicates the prevalence of childhood stunting in Sylhet is astonishingly high, at 50%.[19] This alarming figure provided the rationale for implementation of a comprehensive intervention programme in this region. A large-scale nutrition programme, *Suchana: Ending the Cycle of Undernutrition in Bangladesh; a multi-sectoral nutrition programme,* was undertaken with the aim to prevent chronic malnutrition in Sylhet.

In general, *Suchana* nutrition interventions can be divided into two types: nutrition-sensitive and nutrition-specific.[22] The concept of nutrition-sensitive intervention refers to an intervention that benefits the beneficiaries in terms of food and nutrition security, and also influences the underlying determinants of nutrition. This type of intervention is largely delivered through the agricultural sector (homestead vegetable and fruit production, pro-poor nutrition-sensitive aquaculture), improved technology (mono-sex tilapia and carp-tilapia polyculture, subsistence fishing, fish drying), demonstrations (village model farms and demo ponds, livestock, food security, promotion of climate-smart technologies), and supported income-generating activities (skill development in business management, engagement with the private sector and other sectors). As nutrition-specific interventions were delivered through nutrition-sensitive interventions, their coverage, effectiveness, and scale can be increased. It can meet the targets by lowering them and implementing nutrition-specific interventions. A nutrition-specific intervention addresses the immediate cause of malnutrition. Direct determinants of nutrition are the focus of this intervention. There is a strong focus on nutrition-specific interventions in the health sector. Whether implemented alone or jointly, nutrition-specific interventions improve health outcomes. Some examples of nutrition-specific interventions are: counselling for mothers at the household level, community-based nutrition education for spouses and in-laws, growth monitoring and promotion sessions integrated with *Expanded Programme on Immunization* in communities, *Government of Bangladesh* health facilities equipped with *severe acute malnutrition* service delivery, and support for *National Nutrition Services* service delivery through community clinics, Union Health and Family Welfare Centers, and Upazila health complexes.

The primary objective of the *Suchana* programme was to reduce the prevalence of childhood stunting in the intervention areas. The secondary objectives were to assess the changes in *Suchana* beneficiaries' households, in terms of an increase and diversification of household income, food security status, optimal IYCF practices, haemoglobin status of children, the empowerment of women, and adolescents' nutritional knowledge and practices.[22]

The *Suchana* programme substantially improved nutritional behaviour, maternal healthcare practices, women's empowerment, household income, and household food security in the intervention area compared to the control area.[23] Contrary to predictions, however, *Suchana* did not result in any significant reduction in the prevalence of childhood stunting. Therefore, although most other factors related to childhood stunting improved, this raises the question of why the prevalence of stunting did not reduce after the intervention. An important observation from the *Suchana* survey was that the proportion of households in this study population using hygienic latrines was quite low. This factor was associated with stunting in children,[8] and did not significantly improve by endline in the intervention areas compared to the control areas.

In this study, we aimed to construct a predictive model to attempt to explain whether any improvements in associated factors may promote a significant reduction in stunting among children aged 12-23 months from poor and extremely poor households in the Sylhet region.

Methods

Study design and setting

The *Suchana* programme was implemented in 157 *Unions* over 20 sub-districts in the Sylhet region in the north-east of rural Bangladesh. The *Suchana* programme's protocol has been thoroughly explained elsewhere.[22] *Union*, the smallest local government and administrative entity in rural Bangladesh, was considered as a cluster and divided into four phases at random. Phase-1 was designated as the intervention group, while Phase-4 was the control group, and the other phases were treated as learning phases.[22] For implementation purposes, vulnerable villages were selected within Phase-1 and Phase-4 areas. The staff of the programme chose vulnerable villages in each *Union* based on their vulnerability (e.g., frequent floods or submerging, little or no intervention from other development programmes, poverty or household living circumstances, remoteness and accessibility issues, a high prevalence of superstitions and social taboos). After consultation with the local government representatives, elected officials, and local elites as well as field visits, this selection method was decided upon. The impacts of the intervention on livelihood, health, and nutrition were measured using a pre-post design. A large dataset was collected from two cross-sectional surveys (baseline and endline) under this study. The baseline survey was conducted in November 2016 and February 2017, followed by the endline survey in the same months three years later among the same population and different participants (Supplementary Figure 1).

Outcome variable

The outcome variable in this study was childhood stunting, which was defined as a length-for-age z-score (LAZ)<-2.[2]

Independent variables

Initially, a list of independent variables was finalized through results obtained from descriptive and bi-variate analyses, as well as a comprehensive literature review (Table 1). These included at least four antenatal care (ANC) visits by a skilled service provider, additional resting during pregnancy, additional food consumption during pregnancy, consumption of at least 100 IFA tablets during pregnancy, receiving vitamin A capsule after last delivery, birth attendant/facility, mother involved in income-generating activities, maternal BMI, maternal education, household food insecurity, household monthly income >15000 BDT, involved with aquaculture, hygienic latrine, water and soap available in handwashing place, household size, household dietary diversity, sex of household head, religion, received any grant/allowance/stipend from the government, access of mass media, child's age, child's sex, childhood illness in the last 15 days, minimum dietary diversity, early initiation of breastfeeding, and received colostrum. Household food insecurity access scale was measured using the Food and Nutrition Technical Assistance's Guideline, which categorizes household food insecurity into four levels: a) food secure, b) mildly food insecure, c) moderately food insecure, and d) severely food insecure.[24] In the analysis herein, this indicator was redefined as a binary indicator: severely food insecure or not severely food insecure.

Sample size

The sample size for this study was calculated with the STATA "*clustersampsi*" command module, considering the number of clusters in the surveys and considering the expected prevalence of childhood stunting in the control group (Supplemental Appendix 1). It was estimated that the expected prevalence of stunting was 47%, which was hypothesized to be reduced to 41% after three years of intervention. A sample size of 1520 per arm was calculated based on a 5% level of significance, 80% power, 40 clusters per arm, and an intra-cluster correlation coefficient (ICC) of 0.01. After rounding, the estimated sample size per arm was 1620, and the total sample size was 3200 at baseline, with an equal number of participants in the control and intervention groups. For evaluation purposes, the sample size at endline was doubled to ensure a stratified intervention component, resulting in a total sample size of 9600 mother-child pairs (baseline: 3200 and endline: 6400).[22]

Sampling

The baseline and endline surveys were conducted in a total of eight and twelve villages respectively, which were randomly selected from each *Union* using a list of vulnerable villages provided by Save the Children. The most vulnerable households were identified and verified using the inclusion criteria of the *Suchana* programme (Supplementary Table 1). These households were then given an identification number to prepare the sampling frame and required households were systematically selected for the surveys from the frame. The method of data collection is explained in detail in the Supplemental Appendix 2.

Statistical analysis

General characteristics: Stata-14 software (StataCorp LP, College Station, TX, USA) and R 4.2.2 (*rpart*)[25] were used to analyse the data. Bar diagram was used for data visualization. Descriptive statistics, such as frequency and proportions for categorical variables and mean and standard deviations for quantitative variables, were used to summarize the data at baseline and endline. Cross-tabulation was used to present that outcome variable segregated by intervention and control group at baseline survey as well as the endline survey. The *difference in difference* method was used to estimate the contrast of an intervention by comparing the difference in the outcomes between an intervention group and a control group before and after the intervention.[26]

Predictive model: Three statistical models were used as predictive models. Two parametric models, such as Logistic and Probit regression models, and Decision Tree as a non-parametric model. Logistic and Probit regression models were used as predictive models as well as classifier models. The models were also used to investigate which factors were significantly associated with childhood stunting, and estimate their effect size, in order to predict whether changes in behavioural practices might potentially help to achieve targeted reductions in stunting. Using those variables, a decision tree was applied, and the predictive performance was compared to other models.

For the parametric models, first, Chi-Square test was used to examine the bivariate associations between stunting and all possible explanatory variables. In the second step, variables with *p*-values <0.25 in the simple model were included in the multiple regression models.[27] In the final step, any independent variables thought to be likely predictors were added to the multiple regression model using the stepwise forward selection method. Some indicators, e.g., age, sex, and maternal nutritional status were added regardless of their *p*-value due to their scientific plausibility. The mathematical equation of logistic and probit regression models were given in the Supplemental Appendix 3. As a cluster variable, *Union* was used to adjust the standard errors. Furthermore, for the explanation of the regression model, a *p*-value <0.05 was considered as statistically significant, and the confidence interval (CI) of 95% was also reviewed. From the fitted model, the adjusted effect size (adjusted prevalence difference) against all predictors was estimated using the "*adjrr*" package in Stata. The list of independent variables with the value labels used in the model is given in Table 1.

Table 1. List of all independent variables

Indicators	Code	Stunting Status*	Selection in the model
At least four ANC visits by a skilled service provider			Selected
At least four ANC visits by a skilled service provider	0		
Less than four ANC visits by a skilled service provider	1	Higher prevalence[8]	
Additional resting during pregnancy			Not selected
Took more rest	0		
Did not take more rest	1	Higher prevalence[8]	
Additional food consumption during pregnancy			Not selected
Consumed more food	0		
Did not consumed more food	1	Higher prevalence[7,8]	
Consumption of at least 100 IFA tablets during pregnancy			Not selected
Consumed at least 100 IFA tablets	0		
Did not consumed at least 100 IFA tablets	1	Higher prevalence[9]	
Received vitamin A capsule after last delivery			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	
Birth attendant/facility			Selected
Skilled	0		
Unskilled	1	Higher prevalence[10]	
Mother involved in income-generating activities			Selected
No	0		
Yes	1	Higher prevalence[6,13]	
Maternal BMI			Selected
BMI ≥18.5	0		
BMI <18.5	1	Higher prevalence[6,11]	
Maternal education			Selected

At least one-year formal education	0		
No schooling	1	Higher prevalence[6 11]	
Access of mass media			Selected
Access	0		
No access	1	Higher prevalence[12]	
Household food insecurity			Selected
Below severe	0		
Severe	1	Higher prevalence[8]	
Household monthly income ≥15000 BDT			Selected
≥15000 BDT	0		
<15000 BDT	1	Higher prevalence[11]	
Involved with aquaculture			Selected
Involved	0		
Did not involved	1	Higher prevalence[14]	
Hygienic latrine			Selected
Hygienic latrine	0		
Unhygienic latrine	1	Higher prevalence[6 11 15]	
Water and soap available in handwashing place			Selected
Available	0		
Unavailable	1	Higher prevalence[15]	
Household size			Selected
Below seven	0		
Seven or above	1	Higher prevalence[11]	
Household dietary diversity (HDDS)			Selected
HDDS ≥7	0		
HDDS <7	1	Higher prevalence[8]	
Sex of household head			Not selected
Female	0		
Male	1	Higher prevalence[8]	
Household head education			Not selected
At least one-year formal education	0		
No schooling	1	Higher prevalence[6]	
Religion			Not selected
Muslim	0		
Non-Muslim	1	Lower prevalence[6]	
Received any grant/allowance/stipend from the government			Not selected
Received	0		
Did not receive	1	Higher prevalence[16]	
Child's age			Selected
Age ≤18 months	0		
Age >18 months	1	Higher prevalence[8]	
Child's sex			
Female	0		
Male	1	Higher prevalence[8]	
Childhood illness in the last 15 days			Selected
No	0		
Yes	1	Higher prevalence[17]	
Minimum dietary diversity			Not selected
Received	0		
Did not receive	1	Higher prevalence[8 15]	
Early initiation of breastfeeding			Not selected
Received	0		
Did not receive	1	Higher prevalence[8]	

Received colostrum			
Received	0		Not selected
Did not receive	1	Higher prevalence[8]	

[1]Expected effects based on findings of the literature

Model evaluation: The predictive performance of the three statistical models was evaluated by computing model sensitivity and specificity, and calculating the area under the receiver operating curve (ROC) analysis. To ensure accurate results, the data was randomly split into a training set (75%) and a test set (25%) using a random-number seed 113843. The same training and test datasets were used for evaluating the performance of all algorithms to ensure consistency in the results. The sensitivity and specificity values, as well as the area under the ROC curve, were used to determine the overall accuracy of the algorithms in predicting childhood stunting.[28 29]

Patient and public involvement

Patients and public were not actively involved in formulating the research question and or protocol development, including the outcome measures. To expedite the field implementation, however, local elites e.g. teachers, religious persons, and local government council members were informed about the study.

Results

General characteristics: Out of 9600 cases, 9501 cases were found to be available. The refusal rate was around 1%. With respect to the outcome indicator, stunting in children aged 12-23 months, 52.7% of children were stunted at the baseline survey (intervention group: 52.6%; control group: 52.8%), whereas the proportion of children exhibiting stunting at endline was 50.0% (intervention: 49.9%; control: 50.1%; Figure 1). At both the baseline and endline surveys, there was no significant difference in proportion between intervention and control areas. The *difference-in-difference* in outcomes over time was also insignificant.

Figure 2 describes several other indicators related to maternal and child health, including the status of consuming a minimum acceptable diet (intervention: 35.2%; control: 14.9%), minimum dietary diversity (intervention: 42.8%; control: 20.4%), maternal decision-making (intervention: 45.0%; control: 31.0%), at least four maternal ANC visits by a skilled service provider (intervention: 36.1%; control: 17.7%), minimum dietary diversity for women (intervention: 52.6%; control:

33.5%), a household dietary diversity score of at least seven (intervention: 88.9%; control: 78.3%), and household food security status (intervention: 26.6%; control: 20.2%). Results from the endline survey showed that these indicators were significantly improved in the intervention group compared to the control group. However, the availability of hygienic latrines did not increase in the intervention group (intervention: 44.0%; control: 44.0%). Table 2 shows the households' socio-demographic characteristics, women's general characteristics, and children's characteristics at baseline and endline.

Table 2. General characteristics of the *Suchana* beneficiaries

Indicators, *n* (%)		Baseline *N*=3200	Endline *N*=6301	Total *N*=9501
At least four ANC visits by a skilled service provider				
	Yes	408 (12.8)	1530 (24.3)	1938 (20.4)
	No	2792 (87.2)	4771 (75.7)	7563 (79.6)
Delivery at skilled birth attendant/facility				
	Yes	1000 (31.2)	2769 (44.0)	3769 (39.7)
	No	2200 (68.8)	3532 (56.0)	5732 (60.3)
Access of mass media				
	Access	563 (17.59)	1169 (18.55)	1732 (18.23)
	No access	2637 (82.41)	5132 (81.45)	7769 (81.77)
Mother involved in income-generating activities				
	No	3102 (96.9)	5665 (89.9)	8767 (92.2)
	Yes	98 (3.1)	639 (10.1)	737 (7.8)
Maternal BMI				
	BMI ≥18.5	1859 (58.1)	4073 (64.6)	5932 (62.4)
	BMI <18.5	1341 (41.9)	2231 (35.4)	3572 (37.6)
Mother completed primary education				
	Yes	1721 (53.8)	3808 (60.4)	5529 (58.2)
	No	1479 (46.2)	2496 (39.6)	3975 (41.8)
Maternal age				
	Age <30 years	2145 (67.0)	3559 (56.5)	5704 (60.0)
	Age ≥30 years	1055 (33.0)	2745 (43.5)	3800 (40.0)
Type of delivery				
	Normal	2879 (90.0)	5529 (87.8)	8408 (88.5)
	Caesarean	321 (10.0)	772 (12.3)	1093 (11.5)
PNC				
	No	2152 (67.3)	4128 (65.5)	6280 (66.1)
	Yes	1048 (32.8)	2173 (34.5)	3221 (33.9)
Household severely food insecure				
	Yes	912 (28.5)	1016 (16.1)	1928 (20.3)
	No	2288 (71.5)	5285 (83.9)	7573 (79.7)
Household monthly income ≥15000 BDT				
	Yes	424 (13.2)	1015 (16.1)	1439 (15.1)
	No	2776 (86.8)	5289 (83.9)	8065 (84.9)

Household involved with aquaculture			
Yes	161 (5.0)	561 (8.9)	722 (7.6)
No	3039 (95.0)	5740 (91.1)	8779 (92.4)
Hygienic latrine			
Yes	1121 (35.0)	2782 (44.1)	3903 (41.1)
No	2079 (65.0)	3519 (55.9)	5598 (58.9)
Water and soap available in handwashing place			
Yes	862 (26.9)	3170 (50.3)	4032 (42.4)
No	2338 (73.1)	3131 (49.7)	5469 (57.6)
Household savings			
No	1080 (33.8)	2876 (45.6)	3956 (41.6)
Yes	2120 (66.2)	3425 (54.4)	5545 (58.4)
Sex of household head			
Female	110 (3.4)	501 (8.0)	611 (6.4)
Male	3090 (96.6)	5799 (92.0)	8889 (93.6)
Source of drinking water			
Tube well	2748 (85.9)	5713 (90.7)	8461 (89.0)
Others	452 (14.1)	588 (9.3)	1040 (11.0)
Household dietary diversity score			
HDDS ≥7	2182 (68.2)	5322 (84.5)	7504 (79.0)
HDDS <7	1018 (31.8)	979 (15.5)	1997 (21.0)
Household monthly income (Thousand BDT)[1]	6.7 (5, 10)	7.5 (5.1, 10.8)	7.1 (5, 10.4)
Per capita income (Thousand)[1]	2.6 (1.8, 3.7)	2.9 (2, 4.1)	2.8 (2, 4)
Household size[1]	6.2±2.4	5.9±2.1	6±2.2
Child's age in months[2]	17.9±3.5	17.3±3.6	17.5±3.6
Length-for-age z-score[2]	-2.1±1.2	-2±1.1	-2±1.1
Weight-for-age z-score[2]	-1.7±1.1	-1.5±1.0	-1.5±1.0
Weight-for-length z-score[2]	-0.9±1.0	-0.7±0.9	-0.7±1.0
Child's age			
Age <18 months	1745 (54.5)	3710 (58.9)	5455 (57.4)
Age ≥18 months	1455 (45.5)	2594 (41.1)	4049 (42.6)
Child's sex			
Female	1567 (49.0)	3044 (48.3)	4611 (48.5)
Male	1633 (51.0)	3257 (51.7)	4890 (51.5)
Childhood illness in the last 15 days			
Yes	2867 (89.6)	5763 (91.5)	8630 (90.8)
No	333 (10.4)	538 (8.5)	871 (9.2)

[1]Median (IQR); [2]Mean ± SD

Correlated factors: The study used two parametric predictive models to determine the correlates of childhood stunting. The results, presented in Table 3, showed the adjusted odds ratios (aOR) computed from multiple logistic regression and the adjusted coefficients computed from multiple probit regression. These results provide important insights into the factors that increase the odds of stunting in childhood, and can inform public health interventions aimed at reducing stunting and improving child health. The aORs provide a quantitative measure of the relationship between different factors and childhood stunting, adjusting for *Union* as cluster variable. Understanding the correlates of childhood stunting is critical for addressing this important public health issue and improving the health and well-being of children globally. The results of this study show that a number of maternal, household and children factors were correlated with an increased prevalence of stunting in children. Children of mothers who did not receive at least four ANC visits from a skilled service provider had 1.16 times higher odds of stunting (95% CI: 1.05, 1.30; p-value=0.005). Children of mothers who gave birth with an unskilled birth attendant or facility had 1.11 times higher odds of stunting (95% CI: 1.02, 1.20; p-value=0.012). The odds of stunting were 1.18 times higher in children whose mothers were involved in income-generating activities (95% CI: 1.02, 1.37; p-value=0.030), 1.23 times higher in children of underweight mothers (95% CI: 1.12, 1.36; p-value<0.001), and 1.31 times higher in children of low-educated mothers (95% CI: 1.20, 1.42; p-value<0.001). Furthermore, the lack of exposure to mass media was also found to be associated with stunting, with odds of 1.15 (95% CI: 1.02, 1.30; p-value=0.025) times higher. Children from households with severe food insecurity, lower-income households, households not involved in aquaculture, and households with low dietary diversity, were more likely to be stunted, with odds increasing by 1.12 (95% CI: 1.00, 1.24; p-value=0.041), 1.12 (95% CI: 1.01, 1.25; p-value=0.037), 1.19 (95% CI: 1.03, 1.38; p-value=0.018), and 1.17 (95% CI: 1.07, 1.29; p-value=0.001) times, respectively. The results also showed that the odds of stunting increased with increasing household size (95% CI: 1.11, 1.31; p-value<0.001), the absence of a hygienic latrine (95% CI: 1.10, 1.30; p-value<0.001), the absence of water and soap in the handwashing place (95% CI: 1.08, 1.30; p-value<0.001), increasing child age (95% CI: 1.39, 1.67; p-value<0.001), and being male (95% CI: 1.11, 1.34; p-value<0.001). The odds of stunting were also 1.20 times higher in children with acute illness (95% CI: 1.06, 1.36; p-value=0.003). The logistic and probit regression models were employed to predict stunting in a sample of 9501 individuals. Both models were found to be significant, with log-likelihoods of -6387.94 and -6388.02, respectively, and significant Wald chi-square statistics (p-value < 0.001). Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) are given in Supplementary Table 2a and 2b. The Factors correlating with childhood stunting, as determined by using a decision tree as a non-parametric predictive model, are also presented in Figure 3. The decision tree result suggests that maternal education was the most important variable in predicting childhood stunting, as it was the main root node. The other variables, such as maternal nutrition, hand washing indicators, and hygienic latrine, were also important, as they were next root node variables. This tree model can be used to predict the childhood stunting status with relative ease.

Table 3. Factors correlating with stunting in children aged 12-23 months, computed using logistic and probit regression analyses

Indicators	Logistic		Probit	
	Adjusted OR (95% CI)	p-value	Adjusted Coef. (95% CI)	p-value
At least four ANC visits by a skilled service provider				
Yes	Reference		Reference	
No	1.16 (1.05, 1.30)	0.005	0.09 (0.03, 0.16)	0.005
Birth attendant/facility				
Skilled	Reference		Reference	
Unskilled	1.11 (1.02, 1.20)	0.012	0.06 (0.01, 0.11)	0.012
Mother involved in income-generating activities				
No	Reference		Reference	
Yes	1.18 (1.02, 1.37)	0.030	0.10 (0.01, 0.19)	0.030
Maternal BMI				
BMI ≥18.5				
BMI <18.5	1.23 (1.12, 1.36)	0.000	0.13 (0.07, 0.19)	0.000
Maternal education was primary completed				
Yes	Reference		Reference	
No	1.31 (1.20, 1.42)	0.000	0.17 (0.12, 0.22)	0.000
Access of mass media				
Yes	Reference		Reference	
No	1.15 (1.02, 1.30)	0.025	0.09 (0.01, 0.16)	0.025
Household food insecurity				
Below severe				
Severe	1.12 (1.00, 1.24)	0.041	0.07 (0.00, 0.13)	0.042
Household monthly income ≥15000 BDT				
Yes	Reference		Reference	
No	1.12 (1.01, 1.25)	0.037	0.07 (0.00, 0.14)	0.035
Involved with aquaculture				
Yes	Reference		Reference	
No	1.19 (1.03, 1.38)	0.018	0.11 (0.02, 0.20)	0.018
Household size				
Below seven	Reference		Reference	
Seven or above	1.20 (1.11, 1.31)	0.000	0.12 (0.06, 0.17)	0.000
Hygienic latrine				
Yes	Reference		Reference	
No	1.20 (1.10, 1.30)	0.000	0.11 (0.06, 0.16)	0.000
Water and soap available in handwashing place				
Yes	Reference		Reference	
No	1.19 (1.08, 1.30)	0.000	0.11 (0.05, 0.16)	0.000
Household dietary diversity				
HDDS ≥7	Reference		Reference	
HDDS <7	1.17 (1.07, 1.29)	0.001	0.10 (0.04, 0.16)	0.001
Child's age				
Age ≤18 months	Reference		Reference	
Age >18 months	1.52 (1.39, 1.67)	0.000	0.26 (0.2, 0.32)	0.000

Child's sex					
	Female	Reference		Reference	
	Male	1.22 (1.11, 1.34)	0.000	0.13 (0.07, 0.18)	0.000
Childhood illness in the last 15 days					
	No	Reference		Reference	
	Yes	1.20 (1.06, 1.36)	0.003	0.11 (0.04, 0.19)	0.003
Sample size and regression diagnostic values for logistic and probit regression analyses		n = 9501 Log-likelihood = -6387.94 Wald chi2(17) = 427.79 p-value<0.001 Pseudo R^2 = 0.0298		n = 9501 Log-likelihood = -6388.02 Wald chi2(17) = 441.18 p-value<0.001 Pseudo R^2 = 0.0298	

Unions were adjusted as clusters. Baseline and endline were adjusted as time variables

Predictive performance: Table 4 describes the model validation based on sensitivity, specificity, and whether the model was correctly classified for the overall dataset, as well as the training and test datasets. The sensitivity and specificity of the model were around 60% and 55%, respectively for all models. The correctly classified rate was 59%, and the area under the ROC curve was around 61%. We found that these values were approximately equal among the three datasets (main, training, and test datasets); however, the predictive performance of the model was low.

Table 4. Predictive performance of the model for stunting based on classification, sensitivity, and specificity in the full, training and test datasets with area under the receiver operating characteristic curve analysis

	Logistic regression	Probit regression	Decision tree
Full dataset			
Overall accuracy	58.46	58.38	56.51
Sensitivity	61.21	61.25	61.15
Specificity	55.61	55.41	51.70
Area under the curve	61.54	61.54	56.72
Training Dataset			
Overall accuracy	58.83	58.62	57.66
Sensitivity	61.59	61.70	63.93
Specificity	55.36	55.42	51.61
Area under the curve	61.37	61.37	58.44
Test Dataset			
Overall accuracy	58.11	58.19	56.67
Sensitivity	60.23	60.23	61.58
Specificity	55.90	56.07	51.94
Area under the curve	61.76	61.77	58.01

Discussion

In an effort to understand why the *Suchana* programme was not effective in reducing the prevalence of childhood stunting, this study analyzed data from both the baseline and endline surveys of the programme. The analysis aimed to identify the factors that were significantly correlated with stunting and to evaluate the model's predictive performance. After controlling for the *Union* as a cluster variable, the study found several indicators that were significantly related to stunting. These included the number of ANC visits by a skilled service provider, household dietary diversity, household food security, and household monthly income, all of which improved after the intervention. However, it was noted that the household food security status did not reach the target value of 50%, despite being an important factor associated with childhood stunting.[8 30 31] On the other hand, other outcome indicators of the *Suchana* programme, such as the dietary diversity of children, maternal dietary diversity, and maternal empowerment, despite reaching their target values, were not found to be associated with stunting in this study.

The study found that while the *Suchana* programme showed improvement in certain programme indicators, it did not lead to a significant reduction in childhood stunting. Despite efforts to address key factors such as maternal nutrition and education, household food security, and hygiene practices, these factors remained largely unchanged. However, the study suggests that interventions aimed at adolescent mothers may be more effective in improving maternal nutrition and education, since these are age-dependent variables. Additionally, the results of the study were also impacted by natural disasters in 2017, including heavy rains and flooding in the Sylhet region, which resulted in widespread damage to agriculture, aquaculture, and homes in the study population.[32 33]

The study found a contradictory relationship between stunting and maternal involvement in income-generating activities, with a higher prevalence of stunting observed among children whose mothers were engaged in various earning activities. Although there was a slight increase in the proportion of mothers involved in income-generating activities after the intervention, the lack of childcare support for working mothers resulted in a marked rise in childhood stunting among low-income households. It is important to address this issue by providing adequate childcare support measures for working mothers from poor families to ensure that the child's essential needs are not impacted by the mother's employment status.[13] Additionally, efforts should be made to increase awareness among working mothers regarding the importance of child health and nutrition. This can be achieved through targeted education and outreach programmes that provide information on proper child feeding practices, hygiene, and health-seeking behaviours.

The literature suggests that environmental enteropathy may contribute to poor growth among children in rural Bangladesh and may represent an important factor affecting the study population in the *Suchana* programme.[34] Although it was not specifically assessed in this study, indicators such as unsanitary latrines, unimproved floors, a lack of handwashing practices, and low education levels were available.[18 35] Improving Water, Sanitation and Hygiene (WaSH) variables, particularly latrine facilities and handwashing practices, may help reduce the burden of stunting in young children. One of the components of the intervention was poultry, but our qualitative findings revealed that many households shared living spaces with poultry, ducks, or other animals, which could increase the risk of infections with *Campylobacter* species, a leading food-borne pathogen.[18 36] Previous studies have shown a strong association between stunting and enteropathy among children who do not respond to nutritional interventions, and findings from rural Bangladesh have linked environmental conditions and stunting in children.[37-39] While assessing environmental enteropathy was beyond the scope of the *Suchana* evaluation, collecting data on indicators of enteropathy in the intervention and control areas could help evaluate the impact of appropriate interventions in the future. The failure to achieve the desired outcome may have been due to several factors, including food insecurity and a lack of aquaculture involvement due to natural disasters, poor WaSH status, a lack of focus on maternal education and nutrition, and a lack of focus on the risk of enteropathogen burden.

Another important finding based on the post-estimation findings as well as the value of the area under the ROC curve was that the predictive performance of the model was low. Thus, we need to identify other indicators from similar research contexts that correlated with childhood stunting but were not included in our model. Future research in the field of childhood stunting should give priority to the development of more suitable methods for monitoring and identifying effective interventions. It is also essential to collect data that considers biological and environmental factors related to childhood stunting, following the literature. By considering these diverse factors, we can improve the accuracy and predictive performance of statistical models. This, in turn, can help draw more reliable conclusions about the effectiveness of interventions aimed at reducing childhood stunting in similar contexts. Additionally, evaluating the model on an independent dataset or conducting external validation could help to determine the generalizability of the model to new data.

This study will aid programme managers in prioritizing their focus and designing effective interventions to reduce childhood stunting. Sustainable solutions should be based on the needs of the beneficiaries. Implementing short-term initiatives such as attendance at healthcare-led workshops and campaigns can increase ANC visits, skilled birth attendance, and handwashing practices. Establishing women's healthcare services that focus on maternal and child health and nutrition will also help reduce the incidence of stunting.[23] Improved access to media can help vulnerable communities benefit from government welfare programmes. Food security, income, sanitation, aquaculture, and illness are all time-sensitive factors. Increasing food production through self-production or purchasing can improve household food security and nutrition. However, household wealth and access to nearby markets can impact their ability to buy nutritious food. Climate change adaptation in agriculture is crucial to minimize current risks and prepare for future uncertainties. Using organic fertilizers instead of chemicals in agriculture has environmental benefits, reducing the need for pesticides and protecting human health and biodiversity. Aquaculture can provide a source of protein and improve nutrition, but establishing these facilities takes time. Improving sanitation requires improving socioeconomic status, which is also a time-intensive process. It takes time to improve stunting, as shown by national surveys such as the BDHS and the Food Security and National Surveillance Project (FSNSP).[2 40] Improving maternal nutrition and education is crucial for promoting the optimal growth and development of children. Adequate food, good environmental conditions, and access to schooling facilities during adolescence are necessary for women to maintain their own health and to positively impact the health of their children. Emphasizing the education of female children can break the cycle of poverty and stunting, as it can lead to improved knowledge and decision-making skills related to nutrition and health.[6 11] To reduce childhood stunting in developing countries, comprehensive interventions that include nutritional support, food security, maternal education, income-generating activities for women with childcare support, and addressing domestic violence against women should be implemented. These interventions should be tailored to the specific needs and cultural context of the community in which they are implemented, and community participation and engagement are essential for their success. By addressing the underlying factors contributing to childhood stunting, we can make significant progress towards reducing its prevalence and improving the health and well-being of children in developing countries. Furthermore, continued monitoring and evaluation of these interventions is essential to ensure their effectiveness and to identify areas for improvement.

Recommendation: The *Suchana* model offers a holistic and integrated approach to addressing food and nutrition security, recognizing undernutrition as a complex problem caused by multiple factors. The endline survey of *Suchana* showed significant improvement in programme indicators. The multi-sector approach of *Suchana* is a meaningful solution to addressing undernutrition. However, policy makers should consider implementing additional nutrition-sensitive and specific activities, such as promoting climate-resilient agriculture and increasing water and sanitation coverage. It is also important to have a sustainable mechanism for improving food security and to promote awareness of seasonal diseases associated with livestock and poultry. To further improve the programme, indicators such as child sex, maternal education, and nutrition could be adjusted during the design stage. The *Suchana* programme is one of the largest global nutrition interventions, leading to positive changes in critical indicators, with long-term benefits expected for the health and livelihoods of the beneficiaries.

Strength and limitation: The study had several strengths, including a large sample size, randomization, and appropriate sampling techniques. A dedicated quality control team was involved in checking the data, and the use of precise anthropometry instruments and separate training for the measurement team helped ensure accurate data collection. The study was also designed to avoid seasonality by conducting the baseline and endline surveys at the same time of the year. However, the study results may have been impacted by a lack of selection effect in the implementation of the programme, as well as by the short time horizon of the study. The short duration of the study may not have been enough to see a significant impact on stunting. Additionally, changes in the study population between the baseline and endline surveys could also

have contributed to the lack of differences observed in the results. Another limitation of this study is that we did not collect food intake data but only recall data from the previous 24 hours. These data may be subject to recall bias; thus, caution is necessary when drawing conclusions, especially for indicators such as dietary diversity, household food insecurity, domestic violence, and maternal healthcare. Finally, using a binary indicator of stunting based on a single LAZ cut-off point, which was defined as <-2, may not provide a comprehensive assessment of the severity of malnutrition among children, as it fails to account for micronutrient deficiencies

Conclusion

Our study revealed that childhood stunting was significantly correlated with a multitude of factors, and majority of the factors were found in poor status in our study area. Despite the implementation of an intervention programme, the situation remained unchanged due to factors such as food insecurity, lack of involvement in aquaculture, poor access to WaSH facilities, and a lack of focus on maternal education and nutrition. The study did not include important indicators such as enteropathogen and environmental enteric dysfunction, which might have contributed to the failure to achieve the desired outcome. The results suggest that policy makers and programme planners should consider enhancing collaboration and coordination between nutrition-sensitive and specific activities to address nutritional deficiencies and family health programmes in vulnerable rural populations.

Acknowledgments: The study analyzed baseline survey data of *Suchana*; this intervention has been implemented by a consortium led by Save the Children, with support from the Foreign, Commonwealth and Development Office (FCDO) and European Union (EU). icddr,b acknowledges with gratitude the commitment of Save the Children, FCDO and EU to its research efforts. We also acknowledge with gratitude the commitment of the Government of the People's Republic of Bangladesh to icddr,b's research activities. We also acknowledge the following donors for providing unrestricted support to icddr,b's efforts and advancement of its strategic plan: Canada, Sweden and the United Kingdom. We gratefully acknowledge our core donors for their support and commitment to icddr,b's research efforts. We would like to acknowledge the invaluable contributions of Save the Children as lead agency, our technical partners Helen Keller

International, World Fish, and International Development Enterprises, and the implementing partners Friends In Village Development Bangladesh (FIVDB), Rangpur Dinajpur Rural Services (RDRS), and the Center for Natural Resource Studies (CNRS) who played critical roles in generating and refining the data-collection tools. We would also like to acknowledge Tasnia Alam, Research Assistant and Md. Maniruzzaman, Assistant Professor, Khulna University, Khulna-9208, Bangladesh as the internal reviewers, and Andrea Devlin of Science Editing Experts for editing and linguistic revision of the manuscript.

Funding: (i) This study was made possible by the committed contribution of Foreign, Commonwealth and Development Office (Grant number: 204131-103), and (ii) icddr,b (N/A).

Conflicts of Interest: The authors declare no conflict of interest.

Author Contributions: TA and NC originated the idea for the study and led the protocol design. MAH conceptualized the manuscript. SMTA, SSR, MAH, NC, FDF, and TA contributed to the survey design. MAH performed statistical analysis and drafted the manuscript. NC and ASGF supervised the work, and critically reviewed and provided feedback for revising the manuscript. MAH, NC, MA, FDF, FN, BZW, TJS, ASGF, TA, and SSR contributed to the revision of the final draft for submission. All authors are responsible for the final content of the manuscript.

Ethics approval: This study was approved by the Research Review Committee and Ethical Review Committee, the two obligatory components of the Institutional Review Board (IRB) of icddr,b. Ethics Committee's approval ID# 00001822. Informed written consent was obtained from study participants.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

Reference

1. Bari A, Nazar M, Iftikhar A, et al. Comparison of Weight-for-Height Z-score and Mid-Upper Arm Circumference to Diagnose Moderate and Severe Acute Malnutrition in children aged 6-59 months. *Pakistan journal of medical sciences* 2019;35(2):337-41. doi: 10.12669/pjms.35.2.45 [published Online First: 2019/05/16]

2. National Institute of Population Research and Training (NIPORT), ICF. Bangladesh Demographic and Health Survey 2017-18: Key Indicators. NIPORT and ICF: Dhaka, Bangladesh and Rockville, Maryland, USA, 2019.

3. Development Initiatives. 2018 Global Nutrition Report: Shining a light to spur action on nutrition. Bristol, UK: Development Initiatives, 2018.

4. United Nations Children's Fund (UNICEF), World Health Organization, International Bank for Reconstruction and Development/The World Bank. Levels and trends in child malnutrition: Key Findings of the 2020 Edition of the Joint Child Malnutrition Estimates. Geneva: World Health Organization; 2020. Licence: CC BY-NC-SA 3.0 IGO., 2020.

5. USAID. Bangladesh: Nutrition Profile, 2018.

6. Kumar P, Rashmi R, Muhammad T, et al. Factors contributing to the reduction in childhood stunting in Bangladesh: a pooled data analysis from the Bangladesh demographic and health surveys of 2004 and 2017–18. *BMC public health* 2021;21(1):2101. doi: 10.1186/s12889-021-12178-6

7. Yaya S, Wang R, Tang S, et al. Intake of supplementary food during pregnancy and lactation and its association with child nutrition in Timor Leste. *PeerJ* 2018;6:e5935. doi: 10.7717/peerj.5935 [published Online First: 20181115]

8. Choudhury N, Raihan MJ, Sultana S, et al. Determinants of age-specific undernutrition in children aged less than 2 years-the Bangladesh context. *Maternal & child nutrition* 2017;13(3) [published Online First: 2016/10/19]

568 9. Nisar YB, Dibley MJ, Aguayo VM. Iron-Folic Acid Supplementation During Pregnancy Reduces the Risk of Stunting in Children Less Than 2 Years of Age: A Retrospective Cohort Study from Nepal. *Nutrients* 2016;8(2):67. doi: 10.3390/nu8020067 [published Online First: 20160127]

572 10. Li Z, Kim R, Vollmer S, et al. Factors Associated With Child Stunting, Wasting, and Underweight in 35 Low- and Middle-Income Countries. *JAMA Network Open* 2020;3(4):e203386. doi: 10.1001/jamanetworkopen.2020.3386 [published Online First: 20200401]

576 11. Katoch OR. Determinants of malnutrition among children: A systematic review. *Nutrition* 2022;96:111565. doi: 10.1016/j.nut.2021.111565 [published Online First: 20211211]

578 12. Huo S, Wang K, Liu Z, et al. Influence of Maternal Exposure to Mass Media on Growth Stunting Among Children Under Five: Mediation Analysis Through the Water, Sanitation, and Hygiene Program. *JMIR Public Health and Surveillance* 2022;8(4):e33394. doi: 10.2196/33394 [published Online First: 20220406]

582 13. Win H, Shafique S, Mizan S, et al. Association between mother's work status and child stunting in urban slums: a cross-sectional assessment of 346 child-mother dyads in Dhaka, Bangladesh (2020). *Archives of Public Health* 2022;80(1):192. doi: 10.1186/s13690-022-00948-6

586 14. Iannotti LL, Blackmore I, Cohn R, et al. Aquatic Animal Foods for Nutrition Security and Child Health. *Food and Nutrition Bulletin* 2022;43(2):127-47. doi: 10.1177/03795721211061924 [published Online First: 20211214]

589 15. Prendergast AJ, Chasekwa B, Evans C, et al. Independent and combined effects of improved water, sanitation, and hygiene, and improved complementary feeding, on stunting and anaemia among HIV-exposed children in rural Zimbabwe: a cluster-randomised controlled trial. *The Lancet Child & Adolescent Health* 2019;3(2):77-90. doi: 10.1016/s2352-4642(18)30340-7 [published Online First: 20181218]

16. Anwar F, Khomsan A, Sukandar D, et al. High participation in the Posyandu nutrition program improved children nutritional status. *Nutrition Research and Practice* 2010;4(3):208-14. doi: 10.4162/nrp.2010.4.3.208 [published Online First: 20100628]

17. Orunmoluyi OS, Gayawan E, Manda S. Spatial Co-Morbidity of Childhood Acute Respiratory Infection, Diarrhoea and Stunting in Nigeria. *International journal of environmental research and public health* 2022;19(3) doi: 10.3390/ijerph19031838 [published Online First: 20220206]

18. Haque MA, Platts-Mills JA, Mduma E, et al. Determinants of Campylobacter infection and association with growth and enteric inflammation in children under 2 years of age in low-resource settings. *Scientific reports* 2019;9(1):17124. [published Online First: 2019/11/22]

19. National Institute of Population Research and Training - NIPORT/Bangladesh, Mitra and Associates, ICF International. Bangladesh Demographic and Health Survey 2014. NIPORT, Mitra and Associates, and ICF International: Dhaka, Bangladesh and Rockville, Maryland, USA, 2016.

20. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH). State of food security and nutrition in Bangladesh 2013. HKI and JPGSPH, 2014.

21. Yaya S, Bishwajit G, Ekholuenetale M, et al. Awareness and utilization of community clinic services among women in rural areas in Bangladesh: A cross-sectional study. *PLOS ONE* 2017;12(10):e0187303. doi: 10.1371/journal.pone.0187303

22. Choudhury N, Raihan MJ, Ahmed SMT, et al. The evaluation of Suchana, a large-scale development programme to prevent chronic undernutrition in north-eastern Bangladesh. *BMC public health* 2020;20(1):744. [published Online First: 2020/05/24]

23. Haque MA, Choudhury N, Ahmed SMT, et al. The large-scale community-based programme 'Suchana' improved maternal healthcare practices in north-eastern Bangladesh: Findings from a cluster randomized pre-post study. *Maternal & child nutrition* 2022;18(1):e13258.

24. Coates J, Swindale A, Bilinsky P. Household Food Insecurity Access Scale (HFIAS) for measurement of food access: indicator guide (v. 3). Washington, D.C.: Food and Nutrition Technical Assistance Project, Academy for Educational Development 2007.

25. Therneau T, Atkinson B, Ripley B. rpart: Recursive partitioning and regression trees 2022 [Available from: https://cran.r-project.org/package=rpart2023.

26. Villa JM. Simplifying the estimation of difference-in-differences treatment effects. *The Stata Journal* 2016:52-71.

27. Bursac Z, Gauss CH, Williams DK, et al. Purposeful selection of variables in logistic regression. *Source code for biology and medicine* 2008;3:17.

28. Tardini E, Zhang X, Canahuate G, et al. Optimal Treatment Selection in Sequential Systemic and Locoregional Therapy of Oropharyngeal Squamous Carcinomas: Deep Q-Learning With a Patient-Physician Digital Twin Dyad. *Journal of Medical Internet Research* 2022;24(4):e29455. doi: 10.2196/29455 [published Online First: 20220420]

29. Adamker G, Holzer T, Karakis I, et al. Prediction of Shigellosis outcomes in Israel using machine learning classifiers. *Epidemiology and Infection* 2018;146(11):1445-51. doi: 10.1017/s0950268818001498 [published Online First: 20180608]

30. Weatherspoon DD, Miller S, Ngabitsinze JC, et al. Stunting, food security, markets and food policy in Rwanda. *BMC public health* 2019;19(1):882. doi: 10.1186/s12889-019-7208-0 [published Online First: 2019/07/06]

31. Agho KE, Mukabutera C, Mukazi M, et al. Moderate and severe household food insecurity predicts stunting and severe stunting among Rwanda children aged 6-59 months residing in Gicumbi district. *Maternal & child nutrition* 2019;15(3):e12767.

32. Chowdhury D. Flood situation worsens in Sylhet. *The Daily Star* 2017.

33. ACAPS. ACAPS Briefing Note: Bangladesh - Floods in Moulvibazar and Sylhet (20 June 2018): reliefweb; 2018 [Available from: https://reliefweb.int/report/bangladesh/acaps-briefing-note-bangladesh-floods-moulvibazar-and-sylhet-20-june-20182023.

34. Lin A, Arnold BF, Afreen S, et al. Household environmental conditions are associated with enteropathy and impaired growth in rural Bangladesh. *American Journal of Tropical Medicine and Hygiene* 2013;89(1):130-37. doi: 10.4269/ajtmh.12-0629 [published Online First: 20130429]

35. Amour C, Gratz J, Mduma E, et al. Epidemiology and Impact of Campylobacter Infection in Children in 8 Low-Resource Settings: Results From the MAL-ED Study. *Clinical Infectious Diseases* 2016;63(9):1171-79. doi: 10.1093/cid/ciw542 [published Online First: 08/07]

36. Smith S, Meade J, Gibbons J, et al. The impact of environmental conditions on Campylobacter jejuni survival in broiler faeces and litter. *Infect Ecol Epidemiol* 2016;6:31685-85. doi: 10.3402/iee.v6.31685

37. Chen RY, Kung VL, Das S, et al. Duodenal Microbiota in Stunted Undernourished Children with Enteropathy. *The New England Journal of Medicine* 2020;383(4):321-33. doi: 10.1056/NEJMoa1916004

38. George CM, Oldja L, Biswas SK, et al. Fecal Markers of Environmental Enteropathy are Associated with Animal Exposure and Caregiver Hygiene in Bangladesh. *American Journal of Tropical Medicine and Hygiene* 2015;93(2):269-75. doi: 10.4269/ajtmh.14-0694 [published Online First: 20150608]

39. Perin J, Burrowes V, Almeida M, et al. A Retrospective Case-Control Study of the Relationship between the Gut Microbiota, Enteropathy, and Child Growth. *American Journal of Tropical Medicine and Hygiene* 2020;103(1):520-27. doi: 10.4269/ajtmh.19-0761 [published Online First: 20200514]

40. Helen Keller International (HKI) and James P. Grant School of Public Health (JPGSPH). State of food security and nutrition in Bangladesh 2014. HKI and JPGSPH: Dhaka, BD, 2016.

669 Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline. The p-value of the *difference-in-difference* was estimated using interaction analysis in the multiple logistic regression model.

673 Figure 2. Results framework and *Suchana* log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

676 Figure 3. Factors correlating with stunting in children aged 12-23 months, computed using decision tree analysis. (X_1: Less than four ANC visits by a skilled service provider, X_2: Unskilled birth attendant/facility, X_3: Mother involved in income-generating activities, X_4: Maternal BMI <18.5, X_5: Maternal education: no schooling, X_6: Household severe food insecurity, X_7: Monthly income <15000 BDT, X_8: Did not involve with aquaculture, X_9: Having unhygienic latrine, X_{10}: Soap was unavailable in hand washing place, X_{11}: HH size≥7, X_{12}: HH dietary diversity score <7, X_{13}: Child's age>18, X_{14}: Child's sex was male, X_{15}: Childhood illness in the last 15 days, and X_{16}: Lacked access to mass media)

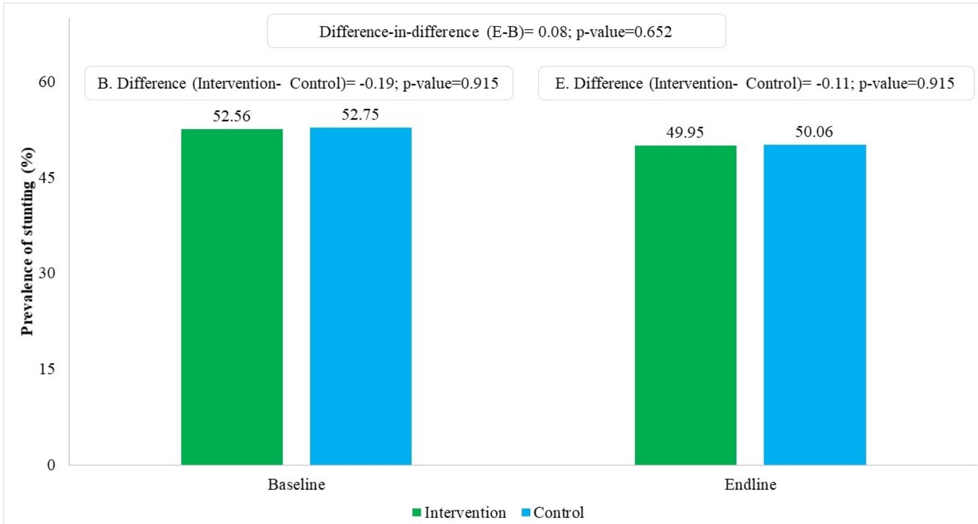


Figure 1. Prevalence of childhood stunting in the intervention and control areas at baseline compared to endline. The p-value of the difference-in-difference was estimated using interaction analysis in the multiple logistic regression model.

108x60mm (300 x 300 DPI)

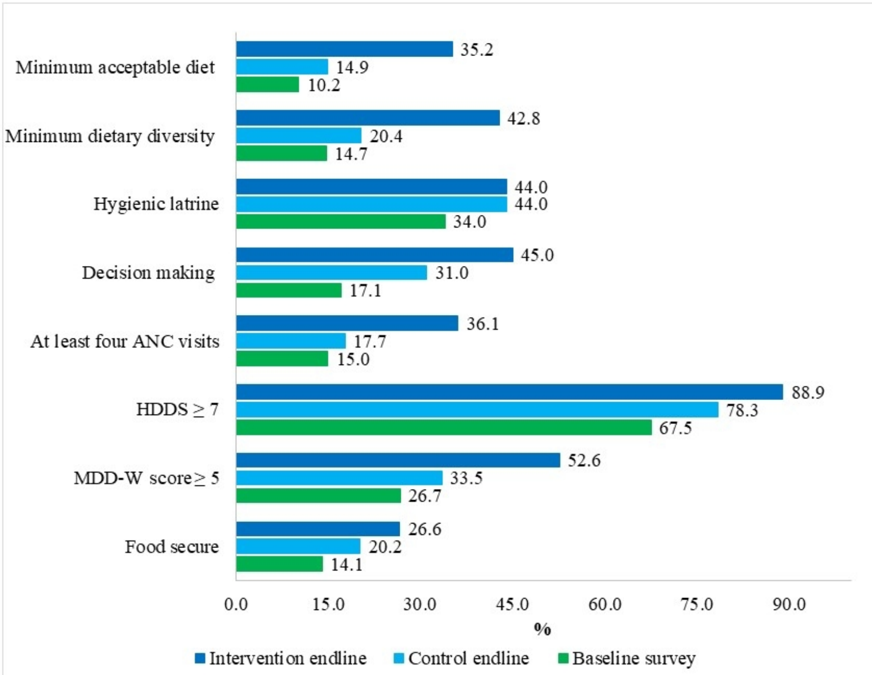


Figure 2. Results framework and Suchana log frame indicators. ANC: antenatal care, HDDS: household dietary diversity score, MDD-w: minimum dietary diversity for women.

254x190mm (96 x 96 DPI)

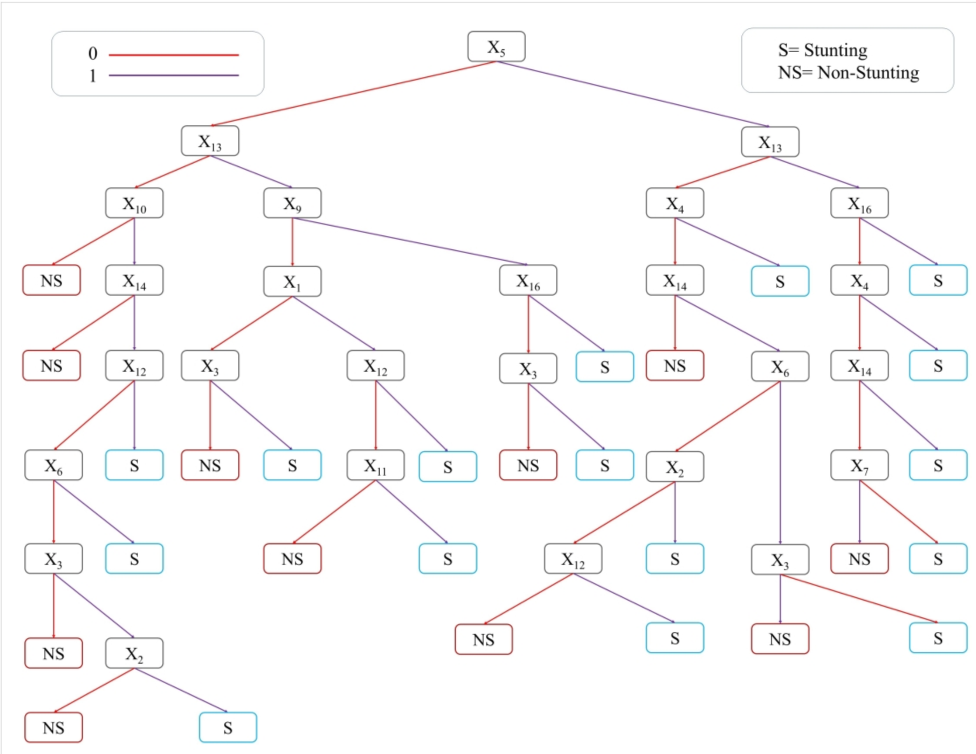


Figure 3. Factors correlating with stunting in children aged 12-23 months, computed using decision tree analysis. (X1: Less than four ANC visits by a skilled service provider, X2: Unskilled birth attendant/facility, X3: Mother involved in income-generating activities, X4: Maternal BMI <18.5, X5: Maternal education: no schooling, X6: Household severe food insecurity, X7: Monthly income <15000 BDT, X8: Did not involve with aquaculture, X9: Having unhygienic latrine, X10: Soap was unavailable in hand washing place, X11: HH size>7, X12: HH dietary diversity score <7, X13: Child's age>18, X14: Child's sex was male, X15: Childhood illness in the last 15 days, and X16: Lacked access to mass media)

325x254mm (300 x 300 DPI)

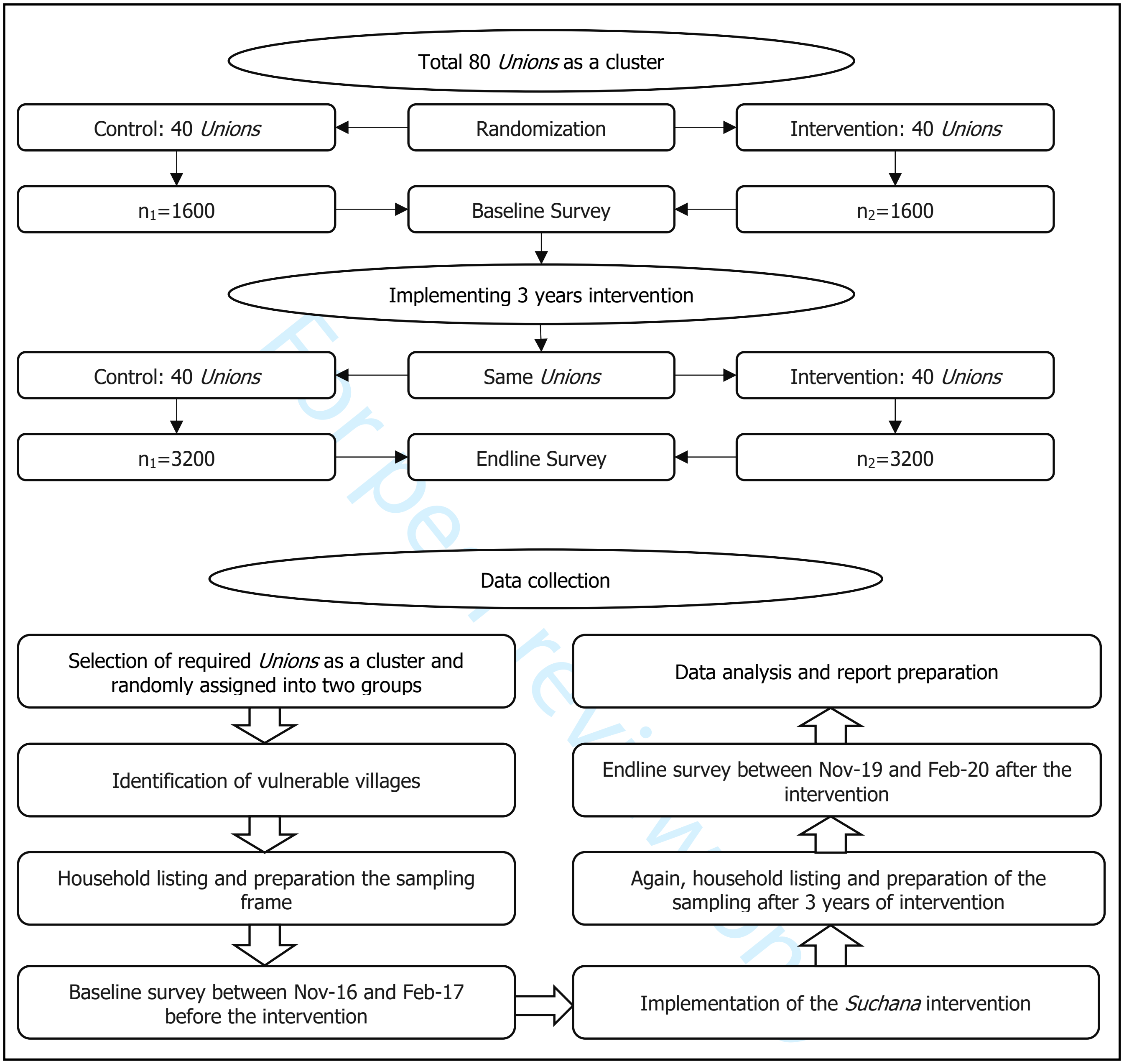
Appendix 1. Sample size calculation

```
clustersampsi, binomial samplesize p1(0.47) p2(0.41) k40) rho0.01)alpha(0.05) beta(0.8)
```

Output of the STATA command for sample size calculation

```
Sample size calculation to determine number of observations required per cluster, for a two-
sample comparison of proportions (using normal approximations) without continuity correction.

For the user specified parameters:
      p1: 0.4700
      p2: 0.4100
      significance level:  0.05
      power:  0.80
      number of clusters available:  40
      intra cluster correlation (ICC):  0.0100
clustersampsi estimated parameters:
      Firstly, assuming individual randomisation: sample size per arm: 1071
      Then, allowing for cluster randomisation: average cluster size required:  38
      sample size per arm:   1520
```



Supplementary Figure 1. The evaluation diagram of *Suchana* programme

Appendix 2. Data collection

The Suchana data collection software contained built-in validation rules. As the data were entered at the interviewer level and the records were uploaded to a server at the icddr,b using the built-in internet connectivity of the devices, maximum validation rules were set in the data system to prevent errors during data entry, which reduced the data entry burden. This allowed the data analysis team to review the

consistency of the data every day. Data were synchronized to the central server "Web Service" developed in Asp.Net based on the C# (C Sharp) code. Activities such as editing (after receiving any feedback from field staff members), updating, range checks, duplication checks, consistency checks, frequency checks and cross tabulation were regularly performed during the data entry period. In case of any unusual observations, the issues were discussed and resolved.

Appendix 3. Equation of logistic and probit regression

$$logit(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

$$probit(y)= \beta_0+ \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \beta_{12}X_{12} + \beta_{13}X_{13} + \beta_{14}X_{14} + \beta_{15}X_{15} + \beta_{16}X_{16}$$

Where,

- x1: Less than four ANC visits by a skilled service provider
- x2: Unskilled birth attendant/facility
- x3: Mother involved in income-generating activities
- x4: Maternal BMI <18.5
- x5: Maternal education: no schooling
- x6: HH severe food insecurity
- x7: Monthly income <15000 BDT
- x8: Did not involve with aquaculture
- x9: Having unhygienic latrine
- x10: Soap was unavailable in hand washing place
- x11: HH size≥7
- x12: HH dietary diversity score <7
- x13: Child's age>18
- x14: Child's sex was male
- x15: Childhood illness in the last 15 days
- x16: Lacked access to mass media

and

$$logit(y) = \log[y/(1-y)]$$

Supplementary Table 1. *Suchana* inclusion criteria for registration of enrolling as vulnerable households

Vulnerable household verification questions	Inclusion criteria
Step 1 • Households currently participating/member of any livelihood, food security or asset transfer program	If "NO" go ahead for next questions
Step 2 • Ability to afford three (3) full meals per day for all family members round the year • Households monthly income BDT 7,500 or more • Household productive asset value worth BDT 15,000 or more (excluding land, pond and homestead) • Ownership of homestead land 10 decimals or more • Ownership of cultivable land 50 decimals or more (excluding homestead or pond)	If anyone is "NO" go ahead for next questions
Step 3 • Households have married women with in child bearing age (15 to 45 years) • Households have pregnant women (including abandoned or widowed woman) • Households have 0-23 months old children • Households have adolescent girls (15-19 years)	If anyone is 'Yes' go ahead for registration of enrolling as vulnerable Household
Sampling frame was prepared for collecting data from mother-child pair if the households had 0-23 months old children	

Supplementary Table 2a. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple logistic regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.07, 6.22)	0.006
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.55, 4.35)	0.012
Mother involved in income-generating activities			
No	54.55 (50.90, 58.19)	Reference	
Yes	50.59 (49.08, 52.11)	3.95 (0.40, 7.51)	0.029
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.41)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.40)	<0.001
HH food insecurity			
Below severe	53.03 (50.91, 55.15)	Reference	
Severe	50.36 (48.63, 52.09)	2.66 (0.11, 5.22)	0.041
HH monthly income ≥15000 BDT			
Yes	51.31 (49.79, 52.84)	Reference	
No	48.58 (45.86, 51.30)	2.73 (0.17, 5.30)	0.037
Involved with aquaculture			
Yes	51.22 (49.72, 52.72)	Reference	
No	46.99 (43.30, 50.69)	4.23 (0.73, 7.73)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.54 (46.74, 50.33)	4.10 (1.83, 6.38)	<0.001
HH size			
Below seven	53.86 (51.98, 55.74)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.92 (51.25, 56.60)	Reference	
HDDS <7	50.10 (48.70, 51.50)	3.83 (1.63, 6.02)	<0.001
Child's age			
Age ≤18 months	56.72 (54.77, 58.67)	Reference	
Age >18 months	46.59 (44.82, 48.35)	10.1 (7.94, 12.32)	<0.001
Child's sex			
Female	53.25 (51.17, 55.34)	Reference	
Male	48.40 (46.78, 50.03)	4.85 (2.59, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.77)	Reference	
Yes	50.49 (48.94, 52.05)	4.41 (1.48, 7.34)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.39, 50.88)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

Supplementary Table 2b. Predictive ability of various indicators for the adjusted prevalence of stunting and adjusted prevalence difference (effect size) in the fitted multiple probit regression model.

	Prediction of adjusted stunting [% (95% CI)]	Prediction of adjusted prevalence difference as effect size*	p-value
At least four ANC visits by a skilled service provider			
Yes	51.64 (50.05, 53.23)	Reference	
No	47.99 (45.46, 50.53)	3.65 (1.08, 6.22)	0.007
Birth attendant/facility			
Skilled	51.87 (50.23, 53.51)	Reference	
Unskilled	49.42 (47.48, 51.36)	2.45 (0.54, 4.35)	0.011
Mother involved in income-generating activities			
No	54.55 (50.90, 58.16)	Reference	
Yes	50.59 (49.08, 52.11)	3.93 (0.39, 7.48)	0.024
Maternal BMI			
BMI ≥18.5	54.04 (52.01, 56.07)	Reference	
BMI <18.5	49.01 (47.21, 50.81)	5.03 (2.66, 7.40)	<0.001
Maternal education was primary completed			
Yes	54.66 (52.58, 56.74)	Reference	
No	48.21 (46.67, 49.75)	6.45 (4.49, 8.41)	<0.001
HH food insecurity			
Below severe	53.01 (50.89, 55.12)	Reference	
Severe	50.37 (48.64, 52.10)	2.64 (0.09, 5.19)	0.042
HH monthly income ≥15000 BDT			
Yes	51.32 (49.79, 52.84)	Reference	
No	48.56 (45.84, 51.28)	2.75 (0.19, 5.32)	0.035
Involved with aquaculture			
Yes	51.22 (49.73, 52.71)	Reference	
No	46.99 (43.28, 50.69)	4.24 (0.73, 7.74)	0.018
Hygienic latrine			
Yes	52.67 (50.94, 54.4)	Reference	
No	48.36 (46.5, 50.23)	4.31 (2.34, 6.28)	<0.001
Water and soap available in handwashing place			
Yes	52.64 (50.71, 54.58)	Reference	
No	48.53 (46.74, 50.33)	4.11 (1.83, 6.39)	<0.001
HH size			
Below seven	53.86 (51.98, 55.73)	Reference	
Seven or above	49.41 (47.70, 51.13)	4.44 (2.43, 6.46)	<0.001
HH dietary diversity			
HDDS ≥7	53.90 (51.23, 56.57)	Reference	
HDDS <7	50.10 (48.71, 51.50)	3.79 (1.60, 5.98)	<0.001
Child's age			
Age ≤18 months	56.72 (54.76, 58.67)	Reference	
Age >18 months	46.59 (44.83, 48.35)	10.1 (7.93, 12.3)	<0.001
Child's sex			
Female	53.25 (51.17, 55.33)	Reference	
Male	48.41 (46.78, 50.03)	4.85 (2.60, 7.10)	<0.001
Childhood illness in the last 15 days			
No	54.90 (52.04, 57.75)	Reference	
Yes	50.50 (48.94, 52.05)	4.40 (1.47, 7.33)	0.003
Access of mass media			
Yes	51.51 (49.88, 53.15)	Reference	
No	48.13 (45.40, 50.86)	3.38 (0.42, 6.34)	0.028

*Differences in the predicted values of stunting between the two groups were calculated using the Stata "*adjrr*" package

STROBE Statement—Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1-2
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	1-2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-6
Objectives	3	State specific objectives, including any prespecified hypotheses	6
Methods			
Study design	4	Present key elements of study design early in the paper	6
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	6
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6-7
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	*6-7*
Bias	9	Describe any efforts to address potential sources of bias	20
Study size	10	Explain how the study size was arrived at	7
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	7
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	8-9
		(*b*) Describe any methods used to examine subgroups and interactions	
		(*c*) Explain how missing data were addressed	
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	8-9
		(*e*) Describe any sensitivity analyses	
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	11
		(b) Give reasons for non-participation at each stage	
		(c) Consider use of a flow diagram	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	11
		(b) Indicate number of participants with missing data for each variable of interest	
Outcome data	15*	Report numbers of outcome events or summary measures	11
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	11-14

		(*b*) Report category boundaries when continuous variables were categorized	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	11-15
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
Discussion			
Key results	18	Summarise key results with reference to study objectives	17
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	20
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	17
Generalisability	21	Discuss the generalisability (external validity) of the study results	17-18
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	22

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.