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RESEARCH ARTICLE

Maternal selenium deficiency was positively associated with the risk of selenium deficiency in children aged 6–59 months in rural Zimbabwe

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Abstract

There is growing evidence showing the existence of selenium (Se) deficiency among women and children in sub-Saharan Africa. Unfortunately, the key drivers of Se deficiency are not clearly understood. This study assessed the determinants of Se deficiency among children aged 6–59 months and Women of Reproductive Age (WRA), in Zimbabwe. This cross-sectional biomarker study was conducted in selected districts in rural Zimbabwe (Murewa, Shamva, and Mutasa). Children aged 6–59 months (n = 683) and WRA (n = 683), were selected using a systematic random sampling approach. Venous blood samples were collected, processed, and stored according to World Health Organization (WHO) guidelines. Plasma selenium concentration was measured using inductively coupled plasma-mass spectrometry (ICP-MS). Anthropometric indices were assessed and classified based on WHO standards. Demographic characteristics were adapted from the Zimbabwe Demographic Health Survey standard questionnaire. Multiple logistic regression analysis showed that children whose mothers were Se deficient were 4 times more likely to be Se deficient compared to those whose mothers were Se adequate (OR = 4.25; 95% CI; 1.55–11.67; p = 0.005). Girl children were 3 times more likely to be Se deficient compared to boys (OR = 2.84; 95% CI; 1.08–7.51; p = 0.035). Women producing maize for consumption were 0.5 times more likely to be Se deficient than non-producers (OR = 0.47; 95% CI; 0.25–0.90; p = 0.022). The risk of Se depletion in children was amplified by maternal deficiency. Therefore, initiation of maternal multiple micronutrient supplementation from preconception through lactation is beneficial to both children and women.

1. Introduction

Selenium deficiency is widespread among children and women in sub-Saharan Africa [1, 2] and has been implicated as a potential causal factor of growth faltering in children [3, 4], and

provided as part of the submitted article, in a format that can be accessed without restrictions.

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fertility impairments in women [5]. Worldwide, up to one in seven people are estimated to have low dietary Se intake [6], and c. 0.5 to 1 billion people are Se deficient [7, 8]. Estimated low dietary mineral supply of Se in Africa [9] may have considerable regional public health significance [10]. The greater prevalence of Se deficiency highlighted in sub-Saharan African countries [1], can be exacerbated by the human immunodeficiency virus [11] which is prevalent in many African settings [12], posing further potential public health concerns. Viral infection simultaneously increases the demand for micronutrients and causes their loss, exacerbating deficiency [11].

Diet is the main source of Se [13] with meat and meat products rich in Se [14]. However, across sub-Saharan Africa diets are predominantly crop-based and it is these sources that provide the majority of dietary Se [15]. Diets in sub-Saharan Africa consist primarily of carbohydrates [16]. In many parts of Africa, rural diets are frequently monotonous, consisting mainly of starchy foods such as grains, tubers, and roots but with limited or negligible intake of animal-source foods [17]. The consumption of animal foods such as meat, poultry, and fish is limited, mainly because of economic, cultural, and religious constraints [15]. Plants can be classified into three main groups based on the Se concentrations in their tissues; non-accumulators, accumulators, and hyperaccumulators [18]. Non-accumulating plants such as grains and grasses contain lower concentrations of Se [18, 19]. Maize grain in sub-Saharan African countries has a sub-optimal Se concentration of < 50 μg/kg dry mass [2] and is not likely to meet human requirements [20]. Typically, Se deficiency is a consequence of inadequate dietary Se intake [14, 21, 22], however, there are multiple proximal risk factors: inflammation [23, 24], body mass index (BMI) [25, 26], gender, age, protein malnutrition [27] and dietary diversity [28]. Socioeconomic and environmental distal factors, such as wealth status and rural or urban residence, influence Se status [22, 29]. In low and middle-income countries macroeconomic volatility is common and severe negative economic shocks can substantially increase poverty, food insecurity, and risks of inadequate dietary diversity [30]. Preliminary estimates for Zimbabwe suggested that the number of extremely poor reached 7.9 million in 2020, 49% of the population [31]. Government data for Zimbabwe [32] indicates that 4% of children between 6–23 months of age receive a minimum acceptable diet and 16% consume the minimum number of food groups recommended for their age. It also reports that the proportion of women of reproductive age (WRA) consuming at least four food groups was 44% [32], and more than 50% of the population is affected by micronutrient deficiencies (MNDs) [33].

Human Se deficiency has been reported previously in Zimbabwe [34, 35]. However, the key drivers of Se deficiency are not clearly understood. Data for this study was collected in rural Zimbabwe as part of a baseline study for a micronutrient biomarker survey. The work was guided by the UNICEF's Conceptual Framework on the Determinants of Maternal and Child Nutrition, 2020 [36] and explored the immediate, underlying, basic, and enabling causes of Se deficiency among children aged 6–59 months and WRA in selected districts (Murewa, Shamva, and Mutasa).

2. Materials and methods

2.1. Ethical statements

The study was conducted in line with the Declaration of Helsinki. Ethical approval was obtained from the Institutional Review Boards of the University of Nottingham (Reference#446–1912) and the Medical Research Council of Zimbabwe (MRCZ/A/2575). Shipping permissions, including a material transfer agreement were secured. Research approval was awarded by local government officials and the Ministry of Health at the provincial, district,

clinic, and village levels. Written informed consent and assent were obtained from all WRA and all child participants before the commencement of data collection, respectively.

2.2. Sampling

A detailed description of the methods has been reported elsewhere [35, 37, 38]. In summary, the current paper presents data from a cross-sectional study on the determinants of Se deficiency in children aged 6–59 months (n = 683) and in WRA (n = 683) from three rural districts; Murewa (17.6502˚S, 31.7787˚E), Shamva (17.04409˚S, 31.6739˚E), and Mutasa (18.6155˚S, 32.6730˚E) in Zimbabwe. Data collection was between 25 October 2021 and 30 January 2022. The sampling design was nested at the level of the National Demographic Health Survey (DHS) sampling approach [33]. Thirty Enumeration areas (EAs) proportional to the most recently recorded population [39], were selected per district. Random systematic sampling without replacement was used to select 10 eligible households from each EA; the Kish Grid [40] was used for the within-household selection of multiple eligible individuals. Participants were directed to the nearest health facility for data and sample collection by trained personnel.

2.3. Data and sample management

A temporary laboratory was established at each collection site to minimize contamination, facilitate accurate record keeping, and for traceability of samples. Strict quality control measures were followed as guided by the CDC [41]. Each participant was assigned a unique numeric identity that was used on data capture forms, sample collection materials, and subsequent analyses to maintain anonymity. Passcode-protected tablets with Kobo Toolbox software (Android v2022.1.2) were used to capture demographic and specimen data.

2.4. Data collection and analysis

2.4.1. Demographic characteristics. A questionnaire adapted from ZDHS [33] was used to collect household demographic data. The questionnaire also assessed socioeconomic characteristics (education level, marital status, and income status), health status, agricultural, water sanitation and hygiene (WASH), and infant and young child feeding practices as adapted from the UNICEF conceptual framework (Fig 1).

2.4.2. Anthropometry. Weight, recumbent length, and height were measured according to World Health Organization (WHO) standard protocols [42] and standardized as required for nutrition assessments [43, 44]. The anthropometric indices, namely height-for-age Z-score (HAZ), weight-for-height Z-score (WHZ), and weight-for-age Z-score (WAZ), for children, were generated using the Emergency Nutrition Assessment software for SMART 2011 [45]. Wasting was defined as WHZ below -2 Standard Deviations (SD), stunting as HAZ below-2SD, underweight as WAZ below -2SD, and overweight as WHZ above +2SD [44]. Birth weight was obtained from the infant's health cards, birth weight below 2.5 kg was defined as low birth weight (LBW) [46]. Body mass index (BMI) was calculated and classified for WRA according to WHO guidelines; BMI below 18.5 was considered as underweight; 18.5–24.9, normal weight; 25.0–29.9, overweight; 30.0–34.9, obesity class I; 35.0–39.9, obesity class II; and above 40 defined as morbid obesity [47]. Maternal short stature was defined as height below 145 cm [48]. While the reference reproductive age for optimal birth outcomes was 18–34 years [49].

2.4.3. Blood. A venous blood sample (6 mL blood) was collected from children 6–59 months and WRA according to the WHO blood collection guidelines [50]. Blood was centrifuged to isolate plasma in the field at 3000 rpm for 10 minutes. Center for Disease Control &

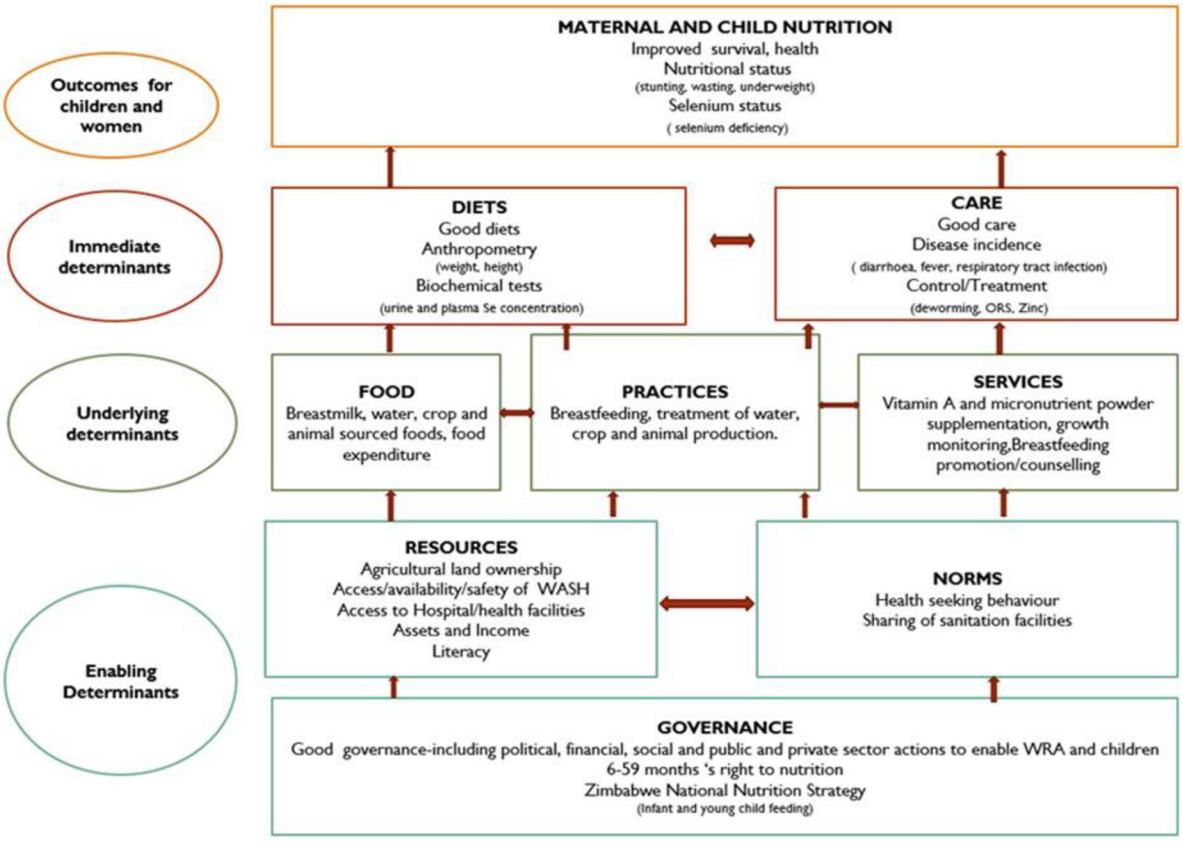

Fig 1. Theoretical framework adapted from UNICEF conceptual framework on the Determinants of Maternal and Child Nutrition 2020 [36].

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Prevention (CDC) guidelines were followed to reduce the risk of hemolysis [51]. A cold chain was maintained during sample transportation and the plasma was stored at -80˚C. Biomarkers of inflammation; C-reactive protein and alpha-1-acid glycoprotein were analyzed by a sandwich ELISA as adapted from Erhardt *et al.*, (2004) [52]. Quantification of plasma Se concentration was conducted using inductively coupled plasma-mass spectrometry (ICP-MS) as described by Belay *et al.* (2020) [53] and Phiri *et al.* (2019) [22]. The limit of detection (LOD) and the limit of quantification (LOQ) were 0.029 and 0.096 μg/L, respectively. All the sample observations were above the LOD/LOQ limits. Average Se recovery was 99% and 102% for reference materials (Seronorm L-1 (Lot 1801802) and Seronorm L-2 (Lot 1801803); Nycomed Pharma AS, Billingstad, Norway), respectively. No significant correlation was observed between plasma Se concentration and any of the inflammation biomarkers measured (S1 Table), thus no correction was applied for inflammation [50, 54].

2.5. Data analysis

Selenium deficiency was determined against plasma Se concentration thresholds of 70 μg/L [53] for children aged 6–59 months and women aged 15–49 years. Statistical analysis used SPSS for Windows version 20 (IBM, New York, USA). Exploratory data analysis was done using, quantile–quantile (QQ) plots to check for outliers and data normality [55]. Selenium concentration data was collapsed into categorical data (Se adequate and Se deficient) and was

considered as the dependent variable singly for children and WRA. Association between the dependent variable and socio-demographic factors (age, sex, education level, marital status, agricultural and WASH factors) and anthropometry indicators were evaluated using the Pearson Chi-square test and two-sided p-values < 0.05 were considered statistically significant. Significant variables (determinants) from the Pearson Chi-square test were further analyzed using logistic regression, with the removal criterion (pR) value set at 0.10 and 0.05 as the entry criterion (p_E) value by the enter method to establish predictors of Se deficiency. All statistical measures were at 95% confidence interval.

3. Results

3.1. Demographic and health characteristics of participants

A total of 683 mother-child pair Se concentration measurements (dependent variable) were matched and analyzed. The sample size in the three districts was proportionate across the two demographic groups as was the boy/girl ratio of the children. The median (Q1, Q3) age for the children was 29 months [18, 44], and that for women was 30 years [24, 37]. The majority of WRA who participated in the study were married (88.7%) and had acquired secondary-level education qualifications (66.2%). A few households (8.5%) earned a monthly household income adequate to meet the total consumption poverty line, set at 63.50 United States dollars per person, as of August 2021 [56]. Land ownership was $\geq$ 5 hectares for most of the households (60.8%). Maize *(Zea mays)* was the most predominant (64%) crop grown for household consumption. Most households had access to water, sanitation, and hygiene (WASH) facilities, with 78.4% having adequate water in the 30 days preceding the survey date, despite the water source being located off-premises for most of the households (66.5%). Almost all households (96.9%) had access to toilet facilities.

Close to a third (27.7%) of the children were classified as stunted, 2.8% were wasted and 13.5% were underweight. The rate of LBW was 9.0%. A high prevalence of breastfeeding was observed in the sampled population, with 69.4% of children exclusively breastfed up to 6 months as recommended by WHO. Vitamin A supplementation was high at >70%, while multiple micronutrient powder (MNP) supplementation coverage was low (9.4%) in children. Disease prevalence 2 weeks preceding the survey date indicated diarrhea had the lowest prevalence (24.6%), followed by fever (34.2%), with respiratory infection having the highest prevalence (35.5%). The prevalence of anemia (Hb <11 g/dL) in children was high at 28.1%, and 96.2% of the children were Se deficient. In WRA, the prevalence of anemia (Hb <12 g/dL) was 19.8% and that of Se deficiency was 70.1%. Based on BMI, a few women (10.9%) were underweight, the majority (52.1%) had normal weight and the proportions of overweight, class I, class II, and morbid obesity were 26.6%, 7.1%, 1.9%, and 1.3%, respectively.

3.2. Sociodemographic factors and Se deficiency

3.2.1. Children 6–59 months. Residency in Murewa district ($p < 0.001$), being a girl ($p = 0.008$), the use of unimproved dug wells as a source of drinking water ($p = 0.014$), and the production of maize ($p < 0.001$), cowpeas (*Vigna unguiculata)* ($p < 0.001$), groundnuts *(Arachis hypogaea)* ($p < 0.001$), sweet potatoes *(Ipomoea batatas)* ($p < 0.001$), sugar beans (*Phaseolus vulgaris*) ($p = 0.005$) and onions *(Allium cepa)* ($p = 0.002$), for household consumption (Table 1) were significantly associated with Se deficiency in children (Pearson's χ^2 test).

3.2.2. Women of reproductive age. Residency in Murewa district ($p < 0.001$), reproductive age of 18–34 years ($p = 0.036$), monthly income of below 10 USD ($p < 0.001$), consumption of water from unimproved dug wells ($p < 0.001$) and production of maize ($p < 0.001$), production of cowpeas ($p < 0.001$), production of groundnuts ($p < 0.001$), production of sweet

Table 1. Sociodemographic characteristics of children 6–59 months in rural Zimbabwe by Se status.

Variable	Total n (%)	‡Se-adequate n (%)	§Se deficient n (%)	P-value†
District				
Mutasa	203 (29.7)	17 (8.4)	186 (91.6)	<0.001*
Shamva	257 (37.6)	5 (1.9)	252 (98.1)	
Murewa	223 (32.7)	4 (1.8)	219 (98.2)	
Sex				
Boy	332 (49.7)	19 (5.7)	313 (94.3)	0.008*
Girl	336 (50.3)	6 (1.8)	330 (98.2)	
Age group (months)				
6–8	25 (3.8)	1 (4.0)	24 (96.0)	0.915
9–11	32 (4.8)	0 (0)	32 (100)	
12–17	91 (13.7)	4 (4.4)	87 (95.6)	
18–23	102 (15.4)	5 (4.9)	97 (95.1)	
24–35	156 (23.5)	5 (3.2)	151 (96.8)	
36–47	132 (19.9)	6 (4.5)	126 (95.5)	
48–59	125 (18.9)	4 (3.2)	121 (96.8)	
Number of children under 5 years in the household				
1	489 (71.6)	23 (4.7)	466 (95.3)	0.073
>1	194 (28.4)	3 (1.5)	191 (98.5)	
Household size				
≤4	265 (38.8)	7 (2.6)	258 (97.4)	0.226
>4	418 (61.2)	19 (4.5)	399 (95.5)	
Household monthly income (USD)				
<10	58 (8.5)	2 (3.4)	56 (96.6)	0.328
10–50	312 (45.7)	7 (2.2)	305 (97.8)	
51–110	170 (24.9)	10 (5.9)	160 (94.1)	
120–210	85 (12.4)	4 (4.7)	81 (95.3)	
>220	58 (8.5)	3 (5.2)	55 (94.8)	
Agricultural land ownership				
No	268 (39.2)	9 (3.4)	259 (96.6)	0.687
Yes	415 (60.8)	17 (4.1)	398 (95.9)	
Livestock ownership				
Chicken /poultry				
1	139 (20.4.)	7 (5.0)	132 (95.0)	0.454
>1	544 (79.6)	19 (3.5)	525 (96.5)	
Common crops grown for consumption				
Maize				
No	233 (36.0)	17 (7.3)	216 (92.7)	<0.001*
Yes	414 (64.0)	6 (1.4)	408 (98.6)	
Cowpeas				
No	337 (53.8)	21 (6.2)	316 (93.8)	<0.001*
Yes	289 (46.2)	2 (0.7)	287 (99.3)	
Groundnuts				
No	321 (51.3)	20 (6.2)	301 (93.8)	<0.001*
Yes	305 (48.7)	3 (1.0)	302 (99.0)	
Sugar beans				
No	425 (67.9)	22 (5.2)	403 (94.8)	0.005*

(*Continued*)

Table 1. (Continued)

Variable	Total n (%)	‡Se-adequate n (%)	§Se deficient n (%)	P-value†
Yes	201 (32.1)	1 (0.5)	200 (99.5)	
Sweet potatoes				
No	345 (55.1)	21 (6.1)	324 (93.6)	<0.001*
Yes	281 (44.9)	2 (0.7)	279 (99.3)	
Onions				
No	417 (66.6)	22 (5.3)	395 (94.7)	0.002*
Yes	209 (33.4)	1 (0.5)	208 (99.5)	
Unimproved dug wells as a source of drinking water				
No	485 (71.0)	24 (4.9)	461 (95.1)	0.014*
Yes	198 (29.0)	2 (1.0)	196 (99.0)	
Location of water source				
Off-premise (elsewhere)	454 (66.5)	16 (3.5)	438 (96.5)	0.443
In-house (own dwelling)	24 (3.5)	0 (0)	24 (100)	
On-premise (own yard/plot)	205 (30.0)	10 (4.9)	195 (95.1)	
Insufficient water in the past month				
No	536 (78.4)	19 (3.6)	517 (96.4)	0.641
Yes	147 (21.6)	7 (4.8)	140 (95.2)	
Treatment of drinking water				
No	604 (88.4)	25 (4.1)	579 (95.9)	0.243
Yes	79 (11.6)	1 (1.3)	78 (11.9)	
Toilet facility				
No	21 (3.1)	1 (4.8)	20 (95.2)	>0.999
Yes	662 (96.9)	25 (3.8)	637 (96.2)	
Toilet facility shared with other households				
No	489 (71.6)	19 (3.9)	470 (96.1)	>0.999
Yes	194 (28.4)	7 (3.6)	187 (96.4)	
Toilet facility on-premise				
No	662 (96.9)	25 (3.8)	637 (96.2)	>0.999
Yes	21 (3.1)	1 (4.8)	20 (95.2)	
Overall, Se deficiency prevalence:	683 (100)	26 (3.8)	657 (96.2)	

Notes:

§ Plasma Se concentration <70 μg/L;

‡ Plasma Se concentration ≥70 μg/L;

*Significant at P <0·05;

†P value from Pearson's χ2 test.

Age categories and average household size used are based on previous demographic health surveys (33)

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potatoes (p <0.001), production of sugar beans (p <0.001) and production of onions (p <0.001) for household consumption, (Table 2) were significantly associated with Se deficiency in WRA (Pearson's χ2 test).

3.3. Factors associated with Se deficiency

3.3.1. Children 6–59 months. Child Se status was significantly associated with maternal Se status (p <0.001). The proportion of Se-deficient children was higher (98.7%) in Se-

Table 2. Sociodemographic characteristics of WRA in rural Zimbabwe by Se status.

Variable	Total n (% of category)	[‡]Se adequate n (%)	[§]Se deficient n (%)	P-value[†]
District				
Mutasa	203 (29.7)	108 (53.2)	95 (46.8)	<0.001*
Shamva	257 (37.6)	62 (24.1)	195 (75.9)	
Murewa	223 (32.7)	34 (15.2)	189 (84.8)	
Reproductive age (years)				
<18	15 (2.2)	9 (60.0)	6 (40.0)	
18–34	426 (62.4)	123 (28.9))	303 (71.1)	0.036*
≥35	242 (35.4)	72 (29.8)	170 (70.2)	
Marital status				
Married monogamy	567 (83.0)	170 (30.0)	397 (70.0)	0.888
Married polygamy	39 (5.7)	13 (33.3)	26 (66.7)	
Separated/divorced	46 (6.7)	14 (30.4)	32 (69.6)	
Single /never married	7 (1.0)	2 (28.6)	5 (1.0)	
Widowed	24 (3.5)	5 (20.8)	19 (79.2)	
Education status				
Tertiary	7 (1.0)	4 (57.1)	3 (42.9)	0.274
Advanced level	6 (0.9)	3 (50.0)	3 (50.0)	
Ordinary level	452 (66.2)	136 (30.1)	316 (69.9)	
Primary	205 (30.0)	59 (28.8)	146 (71.2)	
No formal education	13 (1.9)	2 (15.4)	11 (84.6)	
Number of children under 5 years in the household				
1	489 (71.6)	155 (31.7)	334 (68.3)	0.115
>1	194 (28.4)	49 (25.3)	145 (74.7)	
Household size				
≤4	265 (38.8)	76 (28.7)	189 (71.3)	0.608
>4	418 (61.2)	128 (30.6)	290 (69.4)	
Household monthly income (USD)				
<10	58 (8.5)	9 (15.5)	49 (84.5)	<0.001*
10–50	312 (45.7)	75 (24.0)	237 (76.0))	
51–110	170 (24.9)	67 (39.4)	103 (60.6)	
120–210	85 (12.4)	34 (40.0)	51 (60.0)	
>220	58 (8.5)	19 (32.8)	39 (67.2)	
Agricultural land ownership				
No	268 (39.2)	78 (29.1)	190 (70.9)	0.726
Yes	415 (60.8)	126 (30.4)	289 (69.6)	
Common crops grown for consumption				
Maize				
No	233 (36.0)	17 (7.3)	216 (92.7)	<0.001*
Yes	414 (64.0)	6 (1.4)	408 (98.6)	
Cowpeas				
No	337 (53.8)	21 (6.2)	316 (93.8)	<0.001*
Yes	289 (46.2)	2 (0.7)	287 (99.3)	
Groundnuts				
No	321 (51.3)	20 (6.2)	301 (93.8)	<0.001*
Yes	305 (48.7)	3 (1.0)	302 (99.0)	
Sugar beans				

(*Continued*)

Table 2. (Continued)

Variable	Total n (% of category)	‡Se adequate n (%)	§Se deficient n (%)	P-value†
No	425 (67.9)	22 (5.2)	403 (94.8)	<0.001*
Yes	201 (32.1)	1 (0.5)	200 (99.5)	
Sweet potatoes				
No	345 (55.1)	21 (6.1)	324 (93.6)	<0.001*
Yes	281 (44.9)	2 (0.7)	279 (99.3)	
Onions				
No	417 (66.6)	22 (5.3)	395 (94.7)	<0.001*
Yes	209 (33.4)	1 (0.5)	208 (99.5)	
Livestock commonly reared				
Chicken /poultry				
1	139 (20.4)	47 (33.8)	92 (66.2)	0.299
>1	544 (79.6)	157 (28.9)	387 (71.1)	
Unimproved dug wells as a source of drinking water				
No	485 (71.0)	168 (34.6)	317 (65.4)	<0.001*
Yes	198 (29.0)	36 (18.2)	162 (81.8)	
Location of water source				
Off-premise	454 (66.5)	137 (30.2)	317 (69.8)	0.658
In-house	24 (3.5)	9 (37.5)	15 (62.5)	
On-premise	205 (30.0)	58 (28.3)	147 (71.7)	
Insufficient water in the past month				
No	536 (78.4)	154 (28.6)	382 (71.4)	0.103
Yes	147 (21.6)	50 (34.0)	97 (66.0)	
Treatment of drinking water				
No	604 (88.4)	184 (30.5)	420 (69.5)	0.264
Yes	79 (11.6)	20 (25.3)	59 (74.7)	
Toilet facility				
No	21 (3.1)	3 (14.3)	18 (85.7)	0.147
Yes	662 (96.9)	201 (30.4)	461 (69.6)	
Toilet facility shared with other households				
No	489 (71.6)	140 (28.6)	349 (71.4)	0.267
Yes	194 (28.4)	64 (33.0)	130 (67.0)	
Toilet facility on-premise				
No	662 (96.9)	195 (29.5)	467 (70.5)	0.225
Yes	21 (3.1)	9 (42.9)	12 (57.1)	
Prevalence of Se deficiency (WRA):	683 (100)	204 (29.9)	479 (70.1)	

Notes:

§ Plasma Se concentration <70 μg/L;

‡ Plasma Se concentration ≥70 μg/L;

*Significance level P <0·05;

†P value from Pearson's Chi square test.

Age categories and average household size used are based on previous demographic health surveys [33]. Reproductive age represents the stage of conception where 18–34 years is the reference for optimal reproductive function established from the NHANES (2011–2012)sourced from [57].

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deficient mothers compared to Se-adequate mothers (90.2%) (Table 3), with older children being significantly more Se-deficient compared to the younger children. Among the Se-deficient mothers, children aged 6–8 months were the least Se-deficient (94.4%, p >0.999) while those in the age range 24–35 months were the most Se-deficient (100%, p = 0.004) S2 Table.

3.3.2. Women of reproductive age. There were no significant correlations between Se deficiency and height, body mass index, and anaemia in WRA (Table 4).

3.4. Predictors of Se deficiency in children 6–59 months and WRA

Being a girl (p = 0.035) and having a Se-deficient mother (p = 0.005) were predictors of Se deficiency in children (Table 5). Children whose mothers were Se deficient were 4 times more likely to be Se deficient compared to those whose mothers were not Se deficient (OR = 4.25; 95% CI; 1.55–11.67; p = 0.005) and female children were 3 times more likely to be Se deficient compared to male children (OR = 2.84; 95% CI; 1.08–7.51; p = 0.035). Women producing mainly maize for consumption were 0.5 times more likely to be Se deficient than those not growing maize mainly for consumption (OR = 0.47; 95% CI; 0.25–0.90; p = 0.022).

4. Discussion

4.1. Overview of the current study findings

The study sought to determine the predictors of Se deficiency in children aged 6–59 months and in WRA. It was evident that Se status was inversely associated with immediate determinants such as maternal Se deficiency while underlying determinants included food production practices and WASH, exacerbated by enabling determinants such as residency, income status, and gender. Determinants of inadequate Se status in both women and children included residency in the Murewa district, the use of unimproved dug wells as sources of drinking water, and the production of maize, sugar beans, groundnuts, cowpeas, sweet potatoes, and onions for household consumption. Maternal Se deficiency and being a girl were positively associated with Se deficiency in children. Reproductive age (18–34 years) and low monthly household income were positively associated with Se deficiency in WRA. Predictors of plasma Se status in children were maternal Se status and being a girl, whereas, in women, it was the production of maize as the main crop for consumption (Fig 2).

4.2. Sex differences in Se deficiency

Our results show that girls were more likely to be Se deficient than boys, consistent with previous studies in Vietnam [58] and Zimbabwe [34]. In contrast, studies in Ethiopia found no sex-related differences in Se status [3]. The micronutrient survey conducted in Zimbabwe also indicated a slightly higher prevalence of MNDs in girls than boys [59]. Exploration of sex-based factors that influence Se intake is outside the scope of this study however, the disparity in the prevalence of Se deficiency in girls and boys could be explained by physiological differences in the expression of deficiencies [60]; sexual dimorphic regulation of Se metabolism and selenoprotein expression, namely the trans-selenation pathway by sex hormones strongly implies that selenomethionine metabolism and its consequent selenocysteine formation and availability for selenoprotein synthesis are not the same in both sexes [61]. Selenium is concentrated in male gonads which could explain why male children had lower deficiency than female children [62]; or gender-based vulnerabilities [63, 64] influencing food intake [64]. In India, girls were more likely to be neglected than boys to receive nutritious diets [65], female children were breastfed for a shorter duration and had lower consumption of dairy food compared to male children [66]. These differences can be attributed to gender incongruence in the intra-

Table 3. Nutritional status and morbidities in children aged 6–59 months in rural Zimbabwe by Se status.

Variable	Total n (% of category)	‡ Se adequate n (%)	§Se deficient n (%)	P-value†
Stunted (HAZ)				
Below -2SD	177 (27.7)	3 (1.7)	174 (98.3)	0.106
-2SD and above	462 (72.3)	21 (4.5)	441 (95.5)	
Wasting (WHZ)				
Below -2SD	18 (2.8)	0 (0)	18 (100)	0.641
-2SD and above	623 (97.2)	24 (3.9)	599 (96.1)	
Underweight (WAZ)				
Below -2SD	89 (13.5)	4 (4.5)	85 (95.5)	>0.999
-2SD and above	572 (86.5)	22 (3.8)	550 (96.2)	
Low Birth Weight (kg)				
<2.5	58 (9.0)	1 (1.7)	57 (98.3)	0.498
≥2.5	590 (91.0)	24 (4.1)	566 (95.9)	
Exclusive Breastfeeding				
No	204 (30.6)	4 (2.0)	200 (98.0)	0.124
Yes	462 (69.4)	21 (4.5)	441 (95.5)	
Child still breastfeeding				
No	507 (76.0)	19 (3.7)	488 (96.3)	>0.999
Yes	160 (24.0)	6 (3.8)	154 (96.2)	
Vitamin A supplementation				
No	162 (24.7)	4 (2.5)	158 (97.5)	0.368
Yes	493 (75.3)	21 (4.3)	472 (95.7)	
MNP supplementation				
No	598 (90.6)	20 (3.3)	578 (96.7)	0.124
Yes	62 (9.4)	5 (8.1)	57 (91.9)	
Deworming				
No	490 (76.0)	17 (3.5)	473 (96.5)	0.858
Yes	155 (24.0)	7 (4.5)	148 (95.5)	
Diarrhea				
No	503 (75.4)	17 (3.4)	486 (96.6)	0.496
Yes	164 (24.6)	8 (4.9)	156 (95.1)	
Fever				
No	439 (65.8)	17 (3.9)	422 (96.1)	0.842
Yes	228 (34.2)	8 (3.5)	220 (96.5)	
Respiratory tract infection				
No	430 (64.5)	20 (4.7)	410 (95.3)	0.167
Yes	237(35.5)	5 (2.1)	232 (97.9)	
Anaemia Hb level <11 g / dL				
No	307 (71.9)	16 (5.2)	291 (94.8)	0.461
Yes	120 (28.1)	4 (3.3)	116 (96.7)	
Maternal Se status				
Deficient	479 (70.1)	6 (1.3)	473 (98.7)	<0.001*
Adequate	204 (29.9)	20 (9.8)	184 (90.2)	

Notes: HAZ, height-for-age Z-score; WHZ, weight-for-height Z-score; WAZ, weight-for-age Z-score; SD, Standard deviation;

§ Plasma Se concentration level < 70 μg/L;

‡Plasma Se concentration ≥70 μg/L;

*Significance level P <0·05;

†P value from Pearson's Chi square test.

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Table 4. Nutritional status of WRA in rural Zimbabwe by Se status.

Variable	Total n (% of category)	‡Se–adequate n (%)	§Se deficient n (%)	P-value†
Anaemia Status (haemoglobin g/dL)				
<12	88 (19.8)	30 (34.1)	58 (65.9)	0.463
≥12	357 (80.2)	138 (38.7)	219 (61.3)	
Height (cm)				
<145	8 (1.2)	4 (50.0)	4 (50.0)	0.248
≥145	675 (98.8)	200 (29.6)	475 (70.4)	
Body Mass Index (kg/m2)				
<18.5	74 (10.8)	16 (21.6)	58 (78.4)	0.108
≥18.5	609 (89.2)	188 (30.9)	421 (69.1)	
Nutritional Status				
Underweight	74 (10.9)	16 (8.0)	58 (78.4)	
Normal weight	353 (52.1)	100 (28.3)	253 (71.7)	
Overweight	180 (26.6)	59 (32.8)	121(67.2)	0.087
Class I obese	48 (7.1)	21 (43.8)	27 (56.2)	
Class II obese	13 (1.9)	2 (15.4)	11 (84.6)	
Morbid obese	9 (1.3)	2 (22.2)	7 (77.8)	
Prevalence of Se deficiency	683 (100)	204 (29.9)	479 (70.1)	

Notes:

§ Plasma Se concentration <70 μg / L;

‡ Plasma Se concentration ≥70 μg / L;

†P value significant at $p < 0.05$ from Pearson's Chi-square test.

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household food allocation for children, which is affected by cultural norms in society and women's empowerment in households [67]. In Zimbabwe, sex vulnerability to MNDs is not considered in micronutrient supplementation programming for children aged 6–59 months. Currently, there is a provision of multiple micronutrient powders (MNPs) for point-of-use fortification, a blanket program targeted for children 6–23 months in select districts. Sex variabilities could be implemented in MNP supplementation, as seen in growth monitoring, where growth charts target individual sexes [44]. Multiple micronutrient powders targeted for girls would contain higher Se concentrations >17 μg/g [68] relative to boys, within the upper tolerable limit for Se of 400 μg/day [69]. The recommendation, therefore, would be to conduct further studies at scale to validate the sex disparity and potentially increase the Se concentration of MNPs targeted for girls.

4.3. Maternal Se status and risk of deficiency in children

In this study, maternal Se deficiency was positively associated with childhood Se deficiency. The prevalence of Se deficiency in children from Se deficient WRA was four times higher compared to their counterparts. Intergenerational transmission of micronutrient status was observed in Malawi, Mozambique, Namibia [70] and Zimbabwe [37]. Selenium plays a significant role in female reproductive processes [71] and its deficiency during pregnancy and lactation influences nutrition outcomes in children [72–74]. Our results indicated a lower prevalence of Se deficiency in younger children and a higher prevalence in older children among Se-deficient mothers this can be attributed to the protective effect of breastfeeding. The current study shows a high prevalence of breastfeeding, with an exclusive breastfeeding rate

Table 5. Predictors of Se deficiency among children aged 6–59 months and WRA from rural Zimbabwe.

Variable	B	S.E.	P value[†]	OR	95% C.I.	
					Lower	Upper
Children (6–59 months)						
Murewa district No = 0; Yes = 1	0.29	0.32	0.37	1.33	0.71	2.50
Se deficient mother Adequate = 0; Deficient = 1	1.45	0.52	0.005*	4.25	1.55	11.67
Being a girl (Male = 0; Female = 1)	1.05	0.50	0.035*	2.84	1.08	7.51
Unimproved dug well as a water source (Improved dug well = 0; unimproved = 1)	-0.07	0.91	0.939	0.93	0.16	5.59
Maize production for consumption (No = 0; Yes = 1)	-0.84	0.84	0.319	0.43	0.08	2.25
Cowpea production for consumption (No = 0; Yes = 1)	-0.79	1.18	0.515	0.46	0.05	4.59
Groundnut production for consumption (No = 0; Yes = 1)	0.184	1.037	0.859	1.20	0.16	9.18
Sugar bean production for consumption (No = 0; Yes = 1)	-0.46	1.09	0.675	0.63	0.08	5.36
Sweet potato production for consumption (No = 0; Yes = 1)	-0.72	1.24	0.560	0.49	0.04	5.50
Onion production for consumption (No = 0; Yes = 1)	-0.98	1.23	0.422	0.37	0.03	4.13
Women of Reproductive Age						
Murewa District No = 0; Yes = 1	-0.15	0.13	0.233	0.86	0.68	1.10
Unimproved dug well as a water source (improved = 0; unimproved = 1)	-0.05	0.26	0.850	0.95	0.57	1.59
Reproductive age 18–34 years (<18≥35 years = 0; 18–34 years = 1)	0.02	0.19	0.927	1.02	0.71	1.47
Monthly income below 10 USD (≥10 USD = 0; <10USD = 1)	-0.55	0.44	0.213	0.58	0.25	1.37
Maize production for consumption (No = 0; Yes = 1)	-0.75	0.329	0.022*	0.47	0.247	0.897
Cowpea production for consumption (No = 0; Yes = 1)	-0.14	0.35	0.697	0.87	0.44	1.73
Groundnut production for consumption (No = 0; Yes = 1)	-0.11	0.35	0.755	0.90	0.45	1.78
Sugar bean production for consumption (No = 0; Yes = 1)	-0.26	0.31	0.396	0.77	0.43	1.40
Sweet potato production for consumption (No = 0; Yes = 1)	-0.32	0.34	0.335	0.72	0.38	1.40
Onion production for consumption (No = 0; Yes = 1)	0.00	0.3	0.999	1.00	0.56	1.80

Notes: Selenium deficient mother; Plasma Se concentration <70 μg / L; Selenium adequate mother; Plasma Se concentration ≥70 μg / L,

[†]P value from multiple logistic regression analysis;

*Significant at P<0·05, by the Enter regression model.

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higher than the WHO target (50%) and the global average (44%) [75]. Most Zimbabwean mothers breastfeed their babies for up to 2 years and sometimes beyond [32]. Breastmilk is an important source of Se providing median Se concentrations of up to 15–26 μg/L [76]. The Se concentration and glutathione peroxidase activity in human milk is influenced directly by the

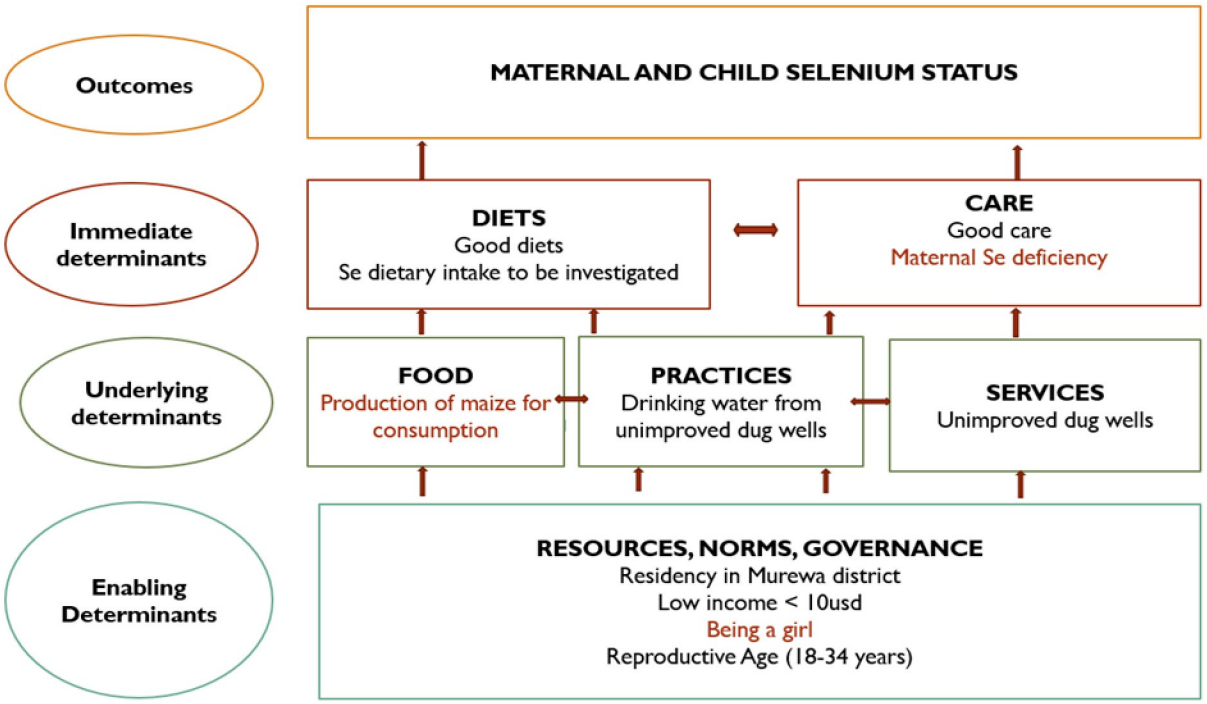

Fig 2. Maternal and child plasma Se deficiency causal framework predictors (red) and determinants (black) for Murewa, Shamva, and Mutasa districts, rural Zimbabwe.

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Se intake of the mother [76–79]. Furthermore, the current study also showed that WRA 18–34 years were the most Se deficient, attributable to the depletion of micronutrient stores due to successive pregnancies and breastfeeding episodes common at this optimal reproductive phase [73]. Selenium concentrations were reported to be low in women of reproductive age in the United Kingdom, decreasing further during pregnancy, thus resulting in low plasma and placental antioxidant enzyme activities [80]. Multiple micronutrient supplementation during pregnancy indicated an upward trend in Se concentration across semesters [81]. The recommendation for Zimbabwe is to scale up the MNP supplementation for children 6–59 months and to initiate maternal multiple micronutrient supplementation for WRA in addition to iron and folate supplementation currently being given during pregnancy, from preconception through lactation, proven to reduce MNDs in both children and women [82]. Further research into placental transfer of Se in utero, diet quality, and birth order which can affect Se sufficiency/insufficiency postpartum is recommended to validate the findings of the current study.

4.4. Maize production for consumption increases the risk of Se deficiency

Primarily, the production of maize for consumption predicted low Se status in women. Maize is the staple crop in Zimbabwe with an estimated maize production of over two million metric tonnes [83]. The average maize consumption for adults in Zimbabwe is over 250 g/person/day, with an energy supply accounting for ~3500 kJ/capita/day [84, 85]. The high consumption of maize makes it a major contributor to dietary Se [29, 86], consumption of 100 grams/person/day of maize contributes to MNDs, Se included [85]. Similar findings were reported in Malawi where Se deficiency is widespread [22], potentially as a result of a Se-deficient maize crop [86], and might consequently be mirrored with human Se status [87]. In Ethiopia, the risk of

human Se deficiency was also associated with the staple diet [88]. Based on our findings, Se agronomic biofortification of the staple crop with fertiliser or point-of-use fortification may be necessary. Minute quantities of Se are required to result in meaningful contributions to grain Se concentration and dietary intake. Studies in Malawi and Ethiopia have shown that agronomic biofortification of staple crops with 20 g/hectare Se has the potential to increase grain Se concentration [89, 90]. Cognisant of that, soil Se concentrations are the primary driver of population Se status, future research should involve the examination of soil, crop, and dietary Se concentrations (for example whole foods using total diet data) to define whether there is a generalized deficiency in these regions. This may be particularly relevant given homestead farming may not regulate the use of fertilizers and/or biofortified crops. Further to this, maize grain in Zimbabwe has been implicated with mycotoxin contamination mainly *fusarium* [91]. *Fusarium* produces T-2 toxin as a secondary metabolite whose synergistic effects with Se deficiency pose potential detrimental health hazards to the Se-deficient population [92]. Investigation of this correlation might be warranted.

5. Limitations of study

The current study is exploratory, tests of statistical significance should be interpreted with caution as false positives may occur due to multiple comparisons. Further studies are warranted to confirm the results. Additionally, the study did not include dietary assessments that could have provided evidence on the foods contributing to Se intake, to assess implications for human Se status. Regardless, the present study contributes to our knowledge of the association between maternal and child Se deficiency.

6. Conclusions

The current study showed that being a girl and maternal Se deficiency were positively associated with Se deficiency in children aged 6–59 months while maize crop production was positively associated with Se deficiency in WRA. Interventions that focus on improving conceptual and maternal nutritional status, micronutrient supplementation, and biofortification may be important strategies to reduce Se deficiency in vulnerable populations from low and lower-middle-income countries in Africa.

Supporting information

S1 Table. Correlation between plasma Se concentration and acute phase proteins.
(DOCX)

S2 Table. Correlation between child and maternal Se status stratified by child age group.
(DOCX)

S1 Data.
(ZIP)

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References

1. Ligowe IS, Phiri FP, Ander EL, Bailey EH, Chilimba ADC, Gashu D, et al. Selenium deficiency risks in sub-Saharan African food systems and their geospatial linkages. NS. 2020; 4. Available from: https://doi.org/10.1017/S0029665120006904 PMID: 32264979
2. Mutonhodza B, Joy EJM, Bailey EH, Lark MR, Kangara MGM, Broadley MR, et al. Linkages between soil, crop, livestock, and human selenium status in Sub-Saharan Africa: a scoping review. Vol. 57, International Journal of Food Science and Technology. 2022: 6336–49. Available from: https://ifst.onlinelibrary.wiley.com/doi/10.1111/ijfs.15979 PMID: 36605250
3. Gashu D, Stoecker BJ, Bougma K, Adish A, Haki GD, Marquis GS. Stunting, selenium deficiency and anemia are associated with poor cognitive performance in preschool children from rural Ethiopia. Nutr J. 2016; 15(1):1–8. Available from: http://dx.doi.org/10.1186/s12937-016-0155-z PMID: 27067274
4. Rosen BP, Liu Z. Transport pathways for arsenic and selenium: A minireview. Vol. 35, Environment International. Elsevier Ltd; 2009: 512–5. https://doi.org/10.1016/j.envint.2008.07.023 PMID: 18789529
5. Barchielli G, Capperucci A, Tanini D. The role of selenium in pathologies: An updated review. Antioxidants. 2022; 11(2). https://doi.org/10.3390/antiox11020251 PMID: 35204134
6. Fordyce FM. Selenium deficiency and toxicity in the environment. In: Essentials of Medical Geology: Revised Edition. 2013: 375–416.
7. Gashu D, Nalivata PC, Amede T, Ander EL, Bailey EH, Botoman L, et al. The nutritional quality of cereals varies geospatially in Ethiopia and Malawi. Nature. 2021 Jun 3; 594(7861):71–6. https://doi.org/10.1038/s41586-021-03559-3 PMID: 34012114
8. Kieliszek M, Błażejak S. Selenium: Significance, and outlook for supplementation. Nutrition. 2013 May 29(5):713–8. https://doi.org/10.1016/j.nut.2012.11.012 PMID: 23422539
9. Joy EJM, Ander EL, Young SD, Black CR, Watts MJ, Chilimba ADC, et al. Dietary mineral supplies in Africa. Physiol Plant. 2014; 151(3):208–29. https://doi.org/10.1111/ppl.12144 PMID: 24524331

10. Wang J, Wang H, Chang S, Zhao L, Fu P, Yu W, et al. The influence of malnutrition and micronutrient status on anemic risk in children under 3 years old in poor areas in China. Chemosphere.2015; 52 (2),585–593. https://doi.org/10.1371/journal.pone.0140840 PMID: 26488490

11. Guillin OM, Vindry C, Ohlmann T, Chavatte L. Selenium, selenoproteins and viral infection. Vol. 11, Nutrients. 2019. 1–33. https://doi.org/10.3390/nu11092101 PMID: 31487871

12. World Health Organization (WHO). HIV/AIDS. World Health Organization. Geneva, Switzerland. 2018. https://www.afro.who.int/health-topics/hivaids

13. Navarro-Alarcon M, Cabrera-Vique C. Selenium in food and the human body: A review. Elsevier, Science Direct.2008: 116–140; https://doi.org/10.1016/j.scitotenv.2008.06.024 PMID: 18657851

14. Fairweather-Tait SJ, Bao Y, Broadley MR, Collings R, Ford D, Hesketh JE, et al. Selenium in human health and disease. Vol. 14, Antioxidants and Redox Signaling. 2011. p. 1337–83. https://doi.org/10.1089/ars.2010.3275 PMID: 20812787

15. Schönfeldt HC, Hall NG. Dietary protein quality and malnutrition in Africa. Br J Nutr. 2012; 108(SUPPL. 2). https://doi.org/10.1017/S0007114512002553 PMID: 23107550

16. Abrahams Z, McHiza Z, Steyn NP. Diet and mortality rates in Sub-Saharan Africa: Stages in the nutrition transition. BMC Public Health. 2011; 11. https://doi.org/10.1186/1471-2458-11-801 PMID: 21995618

17. Onyango AW. Dietary diversity, child nutrition and health in contemporary African communities. Comparative Biochemistry and Physiology—A Molecular and Integrative Physiology. 2003: 61–69. https://doi.org/10.1016/s1095-6433(03)00071-0 PMID: 14527630

18. Saha U. Selenium in the soil-plant environment: A Review. Int J Appl Agric Sci. 2017 Jan 12; 3(1):1. https://doi.org/10.11648/j.ijaas.20170301.11

19. Mayland H. F. James L. F. Panter K. SJL E. Selenium in seleniferous environments. Soil Sci. Soc. Am. J. 23: 1989:15–50. Available from: 166. https://www.semanticscholar.org/paper/Selenium-in-Seleniferous-Environments-Mayland-James/0c758f7b2f418d927907a2dbe97bb963c64ac949

20. Elliott, Pas SA. Dynamics of selenium nutrition of animals in relation to human health. Intermountain Nutrition Conference Proceedings. Salt Lake City. Utah.1996.

21. Rayman MP. Selenium and human health. Lancet. 2012 Mar; 379(9822):1256–68. https://doi.org/10.1016/S0140-6736(11)61452-9 PMID: 22381456

22. Phiri FP, Ander EL, Bailey EH, Chilima B, Chilimba ADC, Gondwe J, et al. The risk of selenium deficiency in Malawi is large and varies over multiple spatial scales. Sci Rep. 2019; 9(1):43013. https://doi.org/10.1038/s41598-019-43013-z PMID: 31024041

23. Galloway P, McMillan DC, Sattar N. Effect of the inflammatory response on trace element and vitamin status. Ann Clin Biochem. 2000; 37(3):289–97. https://doi.org/10.1258/0004563001899429 PMID: 10817241

24. Thurnham DI. Inflammation and Biomarkers of Nutrition. Sight Life Mag Front Nutr. 2015; 2015(1):51–9. https://doi.org/10.52439/bszl2497

25. Combs GF, Watts JC, Jackson MI, Johnson LK, Zeng H, Scheett AJ, et al. Determinants of selenium status in healthy adults. Nutr J. 2011; 10(1):1–10. https://doi.org/10.1186/1475-2891-10-75 PMID: 21767397

26. Fontenelle LC, Cardoso de Araújo DS, da Cunha Soares T, Clímaco Cruz KJ, Henriques GS, Marreiro D do N. Nutritional status of selenium in overweight and obesity: A systematic review and meta-analysis. Clin Nutr. 2022 Apr 1; 41(4):862–84. Available from: http://www.clinicalnutritionjournal.com/article/S026156142200053X/fulltext PMID: 35276570

27. Mathias PM, Jackson AA. Selenium deficiency in kwashiorkor. Lancet. 1982 Jun 5; 319(8284):1312–3. https://doi.org/10.1016/s0140-6736(82)92883-5 PMID: 6123056

28. Gashu D, Marquis GS, Bougma K, Stoecker BJ. Spatial variation of human selenium in Ethiopia. Biol Trace Elem Res. 2018; 1489. https://doi.org/10.1007/s12011-018-1489-5 PMID: 30167960

29. Joy EJM, Kumssa DB, Broadley MR, Watts MJ, Young SD, Chilimba ADC, et al. Dietary mineral supplies in Malawi: spatial and socioeconomic assessment. BMC Nutr. 2015 Dec; 1(1). https://doi.org/10.1186/s40795-015-0036-4

30. Headey DD, Ruel MT. Economic shocks predict increases in child wasting prevalence. Nat Commun. 2022; 13(1). Available from: https://doi.org/10.1038/s41467-022-29755-x PMID: 35444216

31. World Bank. Zimbabwe economic update: COVID-19 further complicates Zimbabwe's economic and social conditions. World bank. 2021. https://www.worldbank.org/en/country/zimbabwe

32. Ministry of Health and Child Care (MoHCC). Zimbabwe national nutrition survey 2018. Nutrition. Harare, Zimbabwe. 2018; https://www.unicef.org/zimbabwe/media/1056/file/Zimbabwe%202018%20National%20Nutrition%20Survey%20Report.pdf

33. Zimbabwe National Statistics Agency (ZIMSTAT). Zimbabwe demographic and health survey 2015. 2015 https://dhsprogram.com/pubs/pdf/FR322/FR322.pdf

34. Kuona P, Mashavave G, Kandawasvika GQ, Dzangare J, Masanganise M, Chandiwana P, et al. Serum selenium levels and nutritional status of school children from an HIV prevention programme in Zimbabwe. J Trop Dis. 2014; 02(02) 1–8. https://doi.org/10.4172/2329-891x

35. Mutonhodza B, Chagumaira C, Dembedza MP, Joy EJ, Manzeke-Kangara MG, Njovo H, et al. A pilot survey of selenium status and its geospatial variation among children and women in three rural districts of Zimbabwe. Frontiers in nutrition. 2023;(July). https://doi.org/10.3389/fnut.2023.1235113 PMID: 37497053

36. United Nations International Children's Emergency Fund (UNICEF). Conceptual framework on maternal and child nutrition. Nutr Child Dev Sect Program Gr 3 United Nations Plaza New York, NY 10017, USA [Internet]. 2021;2–3. www.unicef.org/nutrition

37. Mutonhodza B, Dembedza MP, Lark MR, Joy EJM, Manzeke-Kangara MG, Njovo H, et al. Anemia in children aged 6–59 months was significantly associated with maternal anemia status in rural Zimbabwe. Food Sci Nutr. 2022;(November):1–15. https://doi.org/10.1002/fsn3.3157 PMID: 36911837

38. Mutonhodza B, Dembedza MP., Joy EJ M., Manzeke-Kangara MG., Njovo H, Nyadzayo TK, et al. Urine Se concentration poorly predicts plasma Se concentration at sub-district scales in Zimbabwe, limiting its value as a biomarker of population Se status. Frontiers in nutrition. 2024;(February):1–11. https://doi.org/10.3389/fnut.2024.1288748 PMID: 38385014

39. Zimbabwe National Statistics Agency (ZIMSTAT). Zimbabwe population census 2012 Population Census Office. 2012. Harare, Zimbabwe. http://worldpopulationreview.com/countries/Zimbabwe/

40. Jabkowski P. A meta-analysis of within-household selection impact on survey outcome rates, demographic representation and sample quality in the European social survey. Ask Res Methods. 2017; 26 (1):31–60. https://doi.org/10.18061/1811/81932

41. Centres for Disease Control and Prevention (CDC). Mapping public health. CDC museum. 2020:1–10. https://www.cdc.gov/museum/pdf/cdcm-pha-stem-mapping-public-health-lesson.pdf

42. World Health Organization (WHO). World Health Organization. Training course on child growth assessment. WHO Geneva, Switzerland. 2008. http://www.who.int/childgrowth/training/module_b_measuring_growth.pdf

43. Ralston ME, Myatt MA. Weight estimation for children aged 6 to 59 months in limited-resource settings: A proposal for a tape using height and mid-upper arm circumference. PLoS One 2018 Jun 1; 13(6).

44. World Health Organization (WHO) multicentre growth reference study group. WHO Child Growth Standards: Length/height-for-age, weight-for-age, weight-for-length, weight-forheight and body mass index-for-age: methods and development. Geneva, Switzerland. Acta Pædiatrica 2006; 95:76–85. https://www.who.int/publications/i/item/924154693X

45. Erhardt, Golden, Michael; Seaman, John; Biluka O. ENA for SMART 2011. 2015. http://www.nutrisurvey.de/ena/ena.html

46. World Health Organization. Guidelines on optimal feeding of low birth-weight infants in low-and middle-income countries. WHO Geneva, Switzerland. 2011;16–45. https://www.who.int/publications-detail-redirect/9789241548366

47. World Health Organization (WHO). Global database on body mass index (BMI) classification. WHO Geneva, Switzerland. 2011;(Table 1):36–7. https://www.who.int/data/gho/data/themes/topics/topic-details/GHO/body-mass-index

48. Sumarmi S. Maternal short stature and neonatal stunting: An inter-generational cycle of malnutrition. Int Conf Heal Well-Being. 2016;(August):265–72. Sarubaya, Indonesia. https://publikasiilmiah.ums.ac.id/handle/11617/7411

49. Kozuki N, Lee AC, Silveira MF, Sania A, Vogel JP, Adair L, et al. The associations of parity and maternal age with small-for-gestational-age, preterm, and neonatal and infant mortality: A meta-analysis. BMC Public Health. 2013; 13(SUPPL.3). https://doi.org/10.1186/1471-2458-13-S3-S2 PMID: 24564800

50. World Health Organization (WHO). Micronutrient survey manual. 2020. WHO, Geneva, Switzerland. file:///C:/Users/Harrison/Desktop/Blutooth/9789240012691-eng.pdf

51. Centres for Disease Control and Prevention (CDC). A Quick-Reference Tool for Hemolysis Status. May. 2021. Atlanta, Georgia, USA. https://www.cdc.gov/vector-borne-diseases/php/laboratories/reference-tool-for-hemolysis-status.html

52. Erhardt JG, Estes JE, Pfeiffer CM, Biesalski HK, Craft NE. Combined measurement of ferritin, soluble transferrin receptor, retinol binding protein, and C-reactive protein by an inexpensive, sensitive, and simple sandwich enzyme-linked immunosorbent assay technique. J Nutr. 2004; 134(11):3127–32. https://doi.org/10.1093/jn/134.11.3127 PMID: 15514286

53. Belay A, Joy EJM, Chagumaira C, Zerfu D, Ander EL, Young SD, et al. Selenium deficiency is widespread and spatially dependent in Ethiopia. Nutrients. 2020; 12(6):1–17. https://doi.org/10.3390/nu12061565 PMID: 32471236

54. Suchdev PS, Namaste SML, Aaron GJ, Raiten DJ, Brown KH, Flores-Ayala R. Overview of the biomarkers reflecting inflammation and nutritional determinants of anemia (BRINDA) project. Adv Nutr. 2016; 7(2):349–56. Available from: https://academic.oup.com/advances/article/7/2/349/4558049 PMID: 26980818

55. Chagumaira C, Chimungu JG, Gashu D, Nalivata PC, Broadley MR, Milne AE, et al. Communicating uncertainties in spatial predictions of grain micronutrient concentration. Geosci Commun. 2021; 4 (2):245–65. https://doi.org/10.5194/gc-4-245-2021

56. Zimbabwe National Statistics Agency (ZIMSTAT). Poverty datum lines-May 2021 Main findings concepts and definitions of the lower bound poverty line. 2021; Harare. Zimbabwe. https://www.zimstat.co.zw/wp-content/uploads/publications/Income/Finance/Poverty-Report-2011.pdf

57. Kozuki N, Katz J, Lee ACC, Vogel JP, Silveira MF, Sania A, et al. Short maternal stature increases risk of small-for-gestational-age and preterm births in low- and middle-income countries: Individual participant data meta-analysis and population attributable fraction. J Nutr. 2015 Nov 1; 145 (11):2542–50. Available from: https://academic.oup.com/jn/article/145/11/2542/4616078 PMID: 26423738

58. Van Nhien N, Khan NC, Yabutani T, Ninh NX, Chung LTK, Motonaka J, et al. Relationship of low serum selenium to anemia among primary school children living in rural Vietnam. J Nutr Sci Vitaminol (Tokyo). 2008; 54(6):454–9. https://doi.org/10.3177/jnsv.54.454 PMID: 19155583

59. Ministry of Health and Child Welfare. Zimbabwe national micronutrient survey results, 2012. Harare, Zimbabwe; 2015. https://fliphtml5.com/lvgve/xtvv/basic/

60. Darnton-Hill I, Webb P, Harvey PWJ, Hunt JM, Dalmiya N, Chopra M, et al. Micronutrient deficiencies and gender: Social and economic costs. Am J Clin Nutr. 2005; 81(5):1198–205. https://doi.org/10.1093/ajcn/81.5.1198 PMID: 15883452

61. Seale LA, Ogawa-Wong AN, Berry MJ. Sexual dimorphism in selenium metabolism and selenoproteins. Free Radic Biol Med. 2018; 127:198–205. https://doi.org/10.1016/j.freeradbiomed.2018.03.036 PMID: 29572096

62. Vindry C, Ohlmann T, Chavatte L. Selenium metabolism, regulation, and sex differences in mammals. Mol Integr Toxicol. 2018;89–107. https://link.springer.com/chapter/10.1007/978-3-319-95390-8_5

63. Food and Agricultural Organization (FAO). Policy on gender equality 2020–2030. 2020;28. http://www.wipo.int/amc/en/mediation/rules

64. Ndiku M, Jaceldo-Siegl K, Singh P, Sabaté J. Gender inequality in food intake and nutritional status of children under 5 years old in rural Eastern Kenya. Eur J Clin Nutr. 2011; 65(1):26–31. https://doi.org/10.1038/ejcn.2010.197 PMID: 20877393

65. Borooah VK. Gender bias among children in India in their diet and immunisation against disease. Soc Sci Med. 2004; 58(9):1719–31. https://doi.org/10.1016/S0277-9536(03)00342-3 PMID: 14990373

66. Fledderjohann J, Agrawal S, Vellakkal S, Basu S, Campbell O, Doyle P, et al. Do girls have a nutritional disadvantage compared with boys? Statistical models of breastfeeding and food consumption inequalities among Indian siblings. PLoS One. 2014; 9(9). https://doi.org/10.1371/journal.pone.0107172 PMID: 25229235

67. Li H, Kim Y, Park C, Kang M, Kang Y. Gender-common and gender-specific determinants of child dietary diversity in eight Asia Pacific countries. J Glob Health. 2022; 12. https://doi.org/10.7189/jogh.12.04058 PMID: 36181506

68. World Food Programme (WFP). Technical specifications for micronutrient powder–children 6–59 months. 2015; MIXMNP000(25/05/2016):2–6. http://www.hftag.org

69. World Health Organization (WHO). Selenium in drinking-water. In background document for preparation of WHO guidelines for drinking-water quality. In World Health Organization (WHO/SDE/ WSH/0304/13): Geneva, Switzerland. 2003. https://www.who.int/docs/default-source/wash-documents/wash-chemicals/selenium-2003-background-document.pdf?sfvrsn=624fa2c0_4

70. Ntenda PAM, Nkoka O, Bass P, Senghore T. Maternal anemia is a potential risk factor for anemia in children aged 6–59 months in Southern Africa: A multilevel analysis. BMC Public Health. 2018; 18(1):1–13. https://doi.org/10.1186/s12889-018-5568-5 PMID: 29788935

71. Qazi IH, Angel C, Yang H, Pan B, Zoidis E, Zeng CJ, et al. Selenium, selenoproteins, and female reproduction: A review. Molecules. 2018; 23(12):1–24. https://doi.org/10.3390/molecules23123053 PMID: 30469536

72. Pieczyńska J, Grajeta H. The role of selenium in human conception and pregnancy. J Trace Elem Med Biol. 2015; 29:31–8. https://doi.org/10.1016/j.jtemb.2014.07.003 PMID: 25175508

73. Cane M, Chidassicua B, Craveiro I. Anemia in pregnant women and children aged 6 to 59 months living in Mozambique and Portugal: An overview of systematic reviews. 2022; 13; 19(8):4685. https://doi.org/10.3390/ijerph19084685 PMID: 35457552

74. Martorell R, Zongrone A. Intergenerational influences on child growth and undernutrition. Paediatr Perinat Epidemiol. 2012 Jul [cited 2022 May 18]; 26 Suppl 1(SUPPL. 1):302–14. Available from: https://pubmed.ncbi.nlm.nih.gov/22742617/ https://doi.org/10.1111/j.1365-3016.2012.01298.x

75. United Nations International Children's Emergency Fund (UNICEF). Home—Global Nutrition Report. 2021. https://globalnutritionreport.org/

76. Dorea JG. Selenium and breast-feeding. Br J Nutr. 2002 Nov; 88(5):443–61. https://doi.org/10.1079/BJN2002692 PMID: 12425725

77. Smith AM, Picciano MF, Milner JA. Selenium intakes and status of human milk and formula fed infants. Am J Clin Nutr. 1982; 35(3):521–6. https://doi.org/10.1093/ajcn/35.3.521 PMID: 7064903

78. Mannan S, Picciano MF. Influence of maternal selenium status on human milk selenium concentration and glutathione peroxidase activity. Am J Clin Nutr. 1987 Jul 1; 46(1):95–100. Available from: https://academic.oup.com/ajcn/article/46/1/95/4694663 PMID: 3604976

79. Varsi K, Bolann B, Torsvik I, Eik TCR, Høl PJ, Bjørke-Monsen AL. Impact of maternal selenium status on infant outcome during the first 6 months of life. Nutrients. 2017 May 11; 9(5). https://doi.org/10.3390/nu9050486 PMID: 28492511

80. Duntas LH. Selenium and at-risk pregnancy: challenges and controversies. Thyroid Res. 2020; 13 (1):1–12. https://doi.org/10.1186/s13044-020-00090-x PMID: 33014140

81. Zhang M, Zhang Z, Zhu G, Liu Y, Xia C, Qi L, et al. The dynamic change of urinary selenium concentration during pregnancy and influencing factors: A longitudinal study. J Trace Elem Med Biol. 2022 May 1; 71:126960. https://doi.org/10.1016/j.jtemb.2022.126960 PMID: 35219977

82. Christian P. Evidence of multiple micronutrient supplementation (MMS) in pregnancy. Sight Life Mag Front Nutr. 2015; 2015(1):28–34. https://doi.org/10.52439/bbhv2384

83. Ministry of Lands, Agriculture, Water, Climate and Rural Resettlement (MoLAWCRR). Zimbabwe first round crop and livestock assessment report 2019 / 2020 season Ministry of Lands, Agriculture, Water and Rural Resettlement. Minist Lands, Agric Water, Clim Rural Resettl. 2020;(February). https://fscluster.org/sites/default/files/documents/2nd_round_assessment_report_2020_draft_26_may.pdf

84. Food and Agricultural Organization (FAO). FAOSTAT Database.4-year average (2010–2013) FAOSTAT Food Supply records. FOOD Agric. 2020; FAO, Rome, Italy.

85. Galani YJH, Orfila C, Gong YY. A review of micronutrient deficiencies and analysis of maize contribution to nutrient requirements of women and children in Eastern and Southern Africa. Crit Rev Food Sci Nutr. 2022; 62(6):1568–91. https://doi.org/10.1080/10408398.2020.1844636 PMID: 33176441

86. Chilimba ADC, Young SD, Black CR, Rogerson KB, Ander EL, Watts MJ, et al. Maize grain, and soil surveys reveal suboptimal dietary selenium intake is widespread in Malawi. Sci Rep. 2011; 1:1–9. https://doi.org/10.1038/srep00072 PMID: 22355591

87. Gibson RS, Bailey KB, Ampong Romano AB, Thomson CD. Plasma selenium concentrations in pregnant women in two countries with contrasting soil selenium levels. J Trace Elem Med Biol 2011; 25 (4):230–5. Available from: http://dx.doi.org/10.1016/j.jtemb.2011.10.001 PMID: 22056089

88. Gashu D, Lark RM, Milne AE, Amede T, Bailey EH, Chagumaira C, et al. Spatial prediction of the concentration of selenium (Se) in grain across part of Amhara Region, Ethiopia. Sci Total Environ. 2020 Sep 1; 733. https://doi.org/10.1016/j.scitotenv.2020.139231 PMID: 32446063

89. Ligowe IS, Young SD, Ander EL, Kabambe V, Chilimba ADC, Bailey EH, et al. Agronomic biofortification of leafy vegetables grown in an Oxisol, Alfisol and Vertisol with isotopically labelled selenium (77Se). Geoderma. 2020; 361(November 2019):114106. Available from: https://doi.org/10.1016/j.geoderma.2019.114106

90. Manzeke-Kangara M.G., Amede T., Bailey E.H., Wilson L., Mossa A.W., Tirfessa D., et al. Landscape and micronutrient fertilizer effect on agro-fortified wheat and teff grain nutrient concentration in Western Amhara. Agronomy. 2023; 13(2598). https://doi.org/10.3390/agronomy13102598

91. Nleya N, Adetunji MC, Mwanza M. Current status of mycotoxin contamination of food commodities in Zimbabwe. Toxins (Basel). 2018; 10(5). https://doi.org/10.3390/toxins10050089 PMID: 29751574

92. Liu H, Lin X, Chilufya MM, Qiao L, Bao M, Wen X, et al. Synergistic effects of T-2 toxin and selenium deficiency exacerbate renal fibrosis through modulation of the ERα/PI3K/Akt signaling pathway. Ecotoxicol Environ Saf. 2024; 269(November 2023). https://doi.org/10.1016/j.ecoenv.2023.115748 PMID: 38029582