

Research Article

Nutrient Patterns and Their Associations with Clinical Malaria Among Children Aged 6-23 Months in Siaya County, Kenya: A Cross-sectional Analysis

Michael Mbata^{1,2}, Charles Angira¹, Shehu Awandu¹, John Oguso², Austine Okinyo², Isaac Okeyo^{3,*}, Erick Muok²

¹Department of Biomedical Service, Jaramogi Oginga Odinga University of Science and Technology (JOOUST), Bondo, Kenya

²Center for Global Health Research (CGHR), Kenya Medical Research Institute (KEMRI), Kisumu, Kenya

³Department of Health and Biomedical Sciences, The Technical University of Kenya, Nairobi, Kenya

Abstract

Malaria remains a public health concern among young children in sub-Saharan Africa. Climate change may deplete essential nutrients in major food crops. The impacts of climate-sensitive nutrients on clinical malaria are yet to be established. This study aimed at identifying nutrient patterns and their cross-sectional associations with clinical malaria among young children living in rural Kenya. We used baseline data of a cluster-randomized controlled trial with 506 children aged 6-23 months, recruited within the Siaya Health and Demographic Surveillance System (HDSS) between August and December 2021. We performed physical examinations, malaria microscopy, medical history taking, and questionnaire-based interviews on socio-demographic and dietary variables. Nutrient patterns were derived by Principal Component Analysis (PCA) with orthogonal rotation. Multiple-adjusted logistic regression analyses were used to calculate odds ratios (OR), 95% confidence intervals (CIs), and p-values for the associations of nutrient patterns with clinical malaria (defined as *Plasmodium* spc. with fever ($\geq 37.5^{\circ}\text{C}$) or a history of fever or prescribed anti-malaria medication) and anemia (Hb $< 11\text{g/dL}$). In this study population (boys: 54%; mean age: 15.0 ± 5.0 months), 12% had clinical malaria and 73% had anemia. Two nutrient patterns were identified: The fibre- and micronutrient pattern explained 4% of the variation in nutrient intakes, and the fat- and protein pattern explained 2%. Stronger adherence to the fibre- and micronutrient pattern tended to increase the chance of clinical malaria (OR per 1 score-standard deviation increase: 2.18; 95% CI: 0.86, 5.56). There was no association of the fat- and protein pattern with clinical malaria, and both patterns were not associated with anemia. In conclusion, clinical malaria and anemia are common among young children in Siaya County, Kenya. On this background, enhanced availability of climate-sensitive micronutrients may increase their risk of clinical malaria.

Keywords

Malaria, Climate Change, Nutrient Patterns, Young Children, Kenya

*Corresponding author: isaacokeyo@tukenya.ac.ke (Isaac Okeyo)

Received: 27 September 2023; Accepted: 13 August 2025; Published: 19 September 2025



Copyright: © The Author(s), 2025. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

1. Introduction

Malaria is a dangerous and life-threatening disease. Pregnant women and children below the age of five years are most vulnerable. Every year, malaria kills 600,000 people [1]. It is caused by infections with *Plasmodium species* and is transmitted by female *Anopheles* mosquitoes. Malaria predominates in tropical and sub-tropical regions, including sub-Saharan Africa, South America, and South-East Asia [1]. Many strategies have been applied in malaria control and prevention, ranging from the use of insecticide-treated bed nets, indoor residual spraying, vaccination, malaria prophylaxis, and anti-malarial medication [1]. In Kenya, the latest Malaria Indicator Survey shows that 4.4% of under-fives have malaria infection and 45% have anemia (=low hemoglobin concentration) [2].

At the same time, the worldwide reduction of child undernutrition does not take effect in sub-Saharan Africa. The current trajectories for this subcontinent indicate that 61 million children below 5 years will have chronic undernutrition (height-for-age z-score < -2) in 2025 as compared to 54 million in the year 2000 [3]. This partly results from increased food insecurity due to the COVID19-pandemic [4]. Furthermore, increased atmospheric concentrations of greenhouse gases are causing dilutions of essential nutrients in major food crops. By the year 2050, this will lead to 1.4 billion people at increased risk of iron-deficiency anemia, additional 175 million people with zinc deficiency, and additional 122 million people with protein deficiency [5]. Currently, every fourth child under the age of five in Kenya has chronic undernutrition, frequently accompanied by micronutrient-deficiencies [6].

The relationships between malaria and child nutritional status are not fully understood. Malaria in early childhood impairs the nutritional status of children [7]. Yet, the reverse association is less clear-cut. A recent literature review on this topic reports that “no consistent association between risk of malaria and acute undernutrition was found, [whereas] chronic undernutrition was relatively consistently associated with severity of malaria such as high-density parasitemia and anemia.” [8]. For iron deficiency, there is a direct association with increased malaria morbidity [9]. Yet, iron supplementation in malaria-endemic areas might accelerate the risk of *Plasmodium* infection, and is therefore only recommended if proper malaria prevention and treatment are in place [10]. Finally, it is well established that zinc is important for an intact immune system and normal growth in childhood; zinc supplementation reduces the risk of respiratory infections and diarrhea. Nevertheless, its role for malaria susceptibility has been inconclusive so far [11].

Therefore, this study aimed at identifying the associations between climate-sensitive nutrients and clinical malaria among young children living in rural Kenya. The specific objectives were i) to characterize dietary intakes and identify nutrient patterns; ii) to determine the malariometric profile of

the study population; and iii) to establish the cross-sectional associations of the identified nutrient patterns with clinical malaria and anemia.

2. Materials and Methods

2.1. Study Design and Setting

This study used cross-sectional data from the baseline survey of a cluster-randomized controlled trial of 602 children aged 6-23 months living in Siaya county, Kenya. Kenya ranks among the lower middle-income countries, and the population in rural areas mainly lives on rainfed subsistence farming complemented by fishing in the vicinity of Lake Victoria. Kenya experiences two rainy seasons per year (March to May and October to December). Malaria is holoendemic throughout the year; 45% of under-fives have anemia; and deficiencies in climate-sensitive nutrients are common, including iron, zinc, and protein [2, 3, 6]. Siaya county is located in the former Nyanza province of the southwest part of Kenya. The county occupies a total area of 2,496 km² and lies on the northern shores of Lake Victoria [12]. The study was conducted in the sub-counties Wagai, Lwak, Akala, Ting Wangi, and Siaya.

2.2. Recruitment and Sample Size

The protocol of the cluster-randomized controlled trial has previously been published [13]. In brief, we recruited 683 children at the age of complementary food introduction (6-23 months) within the framework of the Siaya Health and Demographic Surveillance System (HDSS) between August and December 2021. This HDSS was established in the 1990s and spans an area of 700 km² with 220,000 inhabitants in 54,869 households. The children were recruited by experienced research assistants within 5-km perimeter of five local weather stations. They had to be permanent residents in the HDSS area, and have access to at least 40 m² of land and a water source for irrigation.

The sample size was calculated for the primary outcome height-for-age z-score (HAZ) using the parallel group- or cluster-randomized trials (GRT) Sample Size Calculator of the USA National Institutes of Health (NIH) (<https://researchmethodsresources.nih.gov/>). We assumed a group difference in mean HAZ of 0.18 to 0.25, an α -level of 0.05, a statistical power of 80%, and an intra-class correlation coefficient of 0.05. This yielded a sample size of 135 to 260 households. Finally, we planned with 300 children per intervention group to account for potential attrition and loss to follow-up. Under the same assumptions, this sample size allowed to measure a group-difference in the incidence of clinical malaria of 0.16 standard deviation.

2.3. Ethical Considerations

This study firmly adhered to the principles of the conduct of research laid down in the latest version of the World Medical Association Declaration of Helsinki. The study protocol was reviewed and approved by the Ethics Committee of the Medical Faculty, Heidelberg University, Germany, on May 15, 2019 (S-291/2019) and by the Kenya Medical Research Institute's (KEMRI) Scientific and Ethics Review Unit (SERU) in Kenya, on March 11, 2020 (KEMRI/SERU/CGHR/327/3962). Also, we obtained ethical approval from the ethics committee at Jaramogi Oginga Odinga University of Science and Technology (ERC 36/03/23-37). Research permit was granted from the Kenya National Commission for Science, Technology, and Innovation (NACOSTI). All caregivers of the participants gave written informed consent.

2.4. Data Collection

2.4.1. Demographic and Socio-economic Variables

Well-trained study personnel interviewed the caregivers about the demographic and socio-economic characteristics of the child and the mother. This included age and sex of the child, age of the mother, number of people living in the household, maternal ethnic group, marital status, religion, and education.

2.4.2. Malaria-related Variables

Finger-prick blood samples were collected and the hemoglobin concentration (Hb) was measured using the HemoCue® Hb 201+ system. Anemia was defined as Hb <11g/dL. A certified laboratory technologist prepared thick and thin blood films for microscopic detection of asexual Plasmodium parasites after staining with 10% Giemsa (Olympus CX22 binocular microscope, 100 × 100). Parasitemia was determined by counting the number of asexual parasites against 200 leucocytes. Parasite density was calculated assuming 8,000 leukocytes/μL blood. Axillary temperature was measured using a digital thermometer and fever was defined as a temperature ≥ 37.5°C. Caregivers were asked about their child's history of fever within the last 2 weeks, and anti-malaria medication was documented. Clinical malaria was defined as microscopically detected Plasmodium parasites plus fever or a history of fever; clinical malaria also denoted when a child was currently treated with anti-malaria medication. Malarial anemia denoted the presence of Plasmodium parasites by microscopy plus Hb < 11g/dL.

2.4.3. Dietary Variables

The usual dietary intake of children was assessed by a semi-quantitative Food Propensity Questionnaire (FPQ), which was adapted from a tool previously employed in Ghana and Burkina Faso [14]. The FPQ queried for the intake frequencies

of 134 food items that were collapsed into 30 food groups based on their culinary use and nutrient profiles. This tool estimated the intake frequencies of food items in predefined portion sizes, which were indicated by common household utensils. The intake frequencies in combination with portion sizes were then translated into energy and nutrient intakes, using the most recent Kenya Food Composition Table [15].

2.5. Data Management and Analysis

2.5.1. Data Management

All data were collected via a web-based data entry mask (Survey Solutions, version 21.09) employing automatic plausibility checks. The data were uploaded and stored as password-protected files on the shared server of the DFG-funded research unit "Climate Change and Health in sub-Saharan Africa." The data analysis was performed using the Statistical Analysis Software (SAS) version SAS-9.4.

2.5.2. Missing Data Handling

Participants with missing or implausible data in any of the dietary variables, malaria-related variables, and covariables were excluded from the analysis. This led to the exclusion of 177 children and yielded a final analytical sample of 506 individuals.

2.5.3. Descriptive Statistics

For the distributions of demographic and socio-economic characteristics by gender and by malaria status, we calculated means and standard deviations (SDs) for continuous variables and proportions (%), *n* for categorical data. Dietary data are displayed as medians and interquartile ranges (IQR), and were compared by malaria status using Wilcoxon signed rank test for non-normally distributed, continuous variables.

2.5.4. Identification of Nutrient Patterns

For the identification of nutrient patterns, we used Principal Component Analysis (PCA) with an orthogonal rotation to ensure that the identified pattern scores remain uncorrelated. The pattern scores were extracted based on the Eigenvalue criterion (>1), the elbow method of the scree plot, and the interpretability of the patterns (i.e., more than 3 nutrients with factor loadings of >0.4). Each participant was assigned a pattern score, calculated from the standardized nutrient intake multiplied by the factor loading of this nutrient. The distributions of demographic, socio-economic, dietary, and malaria-related characteristics of the children were calculated across quintiles of pattern adherence.

2.5.5. Associations with Nutrient Patterns

In logistic regression models, we calculated odds ratios (ORs), their 95% confidence intervals (CIs), and *p*-values for the associations of nutrient patterns with clinical malaria and

anemia. As a first step, we calculated the associations comparing the fifth quintile of pattern adherence with the first one (reference). Then, we derived estimates for the associations per 1 score-SD increase. We fitted three models: The crude model without adjustments; Model 1 with adjustments for age, sex, and energy intake; and Model 2 with additional adjustments for maternal age, education, marital status, religion, ethnic group, and number of people in the household.

3. Results

3.1. General Characteristics

Table 1 shows the demographic, socio-economic, and dietary characteristics of the study population. The mean age of the children was 15.0 (SD: 5.0) months; 54% were boys, and the mean number of people in their households was 6 (SD: 2). Regarding the mothers, their mean age was below 30 years; the majority belonged to the Luo ethnic group; most of them were married and Christians; and less than one-third had

secondary formal education. Concerning dietary intakes, the median energy consumption was 1806 kcal/d; carbohydrates contributed 61% to the energy intake, total fat 27%, and protein 13%. Median daily intakes of climate-sensitive micronutrients were 14.6 mg/d for iron, 10.9 mg/d for zinc, 0.9 mg/d for retinol-equivalents, and 90.5 µg/d for selenium.

3.2. Malariometric Characteristics

Out of the 506 children, 32 (6.3%) had a microscopically visible infection with *Plasmodium* parasites. Current fever was seen in 10 children (2.0%); and a history of fever was recorded for 213 participants (42.4%). Accounting for the number of children on anti-malarial medication, 60 (11.9%) children (boys: 29; 10.6%) had clinical malaria at a geometric mean parasite density of 116 (range: 6-1350) per µL. Mean Hb was 10.1 (SD: 1.4) g/dL, and anemia was detected in 371 children (73.3%) (boys: 207; 75.8%). Twenty-nine participants (5.7%) also had malarial anemia (boys: 15; 5.5%). There were no differences in the median intakes of energy and nutrients according to clinical malaria (Table 1).

Table 1. Demographic, socio-economic, and dietary characteristics for 506 young children living in Siaya County, by malaria status.

Characteristics	Total	Malaria	No malaria	p-value
N	506	60	446	
Male sex	53.9 (273)	48.3 (29)	54.7 (244)	0.352
Child's age (months)	15.0 ± 5.0	15.9 ± 5.1	14.8 ± 5.0	0.123
Mother's age (years)	29.4 ± 7.8	29.0 ± 6.0	29.5 ± 8.0	0.676
Number of people in the household	6.1 ± 2.2	6.4 ± 2.9	6.1 ± 2.1	0.376
Ethnic group, Luo	95.5 (483)	93.3 (56)	95.7 (427)	0.401
Mother's education				0.759
None	0.6 (3)	0.0 (0)	0.7 (3)	
Primary	64.4 (322)	61.4 (35)	64.8 (287)	
Secondary	30.2 (151)	31.6 (18)	30.0 (133)	
Tertiary	4.8 (24)	7.0 (4)	4.5 (20)	
Mother's marital status				0.408
Married	80.6 (408)	76.7 (46)	81.2 (362)	
Mother's religion				0.602
Christian	97.6 (494)	98.3 (58)	99.3 (436)	
Other	2.4 (12)	3.3 (2)	2.2 (10)	
Energy intake (kcal/d)	1806 (1280, 2421)	1815 (1443, 2276)	1803 (1259, 2436)	0.788
Carbohydrates (energy%)	61.3 (56.6, 64.8)	59.5 (56.1, 63.7)	61.5 (56.9, 64.8)	0.205
Total fat (energy%)	26.5 (22.5, 30.2)	27.2 (22.5, 31.3)	26.4 (22.5, 29.9)	0.410
Protein (energy%)	12.6 (11.6, 13.6)	12.8 (11.8, 13.8)	12.6 (11.6, 13.6)	0.333
Dietary fibre (g/d)	29.6 (20.4, 37.3)	30.4 (22.4, 37.6)	29.5 (20.1, 37.3)	0.445

Characteristics	Total	Malaria	No malaria	p-value
Iron (mg/d)	14.6 (10.4, 18.4)	14.4 (11.1, 18.8)	14.6 (10.3, 18.3)	0.607
Zinc (mg/d)	10.9 (7.2, 14.1)	11.1 (7.4, 13.1)	10.9 (7.2, 14.2)	0.837
Retinol-eq (µg/d)	928.6 (607.6, 1314.7)	963.2 (677.6, 1387.3)	915.7 (599.7, 1306.2)	0.389
Selenium (µg/d)	90.5 (57.6, 123.1)	97.8 (68.7, 125.7)	89.1 (55.5, 123.1)	0.217

Data are presented as means $\pm$ standard deviations for continuous variables and as percentages (n) for categorical data. p-values were calculated by t-test for normally distributed, continuous variables, by Wilcoxon signed rank test for non-normally distributed, continuous variables, and by χ^2 -test for categorical variables.

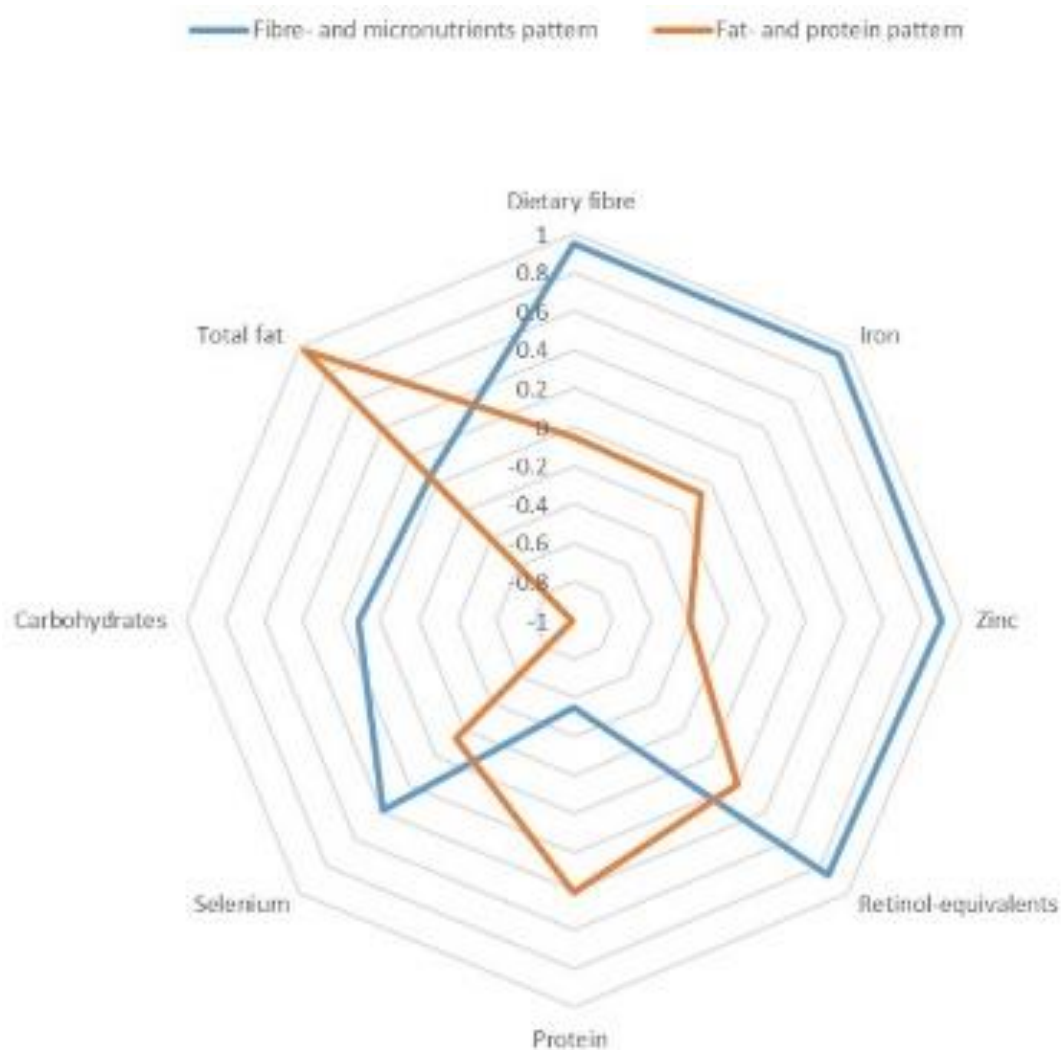


Figure 1. Rotated factor loadings of two exploratory nutrient patterns among 506 young children in Siaya County.

3.3. Nutrient Patterns

Figure 1 shows two identified nutrient patterns and their rotated factor loadings. A fibre- and micronutrients pattern was characterized by positive factor loadings of dietary fibre, iron, zinc, and retinol-equivalents, and was negatively corre-

lated with protein intake. It explained 3.8% of the variation in nutrient intakes. The fat- and protein pattern showed positive factor loadings for total fat and protein and inverse correlations with carbohydrates. This pattern explained 2.2% of the variation in nutrient intakes.

Table A1 shows the demographic, socio-economic, dietary, and malaria-related characteristics of the study population

across quintiles of the identified pattern scores. Children in the fifth quintile of the fibre- and micronutrient pattern were older and had less often mothers with primary education. Stronger adherence to this pattern was characterized by higher energy intakes and more frequent clinical malaria. For the fat- and protein pattern, children in the fifth quintile as compared to the first quintile were older and more frequently male; they had more often mothers with primary education. This pattern also showed positive correlation with energy intake. Malaria infection and malarial anemia were more common in the fifth quintile than in the first quintile (Table A1).

3.4. Associations with Nutrient Patterns

Table 2 presents the associations of the nutrient patterns with clinical malaria. When comparing the fifth with the first

quintile (reference) of the fibre- and micronutrients pattern score, there was a positive but non-significant association with clinical malaria in the crude model. This strengthened after adjustment for age, sex and energy intake in Model 1, and became additionally stronger in Model 2, when accounting for socio-economic factors. The association per 1 score-SD increase showed similar results. In Model 2 the adjusted OR for clinical malaria was 2.18 (95% CI: 0.86, 5.56; $p = 0.101$). There were no associations of the fibre- and micronutrients pattern with anemia (Table 3). Regarding the fat- and protein pattern, we neither observed associations with clinical malaria (Table 2) nor with anemia (Table 3). Due to the low number of cases with malaria infection (parasitemia) and with malarial anemia, we refrained from calculating regression models for the associations with nutrient patterns.

Table 2. Associations of nutrient patterns with clinical malaria among 506 young children living in Siaya County.

Nutrient pattern	Odds ratios (95% confidence intervals) for clinical malaria				
	Quintile 1	Quintile 5	<i>p</i> -value	per 1 score-SD increase	<i>p</i> -value
Fibre- and micronutrients					
Malaria	10 cases / 90 controls	15 cases / 87 controls			
Crude	1.00 (reference)	1.38 (0.73, 2.58)	0.321	1.09 (0.83, 1.42)	0.530
Model 1	1.00 (reference)	1.84 (0.72, 4.66)	0.202	1.76 (0.75, 4.16)	0.197
Model 2	1.00 (reference)	2.24 (0.82, 6.13)	0.118	2.18 (0.86, 5.56)	0.101
Fat- and protein					
Malaria	12 cases / 88 controls	15 cases / 86 controls			
Crude	1.00 (reference)	1.40 (0.74, 2.62)	0.300	1.10 (0.85, 1.43)	0.467
Model 1	1.00 (reference)	1.34 (0.72, 2.60)	0.338	1.08 (0.83, 1.41)	0.558
Model 2	1.00 (reference)	1.49 (0.77, 2.89)	0.238	1.14 (0.87, 1.50)	0.345

Odds ratios, 95% confidence intervals, and *p*-values were calculated by logistics regression analyses. Model 1: adjusted for age, sex, and energy intake. Model 2: Model 1 + mother's age, mother's education, mother's marital status, mother's religion, number of people in the household, and ethnic group.

Table 3. Associations of nutrient patterns with anemia among 506 young children living in Siaya County.

Nutrient pattern	Odds ratios (95% confidence intervals) for anemia				
	Quintile 1	Quintile 5	<i>p</i> -value	per 1 score-SD increase	<i>p</i> -value
Fibre- and micronutrients					
Anemia	76 cases / 24 controls	73 cases / 29 controls			
Crude	1.00 (reference)	0.90 (0.55, 1.45)	0.655	0.91 (0.75, 1.11)	0.372

Nutrient pattern	Odds ratios (95% confidence intervals) for anemia				
	Quintile 1	Quintile 5	<i>p</i> -value	per 1 score-SD increase	<i>p</i> -value
Model 1	1.00 (reference)	0.90 (0.45, 1.80)	0.755	0.72 (0.37, 1.41)	0.340
Model 2	1.00 (reference)	1.02 (0.49, 2.11)	0.964	0.77 (0.38, 1.55)	0.463
Fat- and protein					
Anemia	78 cases / 22 controls	75 cases / 26 controls			
Crude	1.00 (reference)	1.06 (0.65, 1.75)	0.812	0.93 (0.77, 1.13)	0.475
Model 1	1.00 (reference)	1.14 (0.68, 1.89)	0.628	0.96 (0.79, 1.17)	0.700
Model 2	1.00 (reference)	1.27 (0.74, 2.18)	0.382	1.00 (0.81, 1.24)	0.976

Odds ratios, 95% confidence intervals, and *p*-values were calculated by logistics regression analyses. Model 1: adjusted for age, sex, and energy intake. Model 2: Model 1 + mother's age, mother's education, mother's marital status, mother's religion, number of people in the household, and ethnic group.

4. Discussion

4.1. Summary of Main Findings

On the background of climate change-induced losses of essential nutrients in major food crops in malaria-endemic areas, this study aimed at identifying patterns of climate-sensitive nutrients and their cross-sectional associations with clinical malaria and anemia among young children living in rural Kenya. Out of 506 children (boys: 54%; mean age: 15.0 ± 5.0 months), 12% had clinical malaria and 73% had anemia. Two nutrient patterns were identified: The fibre- and micronutrient pattern explained 4% of the variation in nutrient intakes, and the fat- and protein pattern explained 2%. Stronger adherence to the fibre- and micronutrient pattern was associated with increased chance of clinical malaria (OR per 1 score-SD increase: 2.18; 95% CI: 0.86, 5.56). There was no association of the fat- and protein pattern with clinical malaria, and both patterns were not associated with anemia.

4.2. Malariometric and Dietary Profile

In this study population, the proportions of children with malaria infection (6.3%) and with clinical malaria (11.9%) were lower than expected. Previous reports have indicated that 27% of children below the age of five years have malaria parasitemia [16]. First, this discrepancy could stem from the fact that the study was conducted during the rainy season (August through December). Malaria transmission usually peaks at the end of this season [17]. Second, we have selected children aged 6-23 months, while age groups between 48-59 months experience the highest burden of malaria infection [18]. Third, since 2012, Community Case Management for malaria (CCMm) has been introduced in the malaria-endemic

lake zones of western Kenya. For CCMm, Community Health Volunteers (CHVs) are equipped with rapid diagnostic tests (RDTs) for malaria diagnosis and anti-malaria medication (artemether lumefantrine) for the treatment of confirmed, uncomplicated malaria. Given that CHVs reside in the area where they deliver their services, diagnosis and treatment of malaria has become timely and effective [16].

Regarding the dietary intake, the present study population was mainly fed carbohydrate-based foods (61 energy%), while the intakes of total fat (27 energy%) and protein, in particular, (13 energy%) were low as compared to the respective dietary recommendations [19]. For the climate-sensitive micronutrients iron, zinc, vitamin A, and selenium, our findings indicate that dietary supplies might have been adequate in this population. However, this interpretation has to be handled with caution, because we have used a dietary assessment tool that has not been calibrated to the portion sizes of the target age group. Therefore, we cannot exclude that portion sizes were overestimated. The identified nutrient patterns, which are based on the calculated nutrient intakes of the FPQ data, reflect the profiles of foods that are commonly consumed together. The fibre- and micronutrients pattern may mirror a plant-based feeding practice, while the fat- and protein pattern appears to represent the intake of animal-source foods. Indeed, weaning foods for young children in western Kenya comprise starchy purees made from region-specific staples (ugali), green leafy vegetables and legumes [20]. Also, fish is frequently consumed in the lake areas.

4.3. Associations of Climate-sensitive Nutrients with Clinical Malaria and Anemia

None of the identified dietary patterns was associated with anemia, which corroborates our finding that micronutrient supplies appear to be adequate. There was a trend towards

increased odds of clinical malaria for children with stronger adherence to the fibre- and micronutrients pattern. But this was not seen for the fat- and protein pattern. Previous evidence may explain these findings. With regard to iron, the famous iron supplementation trial conducted in Zanzibar in 2003 has raised concerns whether increased iron bio-availability could lead to accelerated risk of malaria in endemic regions [21]. In that trial, daily iron and folic acid supplementation were given to 7,950 children aged 1-35 months, and placebos were administered to 8,006 children of the same age group. The trial was stopped preterm, because the investigators observed that individuals in the treatment group were 12% more likely to die or had a severe adverse event, and they were 11% more likely to be hospitalized [21]. This observation was also made in an independent iron fortification trial among children in Ghana [22]. Indeed, iron deficiency anemia may confer partial protection against malaria infection because of the parasite's dependency on external iron [23], and thus, rapid increase in iron bio-availability may promote parasite growth. With regard to zinc, this trace element is vital for protein synthesis in the human body, including proteins of the immune system and the globin chains in hemoglobin [24]. Therefore, its role in malaria infection and manifestation remains controversial. Some studies have shown increased susceptibility to infection, possibly due to the impaired immune function, while others have shown the opposite, likely caused by a lack of substrates (hemoglobin) for the Plasmodium parasites to grow [25]. Disturbed absorption of micronutrients through dietary fibre [26] may present an alternative explanation for the increased odds of clinical malaria from stronger adherence to the fibre- and micronutrients pattern. In fact, the first pattern shows combined high intakes of climate-sensitive micronutrients and large amounts of dietary fibre, possibly leading to low bio-availability of the micronutrients and adverse consequences for immune function [9, 11].

4.4. Strengths and Limitations

The findings of this study need to be interpreted with caution. In a considerably large dataset of young children living in rural Kenya, we have comprehensively assessed the usual feeding practices and analyzed the intakes of climate-sensitive micronutrients, using the most recent Kenya Nutrient Database. While we acknowledge that the semi-quantitative FPQ cannot estimate the absolute intakes of foods and nutrients, this tool allowed us to rank the study participants according to their intakes, because all of them carry the same measurement error. Therefore, we confidently assigned score points of pattern adherence to each child, which remained uncorrelated due to the orthogonal rotation in PCA. This means, for each child, we were able to estimate the adherence to both identified nutrient patterns. The biggest limitation of our analysis was the cross-sectional nature of the study design, which is

prone to recall bias of the feeding practices by caregivers, and reverse causation. Therefore, it is difficult to disentangle whether high adherence to the fibre- and micronutrients pattern increased the chance of clinical malaria or whether children with clinical malaria are fed differently than healthy children. As a consequence, prospective study designs are required to verify these hypotheses. Ideally, future studies will employ objective measurements of the bio-availability of climate-sensitive micronutrients, such as biomarkers from established invasive methods, including iron transport proteins and zinc concentration [26, 27], as well as from novel, non-invasive technologies, including hand-held spectrometry or saliva testing [28, 29].

5. Conclusions

This cross-sectional study on the associations of nutrient patterns with clinical malaria and anemia among young children in rural Kenya contributes to the concerns that enhanced bio-availability of iron and zinc may confer increased risk of clinical malaria, if the baseline prevalence of anemia is high and malaria is endemic. At the same time, the combined intakes of iron, zinc, selenium and vitamin A with dietary fibre in one of the identified nutrient patterns argue for potential malabsorption of minerals, which might impair immune function and thus, increase the risk of clinical malaria. While future prospective studies remain to verify these associations, our findings advocate for improving nutrition literacy and fluency among caregivers of young children to ensure the introduction of complementary foods that do not inhibit the absorption of climate-sensitive nutrients. At the same time, community-targeted efforts in healthcare, such as household visits by CHVs, may incorporate routine screening for anemia.

Acknowledgments

The authors are grateful to the study team at Kenya Medical Research Institute (KEMRI) for gathering the data and to the volunteers who participated in this study.

Funding

This study was supported by the German Research Foundation (DFG) and East African Consortium for Clinical Research (EACCR) within the framework of the Research Unit "Climate Change and Health in sub-Saharan Africa" (FOR 2936; reference: 409670289).

Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Table A1. Demographic, socio-economic, dietary, and malaria-related characteristics of 506 young children living in Siaya County, Kenya across quintiles of two identified nutrient pattern scores

Characteristics	Fibre- and micronutrients pattern		Fat- and protein pattern	
	Quintile 1 (n = 95)	Quintile 5 (n = 99)	Quintile 1 (n = 97)	Quintile 5 (n = 94)
Demographic and socio-economic				
Mean age $\pm$ SD (months)	11.6 $\pm$ 5.1	16.6 $\pm$ 3.9	13.5 $\pm$ 5.1	15.9 $\pm$ 5.2
Male sex	51.6 (49)	51.5 (51)	48.5 (47)	61.7 (58)
Mean mother's age $\pm$ SD (years)	29.8 $\pm$ 6.6	29.1 $\pm$ 6.0	27.8 $\pm$ 6.7	29.9 $\pm$ 5.4
Mean number of people in household $\pm$ SD	6.3 $\pm$ 2.0	6.4 $\pm$ 3.1	6.4 $\pm$ 2.3	6.3 $\pm$ 2.8
Ethnic group (Luo)	94.7 (90)	96.0 (95)	94.9 (92)	97.9 (92)
Mother's education (primary)	79.3 (73)	58.4 (52)	58.8 (57)	71.3 (76)
Mother's marital status (married)	87.4 (83)	86.9 (86)	76.3 (74)	77.7 (73)
Mother's religion (Christian)	81.1 (77)	75.8 (75)	84.5 (82)	79.8 (75)
Dietary				
Energy (kcal/d)	827 (589, 957)	2999 (2721, 3274)	1544 (1123, 2200)	1719 (1111, 2378)
Carbohydrates (energy%)	61.7 (54.6, 65.6)	61.6 (58.2, 64.4)	68.5 (67.2, 69.6)	52.3 (49.0, 54.3)
Total fat (energy%)	24.6 (20.9, 30.2)	26.9 (24.4, 29.9)	19.4 (17.9, 20.7)	34.3 (32.4, 37.1)
Protein (energy%)	13.8 (12.9, 15.2)	11.3 (10.6, 12.1)	12.1 (11.0, 13.0)	13.3 (12.0, 14.9)
Dietary fibre (g/d)	14.0 (10.8, 16.8)	44.3 (39.6, 49.8)	25.7 (18.0, 35.4)	27.0 (16.3, 37.1)
Iron (mg/d)	6.7 (4.7, 8.6)	21.2 (19.7, 23.7)	12.7 (9.3, 17.5)	13.1 (8.8, 17.5)
Zinc (mg/d)	5.3 (4.0, 6.5)	16.9 (14.7, 18.4)	9.4 (6.3, 12.6)	10.2 (6.7, 14.0)
Retinol-equivalents (mg/d)	382.0 (264.8, 477.1)	1736.3 (1401.7, 2132.1)	609.6 (411.6, 980.2)	969.1 (646.6, 1392.9)
Selenium (μ g/d)	38.4 (26.9, 59.2)	130.7 (106.1, 151.4)	93.6 (52.1, 130.5)	82.1 (48.2, 114.2)
Malaria-related				
Fever ($T \geq 37.5^\circ\text{C}$)	3.2 (3)	3.0 (3)	1.0 (1)	3.2 (3)
History of fever (positive)	40.0 (38)	41.4 (41)	40.2 (39)	40.4 (38)
Anemia (Hb < 11 g/dL)	76.8 (73)	72.7 (72)	79.4 (77)	75.5 (71)
Anemia (Hb < 10 g/dL)	37.9 (36)	41.4 (41)	38.1 (37)	37.2 (35)
Malarial anemia (positive)	4.2 (4)	6.1 (6)	2.1 (2)	11.7 (11)
Malaria infection (positive)	5.3 (5)	6.1 (6)	3.1 (3)	12.8 (12)
Clinical malaria (positive)	10.5 (10)	14.1 (15)	10.3 (12)	16.0 (15)

Data are presented as medians and interquartile ranges (IQR) for continuous variables and as percentages (n) for categorical data, unless otherwise indicated.

References

- [1] World Health Organization (WHO). *World malaria report 2022*. Geneva: World Health Organization; 2022.
- [2] Division of National Malaria Programme (DNMP) [Kenya] and ICF. *Kenya Malaria Indicator Survey 2020*. Nairobi, Kenya and Rockville, Maryland, USA: DNMP and ICF; 2021.
- [3] UNICEF, WHO, World Bank Group. Joint Malnutrition Estimates, May 2022 Edition. Available from: <https://data.unicef.org/resources/dataset/malnutrition-data/> [Accessed 07 November 2023].
- [4] Sestito, P., Velásquez, S. R., Orel, E., Keiser, O. The COVID-19 pandemic and child malnutrition in sub-Saharan Africa: A scoping review. *medRxiv*. 2021, 2021.07.21.21260929.
- [5] Smith, M. R., Myers, S. S. Impact of anthropogenic CO₂ emissions on global human nutrition. *Nature Climate Change*. 2018, 8, 834-839. <https://doi.org/10.1038/s41558-018-0253-3>
- [6] UNICEF. Nutrition in Kenya – Preventing and treating maternal, adolescent and child malnutrition. Available from: <https://www.unicef.org/kenya/nutrition> [Accessed 07 November 2023].
- [7] Nyakeriga, A. M., Troye-Blomberg, M., Chemtai, A. K., Marsh, K., Williams, T. N. Malaria and nutritional status in children living on the coast of Kenya. *Am J Clin Nutr*. 2004, 80(6), 1604-1610.
- [8] Das, D., Grais, R. F., Okiro, E. A., Stepniewska, K., Mansoor, R., van der Kam, S., Terlouw, D. J., Tarning, J., Barnes, K. I., Guerin, P. J. Complex interactions between malaria and malnutrition: a systematic literature review. *BMC Med*. 2018, 16(1), 186.
- [9] World Health Organization (WHO). Daily Iron Supplementation in Adult Women and Adolescent Girls. Available from: http://www.Who.Int/nutrition/publications/micronutrients/guidelines/daily_iron_supp_womenandgirls/en/ [Accessed 31 May 2017].
- [10] World Health Organization (WHO). Conclusions and recommendations of the WHO Consultation on prevention and control of iron deficiency in infants and young children in malaria-endemic areas. *Food Nutr Bull*. 2007, 28(4 Suppl), S621-627.
- [11] Basnet, S., Mathisen, M., Strand, T. A. Oral zinc and common childhood infections – An update. *J Trace Elem Med Biol*. 2015, 31, 163-166.
- [12] Kenya National Bureau of Statistics (KNBS). Leading Economic Indicators 2019. Available from: <https://www.knbs.or.ke> [Accessed 08 November 2023].
- [13] Mank, I., Sorgho, R., Zerbo, F., Kagoné, M., Coulibaly, B., Oguso, J., Mbata, M., Khagayi, S., Muok, M. O. E., Sié, A., Danquah, I. ALIMUS – We are feeding! Study protocol of a multi-center, cluster-randomized controlled trial on the effects of a home garden and nutrition counselling intervention to reduce child undernutrition in rural Burkina Faso and Kenya. *Trials*. 2022, 23, 449. <https://doi.org/10.1186/s13063-022-06423-5>
- [14] Galbete, C., Nicolaou, M., Meeks, K. A., de Graft Aikins, A., Addo, J., Amoah, S. K., Smeeth, L., Owusu-Dabo, E., Klipstein-Grobusch, K., Bahendeka, S., Agyemang, C., Mockenhaupt, F. P., Beune, E. J., Stronks, K., Schulze, M. B., Danquah, I. Food consumption, nutrient intake, and dietary patterns in Ghanaian migrants in Europe and their compatriots in Ghana. *Food Nutr Res*. 2017, 61, 1341809. <https://doi.org/10.1080/16546628.2017.1341809>
- [15] Food and Agriculture Organization (FAO) and Government of Kenya. Kenya Food Composition Tables 2018. Available from: <http://www.fao.org/3/I9120EN/i9120en.pdf> [Accessed 08 November 2023].
- [16] Enock, M., Langat, B., Kinyari, T., Igunda, P., Apat, D., Kimori, J., Carter, J., Kiplimo, R., Muhula, S. Implementation of community case management of malaria in malaria endemic counties of western Kenya: are community health volunteers up to the task in diagnosing malaria? *Malaria Journal*. 2022, 21, 73. <https://doi.org/10.1186/s12936-022-04094-w>
- [17] Milner, E. M., Kariger, P., Pickering, A. J., Stewart, C. P., Byrd, K., Lin, A., Rao, G., Achando, B., Dentz, H. N., Null, C., & Fernald, L. C. H. Association between Malaria Infection and Early Childhood Development Mediated by Anemia in Rural Kenya. *International Journal of Environmental Research and Public Health*. 2020, 17(3), 902. <https://doi.org/10.3390/ijerph17030902>
- [18] Chilanga, E., Collin-Vézina, D., MacIntosh, H., Mitchell, C., & Cherney, K. Prevalence and determinants of malaria infection among children of local farmers in Central Malawi. *Malaria Journal*. 2020, 19(1), 308. <https://doi.org/10.1186/s12936-020-03382-7>
- [19] FAO/WHO. Human vitamin and mineral requirements. Report of a Joint FAO/WHO Expert Consultation. Rome: 2002.
- [20] Mbagaya, G. M. Child feeding practices in a rural western Kenya community. *African Journal of Primary Healthcare & Family Medicine*. 2009, 1(1). <https://doi.org/10.4102/phcfm.v1i1.15>
- [21] Sazawal, S., Black, R. E., Ramsan, M., Chwaya, H. M., Stoltzfus, R. J., Dutta, A., Dhingra, U., Kabole, I., Deb, S., Othman, M. K., Kabole, F. M. Effects of routine prophylactic supplementation with iron and folic acid on admission to hospital and mortality in preschool children in a high malaria transmission setting: community-based, randomized, placebo-controlled trial. *Lancet*. 2006, 367(9505), 133-143. [https://doi.org/10.1016/S0140-6736\(06\)67962-2](https://doi.org/10.1016/S0140-6736(06)67962-2)
- [22] Zlotkin, S., Newton, S., Aimone, A. M., Azindow, I., Amenga-Etego, S., Tchum, K., Mahama, E., Thorpe, K. E., Owusu-Agyei, S. Effect of iron fortification on malaria incidence in infants and young children in Ghana: a randomized trial. *JAMA*. 2013, 310(9), 938-947. <https://doi.org/10.1001/jama.2013.277129>
- [23] Weiss G. Iron and immunity: a double-edged sword. *Eur J Clin Invest*. 2002, 32(suppl 1), 70-78.

- [24] Skalny, A. V., Aschner, M., Tinkov, A. A. Zinc. *Adv Food Nutr Res.* 2021, 96, 251-310.
- [25] Yakoob, M. Y., Theodoratou, E., Jabeen, A., Imdad, A., Eisele, T. P., Ferguson, J., Jhass, A., Rudan, I., Campbell, H., Black, R. E., Bhutta, Z. A. Preventive zinc supplementation in developing countries: impact on mortality and morbidity due to diarrhea, pneumonia and malaria. *BMC Public Health.* 2011, 11(S3), S23. <https://doi.org/471-2458/11/S3/S23>
- [26] Lynch, S., Pfeiffer, C. M., Georgieff, M. K., Brittenham, G., Fairweather-Tait, S., Hurrell, R. F., McArdle, H. J., Raiten, D. J. Biomarkers of Nutrition for Development (BOND)-Iron review. *J Nutr.* 2018, 148, 1001S-1067S. <https://doi.org/10.1093/jn/nxx036>
- [27] Knez, M., Boy, E. Existing knowledge on Zn status biomarkers (1963 – 2021) with a particular focus on FADS1 and FADS2 diagnostic performance and recommendations for further research. *Front Nutr.* 2023, 9, 1057156. <https://doi.org/10.3389/fnut.2022.1057156>
- [28] Heckl, C., Eisel, M., Lang, A., Homann, C., Paal, M., Vogeser, M., Rühm, A., Sroka, R. Spectroscopic methods to quantify molecules of the heme-biosynthesis pathway: A review of laboratory work and point-of-care approaches. *Translational Biophotonics.* 2021, 3: e202000026. <https://doi.org/10.1002/tbio.202000026>
- [29] Mishra, O. P., Agarwal, K. N., Agarwal, R. M. Salivary iron status in children with iron deficiency and iron overload. *J Trop Pediatr.* 1992, 38(2), 64-7. <https://doi.org/10.1093/tropej/38.2.64>