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Dietary staple protein quality and meningitis mortality across 54 African countries: an ecological cross-sectional study

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Dietary staple protein quality and meningitis mortality across 54 African countries: an ecological cross-sectional study

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Abstract:

Background

Low-income populations in sub-Saharan Africa bear a disproportionate burden of bacterial meningitis and depend predominantly on starchy staples. We hypothesised that dietary protein from staples is associated with meningitis mortality through nutritional immune compromise.

Methods

This ecological study included 54 African countries. Outcome was meningitis cause fraction from GBD 2023. Staple protein availability for wheat, rice, maize, millet, sorghum and cassava was obtained from FAOSTAT. Beta regression was fitted separately for each staple. The primary model included diarrhoea cause fraction, malaria cause fraction and animal protein, selected to avoid circularity from shared GBD modelling inputs. Three sensitivity specifications incorporated household air pollution, unsafe sanitation or excluded malaria. A descriptive analysis examined dietary protein and meningococcal A conjugate vaccine (MACV) coverage across 24 belt countries.

Results

Animal protein was independently and inversely associated with meningitis mortality across all six staple models ($\beta=-0{\cdot}024$ to $-0{\cdot}035$, $p<0{\cdot}001$) and in two of three sensitivity specifications. Wheat protein was the only staple to reach independent significance ($\beta=-0{\cdot}024$, $p=0{\cdot}010$). Diarrhoea and malaria were consistently positive predictors. The primary model explained 70–79% of variance (Pseudo $R^2=0{\cdot}701$–$0{\cdot}794$). Attenuation of animal protein in the household air pollution model suggested collinearity ($r=-0{\cdot}658$), not a true absence of association. Belt countries showed 11-fold variation in meningitis mortality despite comparable MACV coverage.

Conclusions

Animal protein availability was independently associated with reduced meningitis mortality, supporting nutritional immune compromise as a modifying factor. Further

subnational investigation is precluded by absence of staple-type disaggregation in DHS and MICS surveys.

Funding: None.

Key words: meningitis belt, staple food protein availability, food balances, Meningococcus A Conjugate Vaccine, ecological study, Africa.

Background

Community acquired meningitides are among the most important causes of death and disability worldwide. Bacterial meningitis is the inflammation of the meninges and subarachnoid space secondary to a bacterial infection. Common organisms causing the infection worldwide are Neisseria meningitidis, Streptococcus pneumoniae and Haemophilus influenzae.[1] In neonates however the commonest organism is Streptococcus agalactae or group B streptococcus, which is commonly transmitted vertically from the mother to neonate.[1] In older children and adults, bacterial meningitis is caused commonly either in epidemics or sporadically, as a community acquired infection. The burden of meningitis in the African meningitis belt falls disproportionately on young children. In 2019, the belt accounted for 50·0% (95% UI 48·1–51·7) of global under-5 meningitis incident cases and 62·9% (57·5–67·8) of global under-5 meningitis deaths, indicating that the disease strikes at a substantially younger age in the belt than in high-income settings, where peak incidence occurs in adolescents and young adults.[2]

The African meningitis belt, is a region comprising of 26 countries in Africa, stretching from Senegal to Ethiopia, and has a very high incidence of meningitis with occurrence of pluriannual epidemics.[2] The belt was first defined by Lapeyssonnie in 1963 by the 300–1,100 mm annual rainfall isohyets — a climatic boundary he immediately contextualised as the zone of subsistence agriculture (agriculture vivrière) practised by the Sahelian peoples of the belt, noting that in this region geographic, climatic, agricultural and demographic conditions are inseparable.[3] Several theories have been advanced to explain the high meningitis rates in the belt, which occur primarily in the dry season.[3,4] These include climatic factors like blowing Harmattan winds damaging the respiratory mucosa and causing epidemics during dry season, smoke from use of household solid fuels, as well as, socio-epidemiological macro-determinants linked to poverty like poor sanitation, undernutrition and low birth weight, high birth rates, poor literacy, higher household occupancy and low gross national income per capita.[5,4] The arid Sahel region in which the belt is located is known to have higher dependence on sorghum and millet, as dietary staples primarily linked to subsistence farming.[6] These staples are known to have higher antinutrients thereby impairing their protein quality.[6]

For most of the developing world cereals provide more protein than animal sources combined.[6] The areas of the meningitis belt have an arid climate with seasonal rainfalls and predominantly grow and consume sorghum and millets for subsistence.[7] While in North Africa the primary staple consumed is wheat, Western, Eastern and Central Africa

have the lowest protein intake per capita and the highest proportions of plant derived protein intake.[6] In these regions, rice and wheat are consumed in varying amounts but the predominant staples in peri-Sahelian countries are millet and sorghum, while further south, cassava and maize are consumed in varying proportions.[6] The FAO recommends the Digestible Indispensable Amino Acid Score (DIAAS) as the preferred metric for evaluating protein quality, recognising the importance of assessing staple foods based on the availability of indispensable amino acids.[8] There is substantial variation in the DIAAS values of starchy staples, particularly for younger ages. The limiting amino acid for most plant staples is Lysine. Combining these staples with other appropriate plant and animal based protein sources can provide complementary amino acid profiles, making such dietary mixtures a practical approach to improving the overall DIAAS of the food matrix.[9]

Vaccination has had a major impact on meningitis prevalence in the belt countries over the last two decades with introduction of the MACV.[10] This has brought down the Meningococcus A disease by 99% with a substantial overall reduction in meningitis prevalence. In fact, current estimates suggest that over the last few decades, non-polio enteroviruses(NPEVs) have supplanted Neisseria meningitidis as the leading aetiological cause.[5] However, this reduction has also been heterogenous across the countries of the belt.[10] For instance, Sudan has had a much lower meningitis prevalence compared to Mali and Chad, despite all three having similar levels of MACV coverage.[10]

We hypothesised that protein availability from predominantly staple-based diets is associated with meningitis mortality across African countries, through mechanisms of nutritional immune compromise that may increase host susceptibility to meningitis-causing pathogens. We further hypothesised that substantial heterogeneity in meningitis mortality persists among belt countries with comparable meningococcal vaccine coverage, consistent with a role for dietary protein complementation as one of several modifying factors.

Methods

The UNICEF conceptual framework for child undernutrition was used to divide the covariates into dietary, disease and care categories with prevalent meningitis deaths by country being the dependent variable.[11] Food balances were obtained from the statistical website of Food and Agriculture Organization(FAO) , the FAOSTAT. Food balances are country level data which take into account production, trade, utilization and consumption of food commodities from which values such as dietary energy and protein supplies are derived and expressed on a daily basis.[12]

Staples considered for the study were rice, wheat, maize, sorghum, millet and cassava. Protein supply quantity for each staple is available in gram per capita per day in FAOSTAT under food balances(2010-).[13] For millets, FAOSTAT does not measure the different millets separately ,hence, the data are an aggregate of values for all millets. An aggregate of protein supply quantity for each staple for five years (2019-2023), was extracted for each country, and, used. Animal protein availability (g/capita/day) was aggregated from all meat, offal, egg, dairy and fish categories in FAOSTAT food balance sheets, averaged over 2019–2023. Non-cereal plant protein was derived from roots, tubers, legumes, nuts, oilseeds and plantains from the same source and period.

The total energy supply per capita (called Kcal per day in our study), was extracted in FAOSTAT from ‘suite of food security indicators’ ,as value from ‘dietary energy supply

used in the estimation of the prevalence of undernourishment(kcal/cap/day)'. The value was available as the aggregates of three years. Two(non-overlapping) sets of values for average dietary energy supply adequacy per capita from years 2022(2021-2023) and 2023(2022-24), were extracted and their aggregate was used. All three, namely, total animal protein per capita per day, total non-cereal plant protein per capita per day and total Kcal per day were together grouped as **dietary** variables.
The diseases considered for modelling were the all age prevalence of deaths due to diarrheal diseases, HIV and malaria(together grouped as **disease** variables) for 2023, taken from GBD 2023. Similarly, other covariates initially taken into consideration were Household air pollution from solid fuels, unsafe sanitation and Sociodemographic index(SDI). Vaccination of three doses of Haemophilus influenzae vaccine(HiB3) as well as three doses of pneumococcal conjugate vaccine(PCV3) were also considered. All the above were together grouped as **Care** variables. All disease as well as care variables were obtained from GBD 2023, through the data repository maintained by Institute of Health Metrics and Evaluation(IHME),the Global health data Exchange (GHDx).

The outcome variable was all-age meningitis cause fraction for 2023 — the proportion of all-cause deaths attributed to meningitis in each country — obtained from the GBD 2023 results tool. It was obtained from GHDx from the GBD results tool for 2023 data from the GBD website(https://vizhub.healthdata.org/gbd-results/). It was modelled data as per the GBD methodology.[5,14] GBD 2023 complies with the GATHER(Guidelines for Accurate and Transparent Health Estimates Reporting) recommendations. The definitions and data sources of study variables are available in **Table S1. Study variables and data sources (Supplementary material)**. A secondary descriptive analysis examined meningitis mortality in relation to dietary protein and vaccination coverage among belt countries with available MACV data.

Missing data:

The values for the aforementioned staple foods, total animal protein and non-cereal plant protein were missing for Central African Republic, Burundi, Somalia, Benin, Chad, Mali, Togo, South Sudan and Sudan. It was confirmed from FAOSTAT that their values are currently under revision. Hence, older data (downloaded earlier) from a different but closer time series (aggregate of 2018-2022) was used for aforementioned countries. For Eritrea and Equatorial Guinea the data was never compiled, and, hence was imputed from the values of their respective regions. For Eritrea it was imputed from Eastern Sub-Saharan Africa, and for Equatorial Guinea, from Central Sub Saharan Africa.
The values of Kcal per day for Burundi, Lesotho and Sudan were not available and we took the aggregate of their respective regions. For Burundi we used Eastern Sub-Saharan Africa values, for Lesotho Southern Sub-Saharan Africa values and for Sudan we took the African countries in North Africa and Middle East GBD region, values.

Statistical analysis and Modelling:

All statistical analyses were conducted in R version 4·5·3.[15] The study outcome was meningitis mortality expressed as a cause fraction — the proportion of total deaths attributable to meningitis — bounded strictly between 0 and 1, which precluded the use of ordinary least squares regression. Beta regression with a logit link function was therefore employed as the primary analytical method, implemented using the **betareg R package (version 3·2·4)**. This approach is appropriate for continuous proportional outcomes that are strictly bounded and may exhibit heteroskedasticity and skewness.

Prior to analysis, all variables were examined for missing values. No missing values were identified in the final analytic dataset (N = 54 African countries). All 24 beta regression models (six staple models × four specifications) were fitted using maximum likelihood estimation on complete observations (N = 54).

Bivariate associations between continuous variables were assessed using non-parametric Spearman rank correlation coefficients, given the non-normal distribution of several variables including the outcome. Variance inflation factors (VIF) were computed from auxiliary ordinary least squares models to assess multicollinearity among candidate covariates using the **car R package (version 3·1·5). Model fit was compared using the Akaike Information Criterion, with a difference of ≥2 units considered indicative of meaningful difference in fit between models.**

Model specification and selection

Four beta regression model specifications were tested for each staple crop. The primary model — comprising diarrhoea, malaria cause fractions and animal protein availability with each staple protein — was designated a priori to minimise analytical circularity arising from shared GBD modelling inputs. Since the study outcome (meningitis cause fraction) is a GBD-modelled estimate, covariates that served as direct inputs to the GBD meningitis model, or to GBD models generating predictor variables, risk introducing circularity that conflates modelling assumptions with genuine epidemiological associations.

Diarrhoea cause fraction was retained in the primary model as an independently modelled GBD output not used as a direct input to meningitis or malaria models. However, both diarrhoea and meningitis share distal upstream GBD modelling inputs — including sanitation, SDI and income — which may induce partial correlation attributable to shared modelling structure rather than purely biological co-occurrence. This indirect circularity is acknowledged as a potential source of upward bias in the diarrhoea coefficient and represents an unavoidable limitation of ecological analyses using GBD-derived estimates.

Sanitation is a Level 1 covariate in GBD diarrhoeal disease modelling and a Level 3 covariate in GBD meningitis mortality modelling — creating dual circularity pathways through both the outcome and the diarrhoea predictor — and was therefore excluded from the primary model. Household air pollution from solid fuels carries no GBD circularity concern but had a high VIF (7·72) in the full candidate variable set, due to collinearity with sanitation (r = 0·82), precluding its inclusion in the primary model. Following the circularity assessment, household air pollution was reconsidered as a sensitivity specification in which sanitation was excluded, yielding an acceptable VIF of 4·14. Animal protein availability and all six staple protein variables are absent from all GBD cause of death modelling frameworks and are entirely free of circularity. Full circularity assessment is presented in Supplementary **Table S1b**.

Three sensitivity model specifications were pre-specified to assess robustness of findings. Sensitivity 1 replaced the care infrastructure variable with household air pollution from solid fuels — the specification with the best statistical fit by Akaike Information Criterion across all six staple models and zero GBD circularity. Sensitivity 2 incorporated sanitation despite its partial circularity concern, to allow direct comparison with prior ecological analyses. Sensitivity 3 excluded malaria to test robustness of diarrhoea and

animal protein associations independently of concurrent infectious disease burden. The designation of the primary model was determined before results were examined, based solely on the circularity criteria described above.

A secondary analysis was conducted within the 26 WHO-defined meningitis belt countries, incorporating mean meningococcal A conjugate vaccine coverage estimates for 2010–2021 derived from Bender et al. Belt countries lacking campaign coverage data were assigned a coverage value of zero, consistent with the absence of documented campaigns in those countries.

Geographic visualisations were produced using the **ggplot2** (version 4·0·2), **sf** (version 1·1·0), **rnaturalearth** (version 1·2·0), **rnaturalearthdata** (version 1·0·0) and **viridis** (version 0·6·5) packages. Country boundaries were obtained from the Natural Earth dataset and joined to country-level data by ISO 3166-1 alpha-3 country codes. Results were exported to Microsoft Excel format using the **writexl** package (version 1·5·4). All figures were exported at 300 dots per inch resolution.

Given the ecological study design and the sample size of 54 countries, which limits statistical power, associations with $p < 0·10$ were considered as indicative of borderline statistical significance and reported as such. These findings are interpreted as hypothesis-generating signals warranting confirmation in subnational analyses rather than as definitive associations in line with the ecological framework of the study. The outcome variable represents GBD 2023 modelled mortality estimates with associated 95% uncertainty intervals. Uncertainty in the input estimates was not propagated into the regression analysis; point estimates were used throughout.

AI assistance declaration: Statistical code for all analyses — including beta regression models, Spearman rank correlation matrices, variance inflation factor computation, and data visualisation comprising choropleth maps, scatter plots, correlation heat matrices and forest plots — was written in R version 4·5·3 with assistance from an AI language model (Claude, claude-sonnet-4-6, Anthropic, April 2026). Language editing and grammar improvement of the manuscript text were also assisted by the same tool. All research design, hypothesis formulation, data collection and curation, covariate selection, model specifications and sensitivity analyses, interpretation of findings, and scientific conclusions are entirely the authors' own. The AI tool was used to implement analytical decisions already made by the authors rather than to generate scientific insights or draw conclusions. All figures were generated by the authors using R statistical software; AI assistance was limited to writing and debugging the underlying code. The complete R code is available alongside the dataset at https://doi.org/10.17632/cpp59686nf.1 . Authors take full responsibility for all content, analyses, and conclusions.

Results:

The geographic co-distribution of meningitis cause fraction and millet and sorghum protein supply across African countries is illustrated in Figure 1, providing the visual basis for the study hypothesis.

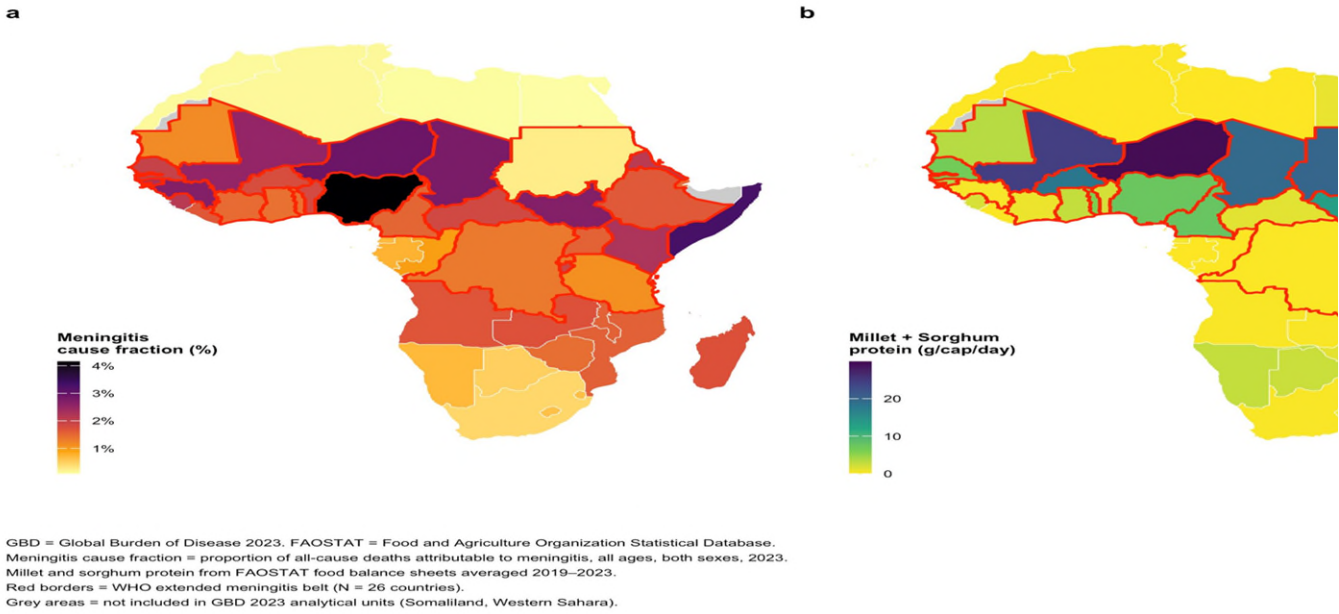


Fig 1: Maps of Africa showing Meningitis cause fraction by country(A). Millet and Sorghum protein supply by FAOSTAT food balances by country (B)

Descriptive statistics

Descriptive statistics for all study variables are presented in Table 1. Meningitis cause fraction varied substantially across the 54 countries, from 0·0008 in Egypt to 0·0415 in Nigeria (median 0·0150 [IQR 0·0067–0·0195]), with belt countries showing nearly three-fold higher median cause fractions than non-belt countries (0·0191 versus 0·0071), consistent with the known geographic concentration of meningitis burden in the Sahelian belt. Belt and non-belt countries also differed markedly across disease and care variables: malaria and diarrhoea cause fractions were substantially higher in belt countries, while SDI, HiB3 coverage and animal protein availability were lower. Notably, PCV3 coverage was comparable between belt and non-belt countries (median 0·698 versus 0·751), indicating that residual heterogeneity in meningitis burden within the belt cannot be attributed to differences in pneumococcal vaccination alone.

Staple protein supply showed pronounced geographic patterning. Millet and sorghum protein were almost exclusively concentrated in belt countries, with belt medians of 0·85 and 1·93 g/capita/day respectively, compared to medians of 0·00 and 0·10 g/capita/day in non-belt countries. The maximum values were 18·3 g/capita/day for millet protein in Niger and 15·7 g/capita/day for sorghum protein in Sudan, while values of zero were recorded in multiple non-belt countries for both crops. In contrast, wheat, rice and maize protein were more widely distributed across both belt and non-belt countries, with zero values rarely observed.

Table 1. Descriptive statistics of study variables across 54 African countries

Values are median [interquartile range] unless otherwise stated. Belt countries = 26 WHO-defined meningitis belt countries. Non-belt = remaining 28 African countries. Cause fractions represent proportion of total deaths attributable to each cause (GBD 2023). Dietary variables from FAOSTAT food balance sheets 2021–2024.

Variable	All Africa (N=54) Median [IQR]	Belt countries (N=26) Median [IQR]	Non-belt countries (Median [IQR]
Outcome			
Meningitis cause fraction 2023	0·0150 [0·0067, 0·0195]	0·0191 [0·0155, 0·0246]	0·0071 [0·0039, 0·0
Disease			
Diarrhea cause fraction 2023	0·0374 [0·0179, 0·0502]	0·0470 [0·0373, 0·0668]	0·0218 [0·0094, 0·0
Malaria cause fraction 2023	0·0410 [0·0031, 0·0805]	0·0524 [0·0290, 0·0862]	0·0033 [0·0000, 0·0
HIV cause fraction 2023	0·0396 [0·0172, 0·0992]	0·0514 [0·0268, 0·0921]	0·0354 [0·0078, 0·1
Care			
Unsafe sanitation SEV (%)	69·70 [56·15, 80·53]	78·15 [68·60, 84·10]	59·25 [26·10, 71·4
Household air pollution (proportion)	0·702 [0·280, 0·936]	0·927 [0·739, 0·968]	0·398 [0·057, 0·6
Socio-demographic Index	0·483 [0·386, 0·577]	0·411 [0·345, 0·482]	0·570 [0·475, 0·6
HiB3 vaccination coverage	0·785 [0·655, 0·890]	0·716 [0·645, 0·820]	0·825 [0·679, 0·9
PCV3 vaccination coverage	0·710 [0·568, 0·855]	0·698 [0·572, 0·818]	0·751 [0·546, 0·8
Diet			
Animal protein (g/capita/day)	17·00 [13·13, 26·55]	14·40 [12·20, 18·10]	23·85 [15·83, 32·1
Non-cereal plant protein (g/capita/day)	8·90 [6·95, 14·78]	11·35 [7·88, 16·90]	8·20 [5·30, 9·73
Total Kcal/day	2572 [2390, 2840]	2509 [2254, 2768]	2603 [2413, 2960
Exposure			
Wheat protein (g/capita/day)	6·12 [3·00, 13·43]	4·15 [2·63, 7·38]	10·30 [5·08, 18·0
Rice protein (g/capita/day)	5·10 [2·03, 9·43]	5·43 [2·00, 9·40]	3·19 [2·10, 8·88
Maize protein (g/capita/day)	4·55 [1·38, 10·18]	6·35 [1·68, 10·60]	3·92 [1·30, 9·18
Millet protein (g/capita/day)	0·20 [0·00, 0·88]	0·85 [0·31, 2·60]	0·00 [0·00, 0·12
Sorghum protein (g/capita/day)	0·60 [0·10, 2·23]	1·93 [0·75, 6·68]	0·10 [0·00, 0·53
Cassava protein (g/capita/day)	0·70 [0·00, 2·75]	1·25 [0·15, 2·60]	0·10 [0·00, 2·83

IQR = interquartile range (25th–75th percentile). Min and Max values refer to the full analytical sample (N=54 African countries). GBD = Global Burden of Disease 2023. SEV = Summary Exposure Value (age-standardised). SDI = Socio-demographic Index. FAOSTAT = Food and Agriculture Organization Statistical Database. HiB3 and PCV3 vaccination coverage expressed as proportions (0–1).

Correlations and covariate selection

Spearman rank correlations between candidate predictor variables and meningitis cause fraction are shown in Table S2a. The strongest positive correlates of meningitis mortality were diarrhoea cause fraction (r = 0·797) and household air pollution (r = 0·789). Among dietary variables, animal protein showed the strongest negative correlation (r = −0·563), followed by wheat protein (r = −0·635). Among staple proteins, millet showed a positive correlation with outcome (r = 0·541), reflecting its geographic concentration in high-burden belt countries. Key inter-variable correlations are presented in Table S2b and visualised in the correlation heat matrix in Figure 2. Notable collinearities included SDI with household air pollution (r = −0·900) and HiB3 with PCV3 vaccination (r = 0·771).

Variance inflation factors ranged from 8·12 for SDI to 1·41 for non-cereal plant protein (Table S2c). A circularity assessment of GBD-derived variables is presented in Table S1b and summarised in a covariate selection flowchart in Figure S3. Six variables were excluded from the final model on grounds of circularity, multicollinearity, or lack of bivariate association: SDI, HiB3, PCV3, HIV cause fraction, non-cereal plant protein, and total Kcal/day. The rationale for each exclusion is detailed in Table S2d. The final primary model covariates were diarrhoea cause fraction, malaria cause fraction, and animal protein availability, with each of the six staple proteins entered separately.

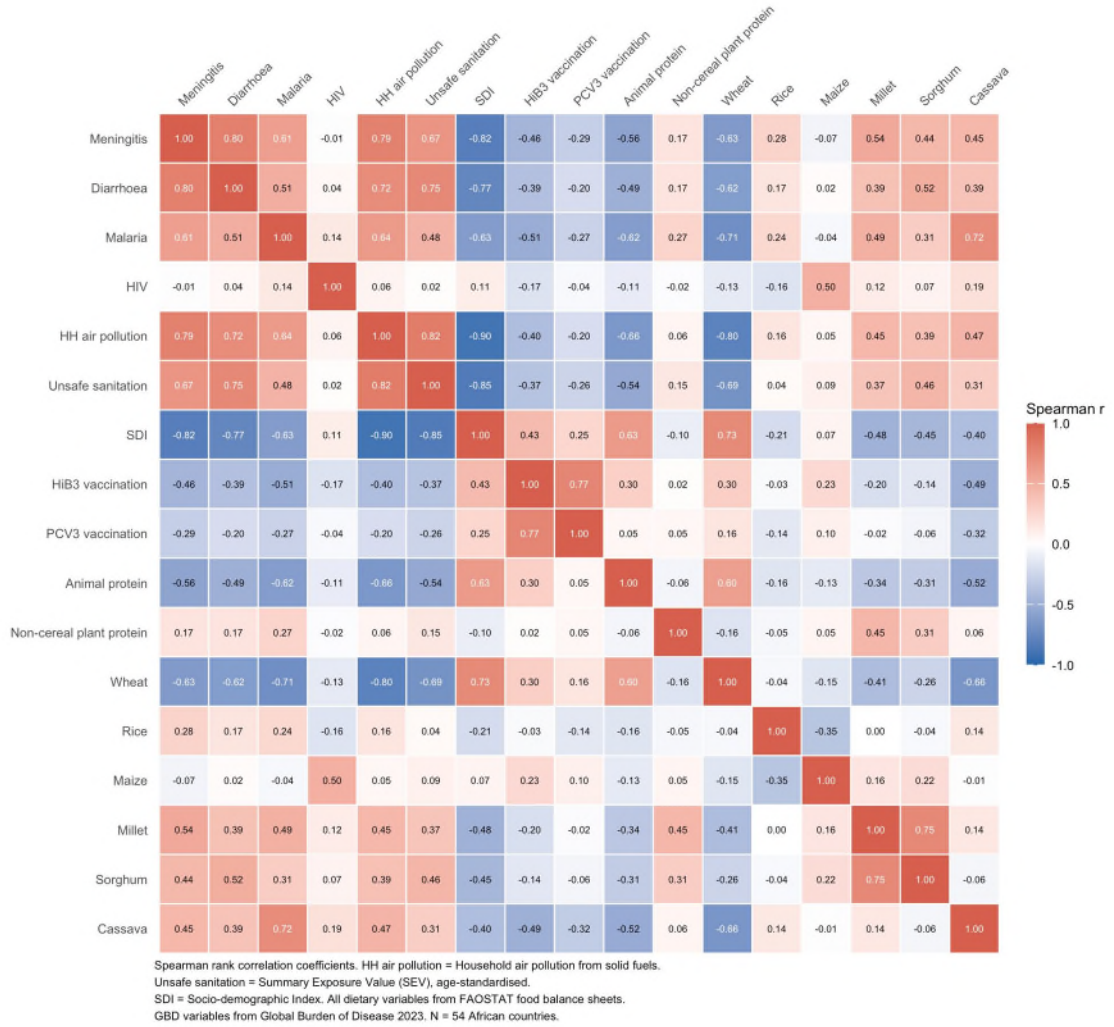


Fig 2: Inter-variable correlation heat matrix of covariates used in the study. HH air pollution= Household air pollution, Unsafe sanitation: SEV of age-standardised exposure to unsafe sanitation. Diarrhoea: Percentage of deaths due to diarrhoeal diseases, all ages and sexes,2023. HIV: Deaths attributable to HIV and AIDS, all ages and sexes 2023. Malaria: Percentages of deaths attributable to Malaria, all ages and sexes,2023. Meningitis deaths: Proportion of all cause deaths attributable to meningitis for both sexes and all ages,2023. HIB3 vaccination: Estimated coverage of three doses of *Haemophilus influenzae* type b vaccine among children,2023. PCV3: Estimated coverage of three doses of pneumococcal conjugate vaccine among children,2023.SDI: Socio-demographic index for 2023. Animal protein: Per capita protein supply from animal sources through food balances . Non-cereal plant protein: Per capita protein supply from non-cereal plant sources through food balances. Wheat, rice, maize, sorghum, millet and cassava protein: Per capita protein from respective staple source through food balances.

Beta regression — primary model

Across all six staple models, diarrhoea cause fraction was consistently and positively associated with meningitis mortality (β ranging 7·38 to 9·58, all p<0·001). Malaria cause fraction was a significant positive predictor in five of six staple models (β ranging 2·98 to 3·78, p ranging 0·011 to 0·038), but did not reach significance in the wheat model (β = 1·733, 95% CI −1·042 to 4·508, p = 0·221). Animal protein coefficients were consistent in magnitude across five of six staple models (β ranging −0·031 to −0·035), with modest attenuation in the wheat model (β = −0·024), likely reflecting partial geographic overlap between high wheat protein availability and higher animal protein intake in North African

countries. Model fit was good, with pseudo-R^2 values ranging from 0·701 (cassava model) to 0·794 (wheat model).

Of the six staple proteins, only wheat protein reached independent statistical significance ($\beta = -0{\cdot}024$ [95% CI −0·042 to −0·006], $p = 0{\cdot}010$). The wheat model also showed the best fit of all six primary staple models (pseudo-$R^2 = 0{\cdot}794$, $\Delta AIC = +1{\cdot}65$ relative to the best-fitting sensitivity specification). Malaria was not a significant predictor in the wheat model ($p = 0{\cdot}221$), in contrast to the other five staple models where it was consistently significant. No other staple protein — millet, sorghum, rice, maize, or cassava — reached significance in the primary model.

Sensitivity analyses

Full sensitivity analysis results are presented in Tables S3a–S3c and summarised in the forest plots in Figures S4a and S4b.

In Sensitivity 1, which replaced the care infrastructure variable with household air pollution (best AIC across all six staple models, zero GBD circularity), diarrhoea and household air pollution were both significantly and positively associated with meningitis mortality across all staple models. Animal protein was attenuated to non-significance in five of six models, with borderline significance retained only in the cassava model ($\beta = -0{\cdot}015$, $p = 0{\cdot}075$). No staple protein was significant in Sensitivity 1. This attenuation reflects collinearity-driven suppression: household air pollution, animal protein availability and malaria burden were highly intercorrelated at country level (Spearman r ranging +0·58 to −0·74, Figure 2), co-occurring as manifestations of shared poverty ecology in sub-Saharan Africa. The attenuation of animal protein in this specification is therefore interpreted as a statistical suppression effect rather than evidence of a true absence of association.

In Sensitivity 2, which added sanitation to the primary model covariates, diarrhoea was positively associated with outcome and animal protein negatively associated across all six staple models. Sanitation was significantly associated with outcome in all staple models except wheat. Wheat retained a negative association with outcome ($\beta = -0{\cdot}018$, $p = 0{\cdot}072$), though this did not reach conventional significance.

Sensitivity 3, which used the same covariates as Sensitivity 2 but excluded malaria, produced results broadly consistent with Sensitivity 2. Animal protein remained a significant negative predictor across all staple models. Wheat protein retained significance ($\beta = -0{\cdot}024$, $p = 0{\cdot}013$). Rice showed a borderline positive association with outcome in this specification.

Descriptive analysis of belt countries

The heterogeneity in meningitis cause fraction, MACV coverage, and dietary protein supply across the 24 belt countries with available coverage data is presented in Table S4. Despite high and broadly comparable MACV coverage across many belt countries, meningitis cause fractions varied more than ten-fold, from 0·0025 in Sudan to 0·0415 in Nigeria. Countries with the lowest animal protein intake and highest millet and sorghum dependence — Niger, Mali, Burkina Faso — showed among the highest meningitis cause fractions despite vaccination coverage exceeding 80%. In contrast, Sudan and Mauritania,

with substantially higher animal protein availability, showed lower meningitis burden relative to their vaccination coverage. A scatter plot of meningitis cause fraction against animal protein supply across all 54 African countries is shown in Figure 3 (r = −0·563). The attenuation of the association within the belt (r = −0·13) compared to all-Africa (r = −0·563) is consistent with range restriction in both variables among belt countries, and with the homogenising effect of MACV campaigns on meningitis mortality across the belt irrespective of dietary differences.

[Table 2 near here] Table 2. Primary model — Beta regression results (N=54 African countries)

Meningitis ~ Diarrhea + Malaria + Animal Protein + Staple. Zero GBD circularity. Animal protein significant in all 6 staple models.

Staple	Variable	Estimate	95% CI	p value	Sig
Millet model | Pseudo R^2 = 0·704 | ΔAIC = +7·53					
	Diarrhea	9·1674	[6·3807, 11·9541]	<0·001	***
	Malaria	3·0000	[0·1647, 5·8353]	0·0381	*
	Animal Protein	-0·0333	[-0·0470, -0·0196]	<0·001	***
	Staple	0·0095	[-0·0170, 0·0360]	0·4824	
Sorghum model | Pseudo R^2 = 0·707 | ΔAIC = +6·96					
	Diarrhea	9·4761	[6·4142, 12·5380]	<0·001	***
	Malaria	3·2171	[0·4018, 6·0324]	0·0251	*
	Animal Protein	-0·0328	[-0·0467, -0·0189]	<0·001	***
	Staple	-0·0004	[-0·0302, 0·0294]	0·9808	
Rice model | Pseudo R^2 = 0·726 | ΔAIC = +5·84					
	Diarrhea	9·5794	[6·9248, 12·2340]	<0·001	***
	Malaria	2·9819	[0·2979, 5·6659]	0·0294	*
	Animal Protein	-0·0311	[-0·0446, -0·0176]	<0·001	***
	Staple	0·0121	[-0·0028, 0·0270]	0·1119	
Wheat model | Pseudo R^2 = 0·794 | ΔAIC = +1·65					
	Diarrhea	7·3770	[4·5497, 10·2043]	<0·001	***
	Malaria	1·7332	[-1·0416, 4·5080]	0·2208	
	Animal Protein	-0·0240	[-0·0379, -0·0101]	<0·001	***
	Staple	-0·0238	[-0·0418, -0·0058]	0·0099	**
Maize model | Pseudo R^2 = 0·706 | ΔAIC = +7·48					
	Diarrhea	9·4423	[6·7206, 12·1640]	<0·001	***
	Malaria	3·1896	[0·4013, 5·9779]	0·0250	*
	Animal Protein	-0·0329	[-0·0468, -0·0190]	<0·001	***
	Staple	-0·0009	[-0·0211, 0·0193]	0·9271	

Staple	Variable	Estimate	95% CI	p value	Sig
Cassava model | Pseudo R^2 = 0·701 | ΔAIC = +6·66					
	Diarrhea	9·2641	[6·5564, 11·9718]	<0·001	***
	Malaria	3·7816	[0·8610, 6·7022]	0·0112	*
	Animal Protein	-0·0345	[-0·0486, -0·0204]	<0·001	***
	Staple	-0·0268	[-0·0862, 0·0326]	0·3772	

**** p<0·001 ** p<0·01 * p<0·05 † p<0·1. Estimates are log-odds coefficients from beta regression with logit link, N=54 African countries. 95% CI = 95% confidence interval. ΔAIC = difference in Akaike Information Criterion relative to best-fitting model per staple (Sensitivity 1, HAP model). Pseudo R^2 shown per staple model.*

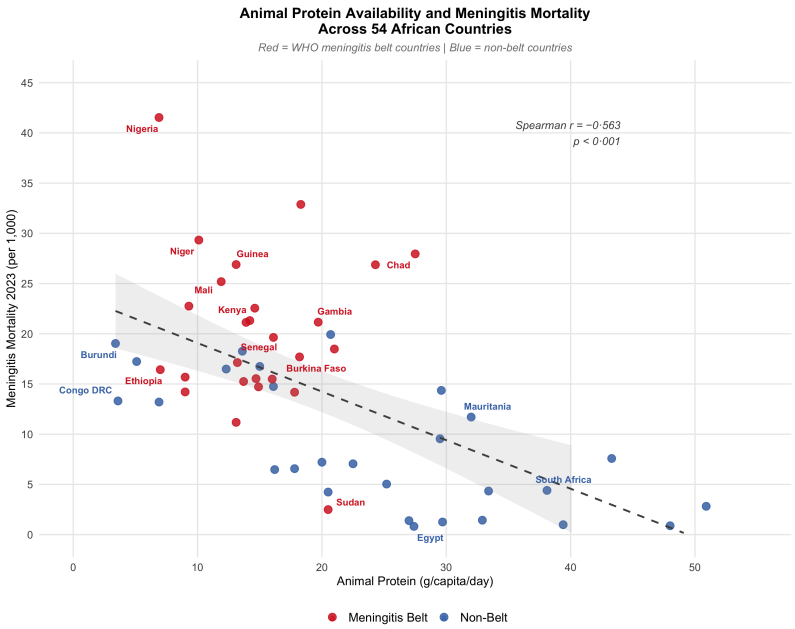


Fig 3: Scatter plot for African countries of meningitis mortality and animal protein supply in gram per capita per day(food balances).

Discussion

In our results, animal protein availability was independently and inversely associated with meningitis mortality across all six staple models, robust to three of four sensitivity specifications. Wheat protein amongst the staples also shows a statistically significant association to outcome in two of the four models. In the sensitivity model incorporating household air pollution from solid fuels — which demonstrated the best overall statistical fit by AIC — the association of animal protein with meningitis mortality was attenuated to non-significance. This attenuation is attributable to collinearity-driven suppression rather than a true absence of association: household air pollution, animal protein availability and malaria burden were highly intercorrelated at the country level (**Fig1**,Spearman r ranging +0·58 to −0·74), reflecting the shared poverty ecology of sub-

Saharan Africa in which low animal protein intake, high solid fuel use and high infectious disease burden co-occur as manifestations of the same underlying deprivation.

Differences in intake of animal protein could be a contributory factor in meningitis susceptibility within communities. The only significant socioeconomic differences between two cohorts of people with(cases) and without meningitis(taken as control) in a Gambian population was greater cattle ownership in the control group , which could plausibly be linked to greater intake of animal source protein in the latter.[16] This similarity in prior antibody titres implies comparable meningococcal exposure between the two groups, raising the possibility that the differential susceptibility reflected by case-control status was mediated through host factors — potentially including nutritional status — rather than differential pathogen exposure, though this interpretation was not advanced by the authors.[16] The advantage of wheat over other staples is also reflected in ecological studies. Grasgruber et al., in a food balance-based ecological study of adult male stature across 105 countries, identified wheat-based diets as intermediate in protein quality — superior to rice-based diets but inferior to dairy and animal-protein-complemented diets, consistent with wheat's relative lysine adequacy compared to other cereals but its inability to substitute for high-quality animal protein sources.[17]

Our results also show a statistically significant positive association in the primary model of diarrheal diseases with meningitis in the context of all staples. Shared covariate architecture with outcome could be contributory. However, this likely represents the fact that diarrhoea is a proximate marker for deprivation in settings were meningitis and socioeconomic backwardness is common. This is corroborated by a recent GBD paper on Diarrhoea which showed that the highest age standardised mortality, for both males and females(above 100 per 100,000), was seen in three countries in the African meningitis belt , namely, South Sudan, Chad and Somalia.[18] Moreover, diarrhoea and nutrition have a known bidirectional relationship which is also replicated between nutrition and infection.[19] A study showing the vulnerability of a rodent model, fed on low protein diet, to cryptosporidiosis, exemplifies this phenomenon.[20] Similarly, a study with rats fed a low protein diet demonstrating increased vulnerability to bacterial infection, mediated by Neutrophil mitochondrial function, which was resolved on giving Nicotinamide, also illustrates both the vulnerability of dietary protein inadequacy to infections, as well as, the relevance of micronutrients in combating infection.[21]

Household air pollution from solid fuels was a consistently significant positive predictor of meningitis mortality across all six staple models in Sensitivity 1, and is independently attributed to 2,690 meningitis deaths globally in GBD 2023.[1] However, if household air pollution were acting as a direct independent causal pathway to meningitis, one would expect disproportionately higher meningitis mortality in women and girls, who bear substantially greater HAP exposure than men due to their role as primary cooks — with personal HAP exposure in sub-Saharan African rural households documented at up to five-fold higher in adult females than adult males.[22] The comparable meningitis mortality rates in males and females documented in GBD 2023 (both 3·2 per 100,000)[1] argue against this interpretation, and are more consistent with household air pollution serving as a marker of shared poverty ecology rather than an independent causal pathway — as reflected in its high collinearity with animal protein availability and malaria burden in our analysis.

Vaccination has had a major contribution in meningitis mortality over the past few decades worldwide, including in Africa.[2] This is exemplified by a dramatic 99% reduction

in Group A Meningococcus infection, in the belt countries since 2010.[10] These campaigns being focussed on the belt countries since 2010, are also likely to have substantially reduced the dietary signals of millet and sorghum to the outcome, as seen from the higher exposure of millet and sorghum in the belt countries in comparison to the others in **Table 1**. Our descriptive analysis of the belt countries also exemplifies the high Meningococcus A conjugate vaccine (MACV) coverage of the belt countries with substantial variation in their meningitis mortality prevalence as well as protein supply from sorghum, millet and animal sources as seen in supplementary materials **Table S4** . Interestingly, in **Table S4** ,the highest meningitis mortality is in Nigeria, which has a substantially lower millet and sorghum protein supply than the next two succeeding countries, Niger and Chad. A closer look at Nigeria shows the highest meningitis prevalence is in the Northern districts.[23] A paper discussing millet and sorghum consumption in Niger and Nigeria shows how the consumption of these staples is distributed widely through all districts of Niger, while it is concentrated almost exclusively in Nigeria's northern districts.[24] This heterogeneity in consumption of sorghum and millet is contributory to the lower supply of millet and sorghum in Nigeria, as seen in Supplementary Table S4. Northern Nigeria also has considerably higher prevalence of child stunting and wasting in comparison to Southern districts.[25] That the above child undernutrition and higher meningitis mortality have not been associated in literature with dietary staple patterns could be due to the fact that surveys like Demographic and health survey(DHS) and multi-indicator-cluster-surveys (MICS), cereals(rice, wheat, maize, millet and sorghum) and tubers(cassava, yam, plantain etc) consumed are recorded as a generic "cereals" and "tubers" respectively, than by type.[26,27] At the subnational level, the absence of crop-disaggregated dietary data in DHS and MICS instruments precludes direct testing of this association with meningitis outcomes.

Cassava has the lowest protein-energy ratios among these staples and is the staple of millions, particularly in Central Africa, which are additionally burdened by low animal protein intake as seen in Burundi and Congo, in Table S4 of supplementary materials. Cassava intake in Kivu, Congo, along with its leaves has been linked to Kwashiorkor, a form of acute malnutrition, through higher thiocyanate levels from cassava leaves and lower content of sulphur containing amino acids like methionine in cassava.[28] Like millet and sorghum in the Sahel, cassava dominance combined with low animal protein intake represents a pattern of poor dietary protein complementation that may similarly increase host susceptibility to bacterial infections. Higher child wasting has been documented in many of the belt countries too.[29] In fact, two of the chief risk factors linked to meningitis mortality in the latest GBD 2023 study are low birth weight and short gestation, both of which are intimately linked to child undernutrition.[1,30] This higher prevalence of child undernutrition in Sub-Saharan Africa, could be relevant to meningitis causation, as is seen by younger age of affected individuals in the African meningitis belt.[2] The GBD meningitis mortality model itself incorporates child underweight as a positive predictor, suggesting that nutritional vulnerability may mediate part of the meningitis burden in these populations — a pathway that warrants formal investigation.[14]

Limitations

Our study being an ecological study can be viewed only as hypothesis generating for further definitive studies. Our choice of nutrients was proteins but other micronutrients

like Niacin, Vit A, Zinc could very well be vital to a dietary pathway to immune compromise, which has not been explored by us. The predictor variables for diarrhoea and malaria mortality in the primary model are GBD cause fractions sharing both the all-cause mortality denominator and underlying covariate architecture — including SDI, sanitation and healthcare access — with the meningitis cause fraction outcome. This compositional and architectural non-independence of many covariates in our study means associations involving these GBD-derived predictors should be interpreted as reflecting shared deprivation context rather than independent biological pathways. Dietary predictors from FAOSTAT and household air pollution from household surveys are unaffected by this limitation. Lack of subnational data about starchy staple consumption, is a major limitation in our study, limiting our extending the analysis to countries in Africa with availability of subnational GBD data. For 9 countries FAOSTAT data was not available and had to be imputed. Moreover, our sample size was limited to 54 countries which limits our degree of freedom. Our food balances are annual averages and do not capture seasonal dietary variations, particularly in the dry season.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used Claude, claude-sonnet-4-6, Anthropic, to assist with language editing and grammar improvement of the manuscript, and for writing and debugging statistical code in R for beta-regression analysis, correlation matrices and data visualisation. AI was not used for study design, data analysis, interpretation of results, or drawing scientific conclusions. All scientific content and conclusions are solely the work of the authors. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declarations

Ethics approval and consent to participate

This study used publicly available aggregate data from the Global Burden of Disease 2023 Results Tool and FAOSTAT Food Balance Sheets. No individual patient data were used and no ethics approval was required.

Consent for publication

Not applicable.

Availability of data and materials

The datasets and R code supporting the conclusions of this article are available in the Mendeley Data repository: https://doi.org/10.17632/cpp59686nf.1. Data are available under embargo until publication.

Competing interests

All authors declare no competing interests.

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Authors' contributions

RKS: Conceptualization, Data curation, Formal analysis, Writing – original draft, Supervision, Project administration. **RGV**: Conceptualization, Data curation, Formal analysis. **DK**: Conceptualization, Data curation, Formal analysis. **TM**: Conceptualization, Data curation, Writing – review and editing, Supervision. **RK**: Data curation, Formal analysis, Supervision. **BK**: Conceptualization, Data curation, Writing – review and editing, Supervision. **AB**: Data curation, Writing – review and editing. **RA**: Data curation, Formal analysis. **MB**: Data curation, Formal analysis. **SAK**: Data curation, Supervision. **RJ**: Data curation, Supervision. **TMit**: Data curation. **KS**: Data curation. All authors read and approved the final manuscript.

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Supplementary material legends

Table S1. Study variables and data sources (S1a) and circularity assessment of study covariates in relation to GBD 2023 cause of death modelling frameworks (S1b). See Additional file 1.

Table S2. Correlation and multicollinearity assessment including Spearman rank correlations (S2a), key inter-variable correlations (S2b), Variance Inflation Factor results (S2c), and candidate covariate selection criteria (S2d). See Additional file 1.

Table S3. Sensitivity analysis results: Sensitivity 1 — HAP model (S3a), Sensitivity 2 — Sanitation model (S3b), Sensitivity 3 — No malaria model (S3c). See Additional file 1.

Table S4. Meningitis mortality, meningococcal A conjugate vaccine coverage and dietary protein availability across 24 WHO meningitis belt countries. See Additional file 1.

Figure S1. Millet protein supply across African countries. See Additional file 1.

Figure S2. Sorghum protein supply across African countries. See Additional file 1.

Figure S3. Covariate selection flowchart for beta regression models. See Additional file 1.

Figure S4a. Forest plot of animal protein beta regression coefficients across six staple models and four model specifications. See Additional file 1.

Figure S4b. Forest plot of staple protein beta regression coefficients across six staple models and four model specifications. See Additional file 1.

Figure S5. Animal protein availability and meningitis mortality across 24 belt countries with available MACV campaign coverage data. See Additional file 1.

Supplementary Files

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