Int.J.Curr.Microbiol.App.Sci (2026) *15*(10): 349-391

International Journal of Current Microbiology and Applied Sciences
ISSN: 2319-7706 **Volume 15 Number 10 (2026)**
Journal homepage: http://www.ijcmas.com

Original Research Article https://doi.org/10.20546/ijcmas.2026.1510.038

Acidity, Microbial Hazards and Cadmium Exposure in Market Garri from Rivers State, Nigeria: A Probabilistic Chemical and Microbial Risk Assessment

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Keywords

Garri; pH; Staphylococci; faecal coliforms; cadmium; microbial risk assessment; left-censored data

Article Info

Received:
05 August 2026
Accepted:
30 September 2026
Available Online:
10 October 2026

A B S T R A C T

Garri, a fermented and roasted cassava granular, often eaten soaked (flake) or reconstituted (eba) that services as the major source of energy to millions of Southern Nigerians. Analysed were 45 samples from 15 markets in three local government areas (LGAs) of Rivers State, Nigeria, for pH, five microbial groups, proximate composition and four metals. Non-detects were censored except in ranking, and chemical risks were simulated probabilistically. Market mean pH (3.65 to 7.30) differed among LGAs (p = 0.031) and was highest in Ogoni (6.10; about 4.0 elsewhere). Staphylococci occurred in 9 markets (up to 3.40 log CFU/g), fungi in 10 (none in Ogoni) and faecal coliforms only at Etche (pH 3.65; 141 CFU/g). Fungal detection was less likely at higher pH (odds ratio 0.17 per unit, p = 0.002), whereas staphylococcal detection was not (p = 0.25). Cadmium (1.00 to 1.40 mg/kg) drove hazard indices of 5.47 to 7.28 and exceeded regional crop values (0.0008 to 0.01 mg/kg), so it needs confirmation with certified reference materials. The lead margin of exposure for nephrotoxicity was below 1 in Ikwerre and Ogoni. An annual infection risk of about 10^{-4} would result if one in a million faecal coliforms were enteroinvasive *Escherichia coli*. Modelled staphylococcal growth was absent at pH 4.0 or below for every assumed minimum pH but substantial in four Ogoni markets. In conclusion, Chokocho in Etche LGA ranked highest for inspection in the main analysis, and acidity did not exclude faecal coliforms.

Introduction

Garri is a precooked, dried cassava granular that is common in sub-Saharan Africa (Dahdouh *et al.,* 2021). It is made by rasping cassava roots, fermenting and pressing the mash and roasting the granules (Escobar *et al.,* 2021), and it is eaten as granules or as eba, a dough made from the granules (Awoyale *et al.,* 2021). Garri is also eaten soaked in water, a habit reported by 46.4% (136 of 293) of Edo State market traders aware of Lassa fever (Tobin *et al.,* 2015). The estimated mean adult garri intake in Nigeria is about 0.303 kg per day (Olorunnado *et al.,* 2024), so a hazard at a low concentration can still produce a substantial dose.

Fermentation drives the acidity of garri from *Lactobacillus plantarum* which account for 54.6% of 139 predominant isolates from fermenting cassava mash in Benin (Kostinek *et al.,* 2005). In cassava dough fermented into garri, the pH falls and titratable acidity rises (Afoakwa *et al.,* 2010). Escobar *et al.,* (2021) identified fermentation and pressing as the operations that control lactic acid content, and Dahdouh *et al.,* (2021) found that the quality of handmade garri depends strongly on the dewatering and roasting parameters chosen by operators; therefore, acidity at the point of garri sale should be ascertained and not assumed.

Market garri is not microbiologically inert as reported by Ogiehor *et al.,* (2007), who examined 300 market samples from southern Nigeria, isolated eight bacterial genera including *Staphylococcus* sp., coliforms, and six fungal genera, and detected aflatoxins; they concluded that production and handling were not standardised. Water activity in trade garri varied from 0.587 initially to 0.934 after storage, and the range of mould species increased with water activity (Samuel & Ugwuanyi, 2014). *Staphylococcus* sp. was among the dominant phylotypes in garri (Dike *et al.,* 2022).

Staphylococcal food poisoning results from ingestion of preformed enterotoxins, which resist heat and proteolytic enzymes and tolerate a wide pH range (Asao *et al.,* 2003; Cieza *et al.,* 2024; Zhu *et al.,* 2024). Staphylococcal growth and enterotoxin formation depend on water activity, pH and temperature (Ding *et al.,* 2016; Valero *et al.,* 2009), and in a cheese model the predicted maximum population exceeded 5 log CFU/g in every combination with detectable enterotoxin (Cai *et al.,* 2023). In soaked garri, acidity may be the main remaining barrier. Identification also matters, because tube coagulase testing alone showed low specificity for *Staphylococcus aureus* among presumptive isolates (Kateete *et al.,* 2010), and coagulase-negative staphylococci from Nigerian fermented foods carried enterotoxin genes (Fowoyo & Ogunbanwo, 2016). Faecal coliforms, the other bacterial indicator examined here, are counted at an elevated temperature that also recovers organisms of environmental origin (Leclerc *et al.,* 2001).

Heavy metals are of concern as reported by Ohiagu *et al.,* (2020) of cadmium concentration above the World Health Organization permissible level in soils and leaves from dumpsites at Onne, Rivers State, whereas cadmium measured 0.01 mg/kg in root tubers from Ogoniland (Peters *et al.,* 2018) and 0.0008 to 0.0027 mg/kg in food crops from an oil-impacted community (Akinkpelumi *et al.,* 2026). The EFSA Panel on Contaminants in the Food Chain (CONTAM, 2011) set a tolerable weekly intake of 2.5 µg/kg body weight, but guidance on dietary cadmium has been questioned because conventional tolerable intakes may not protect the kidney (Satarug *et al.,* 2023). Garri surveys have reported heavy metals such as iron, copper, zinc, nickel and aluminium (Awoyale *et al.,* 2018; Enyoh *et al.,* 2023), whereas the regional cadmium data cited here come from soils and crops and not from market garri.

Values below the limit of detection are often replaced by a fixed number, which can over- or underestimate results (Bahk & Lee, 2021) and obscure patterns (Helsel, 2006); maximum likelihood estimation and robust regression on order statistics performed best in simulations and case studies of food chemical data (Hwang *et al.,* 2023). Quantitative microbial risk assessment (QMRA) comprises hazard identification, hazard characterisation, exposure assessment and risk characterisation (Food and Agriculture Organization of the United Nations [FAO] & World Health Organization [WHO], 2021), but its food applications focus mainly on major foodborne pathogens (Orahovac *et al.,* 2026). Microbiological criteria and sampling plans discriminate defective lots but have limitations (Pérez-Lavalle *et al.,* 2020), and risk-ranking tools are used to set priorities (Bevilacqua *et al.,* 2023). Among the garri studies cited here, none combined censored-data statistics, probabilistic chemical risk assessment and microbial risk assessment.

Analysed were 45 garri samples from 15 markets in three LGAs of Rivers State to studied and describe pH and five microbial groups with methods for censored data, to test whether pH was associated with microbial occurrence and counts, to measure proximate composition and four metals in area composites and estimate dietary chemical risk, to model staphylococcal growth after soaking and the infection risk from faecal coliforms, and to evaluate sampling plans and rank markets for inspection.

Materials and Methods

Study design and sampling

This cross-sectional survey covered three areas of Rivers State, Nigeria: Ikwerre, Etche and Ogoni (Figure 1). Five retail markets were sampled in each area, namely Aluu, Isiokpo, Omagwa, Omahunwa and Rumuchiorlu in Ikwerre; Igbo, Okomoko, Ulakwo, Egwi and Chokocho

in Etche; and Kibaga, Station, Bomu, Kaa and Kpor in Ogoni. Garri was purchased from three vendors in each market, which gave 45 samples (3 areas × 5 markets × 3 vendors). [Sampling dates, criteria for selecting markets and vendors, mass purchased per sample and garri type (white or yellow) to be stated by the authors.] Each sample was packaged in a sterile zip-lock bag, transported in an ice-packed cooler to the food laboratory of the Department of Microbiology and stored at 4 °C until analysis [maximum storage time to be stated]. For proximate and metal analyses, the samples from each area were pooled into one composite and analysed in triplicate. Results for individual vendors were not available for the present analysis, so each market is represented by the mean and standard deviation (SD) of its three samples.

pH and Microbiological Analyses

A 10 g portion of each sample was homogenised in 90 mL of 0.1% peptone water [homogenisation method and duration]. The pH of a 1:10 (w/v) suspension [state whether this was the peptone water homogenate or a suspension in distilled water] was measured with a calibrated meter [meter model and calibration buffers]. Serial tenfold dilutions were prepared, and 0.1 mL of the 10^{-1} dilution and of higher dilutions was spread on nutrient agar for total heterotrophic bacteria (THB), de Man, Rogosa and Sharpe (MRS) agar for lactic acid bacteria (LAB), mannitol salt agar for staphylococci, Sabouraud dextrose agar with chloramphenicol for fungi, and eosin methylene blue (EMB) agar incubated at 44.5 °C for faecal coliforms [incubation temperature, time and atmosphere for each medium]. Colonies were counted according to ISO 7218:2024 (International Organization for Standardization [ISO], 2024). Because 0.1 mL of the 10^{-1} dilution represents 0.01 g of sample, one colony on one plate corresponded to 100 CFU/g, and the limit of detection (LOD) was therefore 2.0 log CFU/g. Here and below, log denotes the base 10 logarithm ($\log_{10}$ in the figures). Colonies on mannitol salt agar were confirmed as staphylococci by the coagulase test [coagulase method, plasma source and number of isolates tested], and the species was not established.

Proximate composition and metals

Moisture, ash, crude fibre, crude lipid and crude protein were determined by the methods of AOAC INTERNATIONAL (Latimer, 2023), and carbohydrate was calculated by difference [protein conversion factor and basis of expression, as is or dry matter]. Lead, chromium, cadmium and copper were determined by atomic absorption spectrophotometry after wet acid digestion [digestion acids and conditions, flame or graphite furnace mode, wavelengths, detection limits, certified reference material and recoveries]. Each composite was determined in triplicate, and results are reported as the mean ± SD of the replicate determinations.

Statistical Analysis

Microbial counts were analysed as log CFU/g. Each market was represented by the mean and SD of its three samples, and comparisons between areas used the 15 market means (five per area). Results are reported at three levels: the general range across the 15 markets, the range and the mean ± SD of the five market means within each area, and the mean ± SD of the three samples from each market.

Areas were compared with Welch's analysis of variance (ANOVA), which tolerates unequal variances (Delacre *et al.,* 2019), followed by Games-Howell tests, and with the Kruskal-Wallis test (effect size $\varepsilon^2 = H/(n - 1)$) followed by Holm-adjusted Dunn tests as a distribution-free check (Terpilowski, 2019; Vallat, 2018). A nested ANOVA reconstructed from the market means, SDs and $n = 3$ partitioned the variance into components among areas, among markets within areas and among samples within markets, in the sense of repeatability (Nakagawa & Schielzeth, 2010). Differences among markets were tested by one-way ANOVA reconstructed from the summary statistics, with Tukey's honestly significant difference test; for staphylococci and fungi, only markets with detections were compared. Detection frequencies were compared between areas with the Fisher-Freeman-Halton exact test, and proportions were given with Clopper-Pearson 95% confidence intervals, which are conservative at small sample sizes (Reiczigel, 2003).

In the univariate, bivariate and regression analyses, counts below the LOD were treated as left-censored and were not replaced by a fixed fraction of the LOD, because substitution can bias estimates and obscure patterns (Helsel, 2006; Hwang *et al.,* 2023). Censored counts were summarised with the Kaplan-Meier estimator after flipping (each value was subtracted from a constant of 10, so that left-censored values became right-censored), which performed best overall for summary statistics when censoring was below 70% in a simulation

study (Antweiler & Taylor, 2008). Hewett and Ganser (2007) did not recommend this estimator for means or high percentiles, so it was used for medians and group comparisons only. Areas were compared with the Peto-Prentice test, one of the survival-analysis tests adapted to non-detects (Shoari & Dubé, 2018), with a permutation *p* value from 10,000 permutations of the area labels. A sensitivity analysis lowered the censoring limit from 2.0 to 1.0 log CFU/g.

Associations were quantified with Kendall's τ-b adapted to censored data, in which two markets were counted as concordant or discordant only if the intervals defined by their values and censoring limits did not overlap, and were otherwise counted as tied; *p* values came from 10,000 permutations. Spearman's ρ was added for pairs without censored values, and a variant that gave every non-detect the lowest tied rank served as a sensitivity analysis. The false discovery rate across the ten pairwise associations was controlled by the Benjamini-Hochberg procedure (Glickman *et al.,* 2014), and *q* denotes an adjusted *p* value.

Linear regressions of THB and LAB on pH (for LAB, also with area as a covariate) used ordinary least squares with analytic confidence intervals, percentile bootstrap intervals from 5,000 resamples (Carpenter & Bithell, 2000) and leave-one-out cross-validation (LOOCV), expressed as Q^2, which is one minus the ratio of the predictive residual sum of squares to the total sum of squares. Cross-validated estimates are themselves highly variable or biased in small samples (Braga-Neto & Dougherty, 2004; Vabalas *et al.,* 2019; Varoquaux, 2018). Counts of fungi and staphylococci were modelled with Tobit regression (left-censored normal errors; maximum likelihood; likelihood-ratio test of the slope), which handles censored outcomes (Lubin *et al.,* 2004) but can mislead when the variance is not constant (Austin *et al.,* 2000).

Detection (yes or no) was modelled with Firth's penalised logistic regression, which gives finite estimates when detections and non-detections separate (Heinze, 2006; Heinze & Schemper, 2002), with profile penalised-likelihood confidence intervals and likelihood-ratio tests. LOOCV gave the area under the receiver operating characteristic curve (AUC) and the Brier score, which was compared with that of an intercept-only model. Firth's method shrinks predicted probabilities towards 0.5 (Puhr *et al.,* 2017), so odds ratios were reported in preference to calibrated probabilities.

Principal component analysis (PCA), which replaces correlated variables with uncorrelated components (Jolliffe & Cadima, 2016), and Ward hierarchical clustering were applied as exploratory analyses to the standardised market means of pH and the four counts. Because both methods need complete data, non-detects were set to log(LOD/2) = 1.70 in the main analysis, and the stability of the clusters was examined with values of 0, 1.0, 1.85 (log(LOD/√2)) and 2.0. Three clusters were extracted, and the cophenetic correlation described how well the dendrogram preserved the distances between markets.

Analyses used Python 3.13.16 with NumPy 2.5.3 (Harris *et al.,* 2020), SciPy 1.18.1 (Virtanen *et al.,* 2020), pandas 3.0.5 (McKinney, 2010), pingouin 0.7.0 (Vallat, 2018), scikit-posthocs 0.17.0 (Terpilowski, 2019) and Matplotlib 3.11.2 (Hunter, 2007). Tests were two-sided with α = 0.05, *p* values were unadjusted unless stated, and random seeds were fixed for all permutation, bootstrap and Monte Carlo procedures.

Dietary chemical risk assessment

The estimated daily intake (EDI, mg/kg body weight per day) of each metal was calculated with Equation (1), where *C* is the concentration in garri (mg/kg), IR is the daily garri intake (kg/day) and BW is body weight (kg). The estimated mean adult garri intake in Nigeria of 0.303 kg per day (Olorunnado *et al.,* 2024) was treated as dry garri, to match the basis of the metal results [confirm the basis of expression of the metal results]. The target hazard quotient (THQ) of each metal and the hazard index (HI) followed Equations (2) and (3), as in an assessment of metals in Nigerian shellfish (Chris *et al.,* 2023). The HI summed the THQ values of cadmium, copper and chromium(III), for which oral reference doses (RfD) were available (Table 1). Lead was assessed by the margin of exposure (MOE; Equation 4), in which the lead EDI is compared with benchmark dose lower confidence limits (BMDL) for nephrotoxicity, systolic blood pressure and developmental neurotoxicity (CONTAM, 2010), and by the incremental lifetime cancer risk (ILCR; Equation 5), which multiplies the EDI by a cancer slope factor (CSF). An MOE below 1 means that the estimated intake exceeds the BMDL. Cadmium intake was also expressed as a percentage of the tolerable daily intake (TDI) of 0.83 µg/kg body weight per day (Satarug *et al.,* 2023) and as a multiple of the tolerable weekly intake (TWI) of 2.5 µg/kg body weight per week set by CONTAM (2011).

$$\mathrm{EDI} = \frac{C \times \mathrm{IR}}{\mathrm{BW}} \quad (1)$$

$$\mathrm{THQ}_i = \frac{\mathrm{EDI}_i}{\mathrm{RfD}_i} \quad (2)$$

$$\mathrm{HI} = \sum_i \mathrm{THQ}_i \quad (3)$$

$$\mathrm{MOE} = \frac{\mathrm{BMDL}}{\mathrm{EDI_{Pb}}} \quad (4)$$

$$\mathrm{ILCR} = \mathrm{EDI} \times \mathrm{CSF} \quad (5)$$

Chromium was measured as total chromium. The oral reference dose of chromium(VI) is far lower than that of chromium(III) (Table 1), and food organic matter can reduce chromium(VI) to chromium(III), which makes speciation in foods difficult (Chung, 2024; Hamilton *et al.,* 2018). The HI therefore used the chromium(III) reference dose, and a worst-case scenario in which all chromium was hexavalent supplied a separate THQ and an ILCR with the oral slope factor of chromium(VI) (U.S. Environmental Protection Agency [US EPA], 2024).

Variability was propagated by Monte Carlo simulation with 100,000 iterations per area. Intake followed a lognormal distribution (mean 0.303 kg/day, coefficient of variation 50%), body weight a normal distribution (mean 60 kg, SD 10 kg) truncated at 40 and 100 kg, and each metal concentration a lognormal distribution defined by the area mean and the SD of the replicate determinations (Table 1). The shapes of the intake and body weight distributions and the body weight parameters were assumed, because consumption and anthropometric data for Rivers State were not available. Because each area is represented by one composite, the simulated concentration variability reflects analytical replication only. Sensitivity was assessed with Spearman rank correlations between each input and the HI; in a comparison of ten sensitivity methods applied to a food safety risk model, most methods ranked the key inputs similarly (Patil & Frey, 2004). Results were reported as the deterministic value (intake 0.303 kg/day and body weight 60 kg) and as the 5th, 50th and 95th percentiles of the simulation.

To judge whether the cadmium results were plausible, the concentration expected in garri was estimated from the cadmium concentration of cassava tubers from Ogoniland, 0.01 mg/kg (Peters *et al.,* 2018). Dewatering and roasting remove water, so a constituent retained in the dry matter is concentrated by a factor equal to the dry matter fraction of garri, (100 − moisture)/100, divided by the dry matter fraction of fresh roots.

The dry matter of fresh roots was assumed to be 20 to 25%, cadmium was assumed to remain with the dry matter, and the tuber value was assumed to be expressed on a fresh weight basis; none of these assumptions is supported by a cited source. The measured concentrations were compared with this expected range and with the concentrations at which a daily intake of 303 g would equal the TWI or the TDI for a 60 kg adult.

Microbial risk assessment of faecal coliforms

The assessment followed the four steps of FAO and WHO (2021). Counts of faecal coliforms on EMB agar at 44.5 °C served as an indicator of faecal contamination, and enteroinvasive *Escherichia coli* was the reference pathogen, with the dose-response parameters listed for it in the QMRAwiki database (CAMRA, n.d.).

A colony count at 44.5 °C is not proof of faecal origin or of *E. coli* (Leclerc *et al.,* 2001), so the proportion of faecal coliforms that are pathogenic, f, was an unknown scenario variable between 10^{-7} and 1. Two concentration scenarios were evaluated: the mean count of the market with faecal coliforms above the LOD (Chokocho; 141 CFU/g) and the LOD itself (100 CFU/g), which is an upper bound for markets without detection. A consumer was assumed to eat 303 g of garri (dry mass) per day without heating, with no growth or die-off, so that the daily dose of pathogenic cells was $f \times C_{\mathrm{FC}} \times M$.

The probability of infection per serving followed the approximate beta-Poisson model (Equation 6), and the annual probability assumed 365 independent daily exposures at constant contamination (Equation 7). The approximation was checked against the exact beta-Poisson function, because the approximation can deviate at low doses (Teunis & Havelaar, 2000). The annual risk was compared with a benchmark of 10^{-4} infections per person per year, a common position in drinking-water guidelines that is not a food standard (Signor & Ashbolt, 2009).

Equations (6) and (7) were also solved for the pathogenic fraction and the pathogen concentration at which the benchmark is reached.

$$P_{\text{inf}} = 1 - \left[1 + \frac{f\, C_{\text{FC}}\, M\left(2^{1/\alpha} - 1\right)}{N_{50}}\right]^{-\alpha} \quad (6)$$

$$P_{\text{ann}} = 1 - (1 - P_{\text{inf}})^{n} \quad (7)$$

Growth potential and threshold exceedance of staphylococci

For each market with detections, the margin to a screening threshold of 5 log CFU/g was calculated as 5 minus the market mean. The threshold is the population exceeded in every combination with detectable enterotoxin in a cheese model (Cai *et al.,* 2023). The probability that one sample exceeded the threshold was 1 − Φ((5 − mean)/SD), where Φ is the standard normal distribution function and the mean and SD are those of the market, and the dose per serving (log CFU) was the market mean plus log 303. For comparison with regulatory guidance, counts were assigned to the categories for coagulase-positive staphylococci in ready-to-eat foods (UK Health Security Agency [UKHSA], 2024), on the assumption that coagulase-confirmed colonies were coagulase-positive. The categories are satisfactory (less than 20 CFU/g), borderline (20 to 10^4 CFU/g) and unsatisfactory (more than 10^4 CFU/g). The method LOD of 100 CFU/g exceeds the satisfactory limit, so markets without detection could not be classified.

Growth after reconstitution was described with a cardinal pH function (Equation 8) that gives the relative growth rate γ, from 0 to 1, as a function of the pH of the garri, with minimum (pH_{min}), optimum (pH_{opt}) and maximum (pH_{max}) values for growth. The multiplicative form treats pH as one of several independent effects on the growth rate, an assumption that interaction terms can relax (Le Marc *et al.,* 2002). The pH_{opt} of 7.0 and pH_{max} of 9.6 were assumed. The pH_{min} was drawn from a uniform distribution between 4.0 and 4.5 (100,000 draws), with 4.25 as the central value, because growth has been observed at pH 4.5 at high water activity (Valero *et al.,* 2009) and the minimum pH of the staphylococci in garri is unknown. A sensitivity grid used pH_{min} values of 4.0, 4.25, 4.5 and 5.0. These cardinal values are assumptions and not estimates fitted to garri. The time to reach 5 log CFU/g was $(5 - N_0)/\gamma$, in units of the time for a one log increase at optimum pH, where N_0 is the initial count in log CFU/g; lag, temperature, water activity and competing organisms were not modelled. For markets without detection, N_0 was set to the LOD (2.0) as a lower bound, with 1.0 as a sensitivity value.

$$\gamma(\text{pH}) = \frac{(\text{pH} - \text{pH}_{\text{min}})(\text{pH} - \text{pH}_{\text{max}})}{(\text{pH} - \text{pH}_{\text{min}})(\text{pH} - \text{pH}_{\text{max}}) - (\text{pH} - \text{pH}_{\text{opt}})^{2}} \quad (8)$$

Sampling plans, ranking and classification of markets

The probability that a lot is accepted by a sampling plan was computed from the operating characteristic function, assuming that log counts of staphylococci among samples within a lot are normally distributed with an SD of 0.37 log CFU/g, the pooled within-market SD of markets with detections. A two-class plan (n = 5 sample units, c = 0, limit $m = 10^3$ CFU/g) accepts a lot when no sample exceeds m. A three-class plan (n = 5, c = 2, $m = 10^3$ and $M = 10^4$ CFU/g) accepts a lot when no sample exceeds M and at most c samples lie between m and M. For a true mean log count μ, the probabilities that a sample exceeds m and M are $p_m = 1 - \Phi((\log m - \mu)/\sigma)$ and $p_M = 1 - \Phi((\log M - \mu)/\sigma)$, and the probability of acceptance P_a for the three-class plan is given by Equation (9); for the two-class plan, $P_a = (1 - p_m)^n$. The limits are illustrative and are not a published criterion for garri. Microbiological criteria discriminate defective lots but have limitations (Pérez-Lavalle *et al.,* 2020), so acceptance does not prove the absence of a hazard, and three samples per market give little information on heterogeneous or localised contamination (Jongenburger *et al.,* 2015). The acceptance probability of each market was computed at its mean count, with non-detects bounded at the LOD.

$$P_a = \sum_{k=0}^{c} \binom{n}{k} (p_m - p_M)^k (1 - p_m)^{n-k} \quad (9)$$

Markets were ranked on four hazards: the relative growth rate γ at pH_{min} = 4.25, and the counts of staphylococci, faecal coliforms and fungi. Each criterion was scaled from 0 to 1 across the 15 markets, and the composite score was the unweighted mean of the four scaled values. Non-detects were set to log(LOD/2) = 1.70 in the main analysis and to 0 and 2.0 in sensitivity analyses. To test the dependence on the weights, 20,000 weight vectors were drawn from a Dirichlet distribution with equal parameters, and the proportion of draws in which a

market ranked among the three highest-scoring markets was recorded. Risk-ranking tools such as Risk Ranger are commonly used in microbiological risk assessment (Bevilacqua *et al.,* 2023). Markets were also assigned to three classes by rules defined by the authors. Priority action applied when faecal coliforms were detected, when the mean count of staphylococci exceeded 4.0 log CFU/g (the upper limit of the borderline category), or when staphylococci were detected and the pH exceeded 4.5. Monitor applied when staphylococci were detected or the pH exceeded 4.5, and Low concern applied otherwise. These rules are screening rules and not a published criterion.

Data audit, assumptions and sensitivity analyses

The tables supplied for analysis were audited for internal consistency before analysis, and every change is described in this section. The recorded moisture values duplicated the ash values, so moisture was recovered as 100 − (ash + crude fibre + crude lipid + crude protein + carbohydrate), which is valid because carbohydrate had been calculated by difference from the original moisture [original moisture values to be inserted]. Two decimal-place errors in the source tables were corrected: crude protein in Ikwerre garri from 0.063 to 0.63% and chromium in Etche garri from 90.325 to 0.325 mg/kg [confirm against laboratory records]. Four market means were below the nominal LOD of 2.0 log CFU/g: staphylococci at Rumuchiorlu (1.75), THB at Kpor (1.50) and LAB at Station (1.50) and Kaa (1.30). One colony from 0.1 mL of the 10^{-1} dilution already corresponds to 2.0 log CFU/g, so the origin of these values requires confirmation [explain how counts below 100 CFU/g were obtained]. They were retained as reported and tested in sensitivity analyses in which they were set to 2.0 log CFU/g or, for staphylococci at Rumuchiorlu, treated as censored. The Etche lead value (0.005 ± 0.000 mg/kg) may be close to the detection limit of the method [detection limit to be stated] and was used as reported.

Where data were not available, assumptions were made explicit (Table 1). They concern body weight and the shape of the intake distribution, the dry matter of fresh roots, the cardinal pH values, the pathogenic fraction of faecal coliforms, the sampling-plan limits and the substitution of non-detects in the multivariate and ranking analyses. Each of them is an assumption and not a measurement, and the sensitivity of the main results to the most influential of them is reported with the results.

Results and Discussion

Acidity

Market mean pH ranged from 3.65 at Chokocho to 7.30 at Station across the 15 markets (mean of the market means 4.73 ± 1.23; Figure 2a). Market means ranged from 3.80 to 4.40 in Ikwerre (4.03 ± 0.24), from 3.65 to 4.40 in Etche (4.05 ± 0.32) and from 4.20 to 7.30 in Ogoni (6.10 ± 1.27). The areas differed (Welch $F(2, 7.05) = 5.93$, $p = 0.031$; Kruskal-Wallis $H = 7.30$, $p = 0.026$, $\varepsilon^2 = 0.52$). In Games-Howell tests, Ogoni exceeded Ikwerre ($p = 0.044$) and Etche ($p = 0.045$), whereas Ikwerre and Etche did not differ ($p = 0.990$). Holm-adjusted Dunn tests gave $p = 0.053$ for Ogoni against each of the other two areas and $p = 0.943$ for Ikwerre against Etche. Areas accounted for 67.6% of the variance in pH, markets within areas for 29.9% and samples within markets for 2.5%.

The market means in Ikwerre were 4.10 ± 0.14 at Aluu, 3.83 ± 0.04 at Isiokpo, 3.80 ± 0.14 at Omagwa, 4.00 ± 0.00 at Omahunwa and 4.40 ± 0.15 at Rumuchiorlu (Figure 3). In Etche, they were 4.10 ± 0.10 at Igbo, 3.80 ± 0.10 at Okomoko, 4.30 ± 0.00 at Ulakwo, 4.40 ± 0.10 at Egwi and 3.65 ± 0.05 at Chokocho. In Ogoni, they were 5.50 ± 0.21 at Kibaga, 7.30 ± 0.14 at Station, 6.45 ± 0.21 at Bomu, 7.05 ± 0.71 at Kaa and 4.20 ± 0.14 at Kpor. The SD among the three samples of a market ranged from 0.00 to 0.71 (Kaa). Markets differed (one-way ANOVA $F(14, 30) = 93.93$, $p < 0.001$), and Tukey comparisons formed five overlapping groups (a to e, from the highest to the lowest means), with Station in group a, Kaa in group ab and Chokocho in group e (Table 2).

Total heterotrophic bacteria and lactic acid bacteria

Market mean counts of total heterotrophic bacteria (THB) ranged from 1.50 log CFU/g at Kpor to 5.91 log CFU/g at Aluu (mean of the market means 3.24 ± 1.05; Figure 2b). Market means ranged from 3.07 to 5.91 in Ikwerre (4.27 ± 1.07), from 2.30 to 3.40 in Etche (2.96 ± 0.44) and from 1.50 to 3.10 in Ogoni (2.49 ± 0.65). The Kruskal-Wallis test gave $H = 8.24$ ($p = 0.016$, $\varepsilon^2 = 0.59$), and Welch's analysis of variance gave $F(2, 7.25) = 4.63$ ($p = 0.051$). Ikwerre exceeded Ogoni (Games-Howell $p = 0.039$; Dunn-Holm $p = 0.014$), whereas Ikwerre and Etche did not differ ($p = 0.107$ and 0.132, respectively)

and Etche and Ogoni did not differ (p = 0.415 and 0.322). Areas accounted for 45.3% of the variance, markets within areas for 26.9% and samples within markets for 27.7%.

The THB means in Ikwerre were 5.91 ± 0.71 at Aluu, 4.60 ± 0.14 at Isiokpo, 3.95 ± 0.01 at Omagwa, 3.80 ± 0.01 at Omahunwa and 3.07 ± 0.01 at Rumuchiorlu. In Etche, they were 3.40 ± 0.42 at Igbo, 3.30 ± 0.71 at Okomoko, 2.95 ± 1.41 at Ulakwo, 2.85 ± 0.92 at Egwi and 2.30 ± 0.71 at Chokocho. In Ogoni, they were 3.10 ± 0.21 at Kibaga, 2.90 ± 0.00 at Station, 2.75 ± 1.27 at Bomu, 2.20 ± 0.71 at Kaa and 1.50 ± 0.00 at Kpor, a value below the LOD of 2.0 log CFU/g. The SD among the samples of a market ranged from 0.00 to 1.41 (Ulakwo). Markets differed (F(14, 30) = 7.41, p < 0.001), and Tukey comparisons formed four overlapping groups (a to d; Table 2).

Market mean counts of lactic acid bacteria (LAB) ranged from 1.30 log CFU/g at Kaa to 4.70 log CFU/g at Kpor (mean of the market means 2.68 ± 0.79; Figure 2c). Market means ranged from 2.15 to 3.05 in Ikwerre (2.59 ± 0.38), from 2.44 to 3.30 in Etche (2.78 ± 0.34) and from 1.30 to 4.70 in Ogoni (2.68 ± 1.38). The areas did not differ (Welch F(2, 7.23) = 0.30, p = 0.749; Kruskal-Wallis H = 0.25, p = 0.885, ε^2 = 0.02), and no pair of areas differed (Games-Howell p = 0.707 to 0.989; Dunn-Holm p = 1.000). Areas accounted for 0.0% of the variance, markets within areas for 78.8% and samples within markets for 21.2%.

The LAB means in Ikwerre were 2.85 ± 0.21 at Aluu, 2.25 ± 0.71 at Isiokpo, 2.65 ± 0.07 at Omagwa, 2.15 ± 0.21 at Omahunwa and 3.05 ± 0.71 at Rumuchiorlu. In Etche, they were 3.30 ± 0.64 at Igbo, 2.44 ± 0.07 at Okomoko, 2.91 ± 0.71 at Ulakwo, 2.65 ± 0.14 at Egwi and 2.58 ± 0.55 at Chokocho. In Ogoni, they were 3.20 ± 0.00 at Kibaga, 1.50 ± 0.00 at Station, 2.70 ± 0.42 at Bomu, 1.30 ± 0.29 at Kaa and 4.70 ± 0.28 at Kpor; the means at Station and Kaa were below the LOD. The SD among the samples of a market ranged from 0.00 to 0.71. Markets differed (F(14, 30) = 10.53, p < 0.001), and Tukey comparisons formed four overlapping groups (a to d), of which Kpor alone occupied group a (Table 2).

Staphylococci, fungi and faecal coliforms

Staphylococci were reported in 9 of 15 markets (60.0%; 95% confidence interval [CI] 32.3 to 83.7%), with market means from 1.75 log CFU/g at Rumuchiorlu, a value below the LOD, to 3.40 log CFU/g at Okomoko (Figure 2d). Detections numbered 3 of 5 markets in Ikwerre (market means 1.75 to 2.10), 5 of 5 in Etche (2.45 to 3.40) and 1 of 5 in Ogoni (2.40 at Station). The frequency of detection did not differ significantly among areas (Fisher-Freeman-Halton p = 0.066), whereas the censored-data comparison of the counts did (Peto-Prentice χ^2 = 16.03, permutation p < 0.001; Figure 4a). Kaplan-Meier medians were 1.75 log CFU/g in Ikwerre and 2.55 log CFU/g in Etche, and the median in Ogoni was below the LOD.

The market means of staphylococci in Ikwerre were 2.00 ± 0.00 at Omagwa, 2.10 ± 0.00 at Omahunwa and 1.75 ± 0.00 at Rumuchiorlu, and staphylococci were not detected at Aluu or Isiokpo. In Etche, the means were 2.55 ± 0.14 at Igbo, 3.40 ± 0.42 at Okomoko, 2.55 ± 0.00 at Ulakwo, 2.45 ± 0.64 at Egwi and 2.60 ± 0.78 at Chokocho. In Ogoni, staphylococci were detected only at Station (2.40 ± 0.00) and not at Kibaga, Bomu, Kaa or Kpor. The nine market means corresponded to 56 CFU/g (Rumuchiorlu) to 2,512 CFU/g (Okomoko).

Among the nine markets with detections, counts differed (one-way ANOVA F(8, 18) = 4.88, p = 0.003), and Okomoko exceeded Omagwa, Omahunwa and Rumuchiorlu in Tukey comparisons (Table 2).

Fungi were reported in 10 of 15 markets (66.7%; 95% CI 38.4 to 88.2%), with market means from 2.10 log CFU/g at Ulakwo to 3.16 log CFU/g at Egwi (Figure 2e). Detections numbered 5 of 5 markets in both Ikwerre (2.25 to 3.10) and Etche (2.10 to 3.16) and 0 of 5 in Ogoni. The frequency of detection differed among areas (Fisher-Freeman-Halton p = 0.001), as did the counts in the censored-data comparison (Peto-Prentice χ^2 = 9.66, permutation p = 0.010; Figure 4b). Kaplan-Meier medians were 2.25 log CFU/g in Ikwerre and 2.70 log CFU/g in Etche, and the median in Ogoni was below the LOD.

The market means of fungi in Ikwerre were 3.10 ± 0.14 at Aluu, 2.25 ± 0.71 at Isiokpo, 2.25 ± 0.00 at Omagwa, 2.30 ± 0.07 at Omahunwa and 2.25 ± 0.07 at Rumuchiorlu. In Etche, the means were 3.00 ± 0.00 at Igbo, 2.30 ± 0.14 at Okomoko, 2.10 ± 0.21 at Ulakwo, 3.16 ± 0.00 at Egwi and 2.70 ± 1.41 at Chokocho, and fungi were not detected at any market in Ogoni. The ten market means corresponded to 126 CFU/g (Ulakwo) to 1,445 CFU/g (Egwi), and counts did not differ among these markets (F(9, 20) = 1.93, p = 0.106; Table 2).

Faecal coliforms were detected in 1 of 15 markets (6.7%; 95% CI 0.2 to 31.9%), namely Chokocho in Etche, with a mean of 2.15 ± 0.21 log CFU/g (141 CFU/g; Figure 2f; Table 2). They were not detected in Ikwerre, at the other four markets in Etche or in Ogoni, and the frequency of detection did not differ among areas (Fisher-Freeman-Halton $p = 1.000$).

Association of pH with microbial occurrence and counts

Across the 15 markets, censored Kendall's τ-b between pH and the counts was −0.33 for THB ($p = 0.101$), +0.01 for LAB ($p = 0.999$), −0.27 for staphylococci ($p = 0.203$) and −0.42 for fungi ($p = 0.045$; Figure 5a). After the Benjamini-Hochberg adjustment across ten pairs, no association was significant ($q \geq 0.293$). Among the microbial groups, τ-b ranged from −0.13 (LAB with staphylococci, $p = 0.552$) to +0.36 (THB with fungi, $p = 0.085$), and staphylococci with fungi gave +0.35 ($p = 0.117$). Spearman's ρ for pairs without censored values was −0.46 for pH with THB ($p = 0.083$), +0.02 for pH with LAB ($p = 0.949$) and −0.02 for THB with LAB ($p = 0.940$). When non-detects were assigned the lowest tied rank, τ-b for pH with fungi was −0.42 ($p = 0.043$, $q = 0.250$) and for pH with staphylococci it was −0.31 ($p = 0.131$, $q = 0.263$).

Ordinary least squares regression gave a slope of −0.288 log CFU/g per pH unit for THB (SE 0.223, $p = 0.218$, $R^2 = 0.114$, $Q^2 = −0.093$; analytic 95% CI −0.77 to 0.19; bootstrap 95% CI −0.63 to −0.02) and a slope of −0.303 for LAB (SE 0.157, $p = 0.076$, $R^2 = 0.222$, $Q^2 = −0.023$; analytic CI −0.64 to 0.04; bootstrap CI −0.52 to 0.37). With area added as a covariate, the pH slope for LAB was −0.909 (SE 0.191, $p < 0.001$, $R^2 = 0.676$, $Q^2 = 0.359$; analytic CI −1.33 to −0.49; bootstrap CI −1.11 to 0.70; four coefficients; Table 3).

In Tobit regression (Table 3), the slope of fungal counts on pH was −0.516 log CFU/g per pH unit (SE 0.267; likelihood-ratio statistic 9.51, $p = 0.002$), whereas the Wald interval (slope ± 1.96 SE) ran from −1.04 to 0.01. The slope for staphylococci was −0.163 (SE 0.141; likelihood-ratio statistic 1.40, $p = 0.237$; Figure 4d). With the censoring limit lowered to 1.0 log CFU/g, the slopes were −1.107 for fungi (SE 0.437, $p < 0.001$) and −0.360 for staphylococci (SE 0.278, $p = 0.189$). In Firth logistic regression, the odds ratio for detection of fungi was 0.172 per pH unit (profile 95% CI 0.0006 to 0.618; likelihood-ratio statistic 9.22, $p = 0.002$). The predicted probability of detection was 0.5 at pH 5.13, the leave-one-out AUC was 0.82, and the Brier score was 0.091 against 0.253 for an intercept-only model (Figure 4c). For staphylococci, the odds ratio was 0.633 (95% CI 0.247 to 1.384; likelihood-ratio statistic 1.31, $p = 0.253$), the predicted probability of detection was 0.5 at pH 5.62, the AUC was 0.44, and the Brier score was 0.286 against 0.273.

Multivariate structure of the markets

Principal component analysis of the standardised market means of pH and the four counts gave three components that explained 42.1%, 25.4% and 22.4% of the variance (Figure 5b). The loadings on the first component were 0.88 for pH, −0.56 for THB, −0.30 for LAB, −0.39 for staphylococci and −0.88 for fungi, and those on the second component were −0.30, −0.51, 0.92, −0.20 and −0.20, respectively. Ward clustering (cophenetic correlation 0.692) gave three clusters (Figure 5c). Cluster 1 contained all ten Ikwerre and Etche markets, cluster 2 contained Kibaga, Station, Bomu and Kaa, and cluster 3 contained Kpor alone. The same partition resulted when non-detects were set to 0, 1.0 or 1.85 log CFU/g (first component 40.7% to 46.6% of the variance; cophenetic correlation 0.67 to 0.87). When non-detects were set to the LOD (2.0 log CFU/g), the first component explained 38.9% of the variance (cophenetic correlation 0.67), and the partition changed: cluster 1 contained Aluu, Igbo, Okomoko, Egwi and Chokocho; cluster 2 contained Station and Kaa; and cluster 3 contained the remaining eight markets (Isiokpo, Omagwa, Omahunwa, Rumuchiorlu, Ulakwo, Kibaga, Bomu and Kpor).

Proximate composition and metal concentrations

Across the three area composites, moisture ranged from 7.48 to 8.94 g/100 g, ash from 1.31 to 1.65 g/100 g, crude fibre from 0.62 to 0.85 g/100 g, crude lipid from 0.32 to 0.61 g/100 g, crude protein from 0.63 to 1.00 g/100 g and carbohydrate from 87.25 to 89.12 g/100 g (Figures 6a and 6b). The Ikwerre composite contained 7.48 g/100 g moisture, 1.32 ± 0.01 g/100 g ash, 0.85 ± 0.01 g/100 g crude fibre, 0.61 ± 0.01 g/100 g crude lipid, 0.63 ± 0.01 g/100 g crude protein and 89.12 ± 0.16 g/100 g carbohydrate. The Etche composite contained 8.94 g/100 g moisture, 1.65 ± 0.28 g/100 g ash, 0.62 ± 0.01 g/100 g crude fibre, 0.55 ± 0.21 g/100 g crude lipid, 1.00 ± 0.00 g/100 g crude protein and 87.25 ± 0.35 g/100 g carbohydrate. The Ogoni composite contained 8.50 g/100 g moisture, 1.31 ± 0.01 g/100 g ash, 0.73 ± 0.00 g/100 g

crude fibre, 0.32 ± 0.02 g/100 g crude lipid, 0.94 ± 0.00 g/100 g crude protein and 88.20 ± 0.28 g/100 g carbohydrate (Table 4). The moisture values were recovered by difference and have no SD.

Across the composites, metal concentrations ranged from 0.005 to 0.275 mg/kg for lead, from 0.220 to 0.555 mg/kg for chromium, from 1.004 to 1.400 mg/kg for cadmium and from 0.85 to 3.17 mg/kg for copper (Figure 6c; Table 4). The Ikwerre composite contained 0.245 ± 0.007 mg/kg lead, 0.555 ± 0.035 mg/kg chromium, 1.400 ± 0.141 mg/kg cadmium and 1.65 ± 0.03 mg/kg copper. The Etche composite contained 0.005 ± 0.000 mg/kg lead, 0.325 ± 0.021 mg/kg chromium, 1.063 ± 0.004 mg/kg cadmium and 0.85 ± 0.02 mg/kg copper, and the Ogoni composite contained 0.275 ± 0.035 mg/kg lead, 0.220 ± 0.010 mg/kg chromium, 1.004 ± 0.006 mg/kg cadmium and 3.17 ± 0.02 mg/kg copper.

Dietary chemical risk

The estimated daily intake of cadmium was 424 µg in Ikwerre, 322 µg in Etche and 304 µg in Ogoni, which corresponded to 852%, 647% and 611% of the TDI and to 19.8, 15.0 and 14.2 times the TWI (Figure 7b; Table 5). Deterministic target hazard quotients in Ikwerre, Etche and Ogoni were 7.07, 5.37 and 5.07 for cadmium; 0.21, 0.11 and 0.40 for copper; and 0.0019, 0.0011 and 0.0007 for chromium(III), which gave hazard indices of 7.28, 5.48 and 5.47 (Figure 7a). In the Monte Carlo simulation, the median hazard index (5th to 95th percentile) was 6.50 (2.82 to 14.92) in Ikwerre, 4.90 (2.17 to 11.13) in Etche and 4.90 (2.17 to 11.13) in Ogoni, and the hazard index exceeded 1 in 99.99%, 99.93% and 99.93% of the iterations. In the chromium(VI) scenario, the hazard quotient was 3.11, 1.82 and 1.23 (Table 5).

The lead margin of exposure based on nephrotoxicity was 0.51 in Ikwerre, 24.95 in Etche and 0.45 in Ogoni. Based on systolic blood pressure, it was 1.21, 59.41 and 1.08, and based on developmental neurotoxicity, it was 0.40, 19.80 and 0.36 (Figure 7c; Table 5). In the simulation, the median margin for nephrotoxicity was 0.57 (5th to 95th percentile 0.25 to 1.29), 27.86 (12.26 to 63.03) and 0.51 (0.22 to 1.19), and it fell below 1 in 87.0%, 0.0% and 90.5% of the iterations. The median margin for systolic blood pressure was 1.35 (0.60 to 3.07), 66.33 (29.20 to 150.08) and 1.22 (0.52 to 2.83), and it fell below 1 in 27.2%, 0.0% and 35.1% of the iterations.

The incremental lifetime cancer risk of lead was 1.05×10^{-5} in Ikwerre, 2.15×10^{-7} in Etche and 1.18×10^{-5} in Ogoni (simulated medians 9.41×10^{-6}, 1.92×10^{-7} and 1.05×10^{-5}). In the chromium(VI) scenario, it was 4.48×10^{-4}, 2.63×10^{-4} and 1.78×10^{-4}, and it exceeded 10^{-4} in 99.7%, 95.5% and 82.3% of the iterations (Figure 7d; Table 5). The Spearman correlation between the hazard index and the intake rate was 0.93 in Ikwerre and 0.94 in Etche and Ogoni, and that with body weight was −0.29 in Ikwerre and −0.30 in the other two areas. The correlations with the concentration of cadmium were 0.18 in Ikwerre, 0.008 in Etche and 0.011 in Ogoni, those with the concentration of chromium were 0.005 to 0.006, and those with the concentration of copper were below 0.001 in absolute value.

Plausibility of the cadmium concentrations

For the assumed fresh-root dry matter of 20 to 25% and the moisture of the composites (7.48 to 8.94 g/100 g), the dewatering factor was 3.70 to 4.63 in Ikwerre, 3.64 to 4.55 in Etche and 3.66 to 4.58 in Ogoni (overall 3.64 to 4.63). From the cadmium concentration of cassava tubers from Ogoniland (0.01 mg/kg), the expected concentration in garri was 0.036 to 0.046 mg/kg. The measured concentrations of 1.004 to 1.400 mg/kg were 21.7 to 38.4 times the expected range and 100 to 140 times the tuber value, and they were 372 to 1,750 times the values (0.0008 to 0.0027 mg/kg) reported for food crops from an oil-impacted community. A daily intake of 303 g supplied the TWI at 0.071 mg/kg and the TDI at 0.164 mg/kg for a 60 kg adult, and all three measured concentrations exceeded both values (Figure 8).

Infection risk from faecal coliforms

The mean count of faecal coliforms at Chokocho (141 CFU/g) gave 4.28×10^4 cells in a 303 g serving of dry garri, and the LOD (100 CFU/g) gave 3.03×10^4 cells. The approximate beta-Poisson probability differed from the exact value by a relative difference of no more than 6.4×10^{-6}. With a pathogenic fraction f of 10^{-6}, the probability of infection per serving was 2.72×10^{-7} at the Chokocho count and 1.93×10^{-7} at the LOD, and the annual risks were 9.93×10^{-5} and 7.03×10^{-5}. At the Chokocho count, the probability of infection per serving was 2.72×10^{-5} at $f = 10^{-4}$ and 2.69×10^{-3} at $f = 10^{-2}$ (Figure 9a).

At the Chokocho count, the annual risk was 9.93×10^{-6}, 9.93×10^{-5}, 9.92×10^{-4}, 9.88×10^{-3}, 0.094, 0.626, 1.000

and 1.000 for $f = 10^{-7}$, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1} and 1, respectively. At the LOD, the annual risk was 7.03×10^{-6}, 7.03×10^{-5}, 7.03×10^{-4}, 7.00×10^{-3}, 0.068, 0.503, 0.999 and 1.000 (Figure 9b). The annual risk reached 10^{-4} at $f = 1.01 \times 10^{-6}$ at the Chokocho count and at $f = 1.42 \times 10^{-6}$ at the LOD. These values corresponded to a daily dose of 0.0431 pathogenic cells, which equals a pathogen concentration of 1.42×10^{-4} CFU/g, or one cell per 7.0 kg of garri. The LOD was 7.03×10^5 times (5.85 log units) this risk-based concentration (Figure 9c).

Growth potential and threshold exceedance of staphylococci

In the nine markets with detections, the margin between the market mean and the screening threshold of 5 log CFU/g ranged from 1.60 log units at Okomoko to 3.25 log units at Rumuchiorlu (Figure 10c). The margins were 3.00 at Omagwa, 2.90 at Omahunwa, 2.45 at Igbo, 2.45 at Ulakwo, 2.55 at Egwi, 2.40 at Chokocho and 2.60 at Station. The estimated dose per serving ranged from 4.23 log CFU at Rumuchiorlu to 5.88 log CFU at Okomoko. The probability that a sample exceeded the threshold was 1.05×10^{-3} at Chokocho, 6.96×10^{-5} at Okomoko and 3.38×10^{-5} at Egwi, and it was zero to numerical precision at the other markets (Table 6). All nine markets with detections fell into the borderline category of the UKHSA, at 56 CFU/g (Rumuchiorlu) to 2,512 CFU/g (Okomoko), and the six markets without detection could not be classified (Figure 3; Table 2).

With a minimum pH for growth of 4.25, the relative growth rate γ was zero at Aluu, Isiokpo, Omagwa, Omahunwa, Igbo, Okomoko, Chokocho and Kpor. It was 0.103 at Rumuchiorlu and Egwi, 0.035 at Ulakwo, 0.695 at Kibaga, 0.958 at Bomu, 0.987 at Station and 1.000 at Kaa (Figure 10a; Table 6). When the minimum pH was drawn from a uniform distribution between 4.0 and 4.5, the probability of growth was 0.20 at Aluu and Igbo, 0.60 at Ulakwo, 0.80 at Rumuchiorlu and Egwi, 0.40 at Kpor, 1.00 at Kibaga, Station, Bomu and Kaa, and 0 at the remaining markets.

Growth was not predicted at pH 4.0 or below for any assumed minimum pH. The values of γ at minimum pH values of 4.0, 4.25, 4.5 and 5.0 were 0.73, 0.69, 0.65 and 0.48 at Kibaga; 0.99, 0.99, 0.99 and 0.98 at Station; and 0.96, 0.96, 0.95 and 0.94 at Bomu; at Kaa, they were 1.00 for all four values. At minimum pH values of 4.5 and 5.0, γ was zero at every market in Ikwerre and Etche and at Kpor (Figure 10b).

The time to reach 5 log CFU/g after reconstitution, in units of the one-log growth time at optimum pH, was 2.6 at Station, 24.6 at Egwi, 31.4 at Rumuchiorlu and 69.8 at Ulakwo, and no time could be computed at the markets with γ equal to zero. For the markets without detection and with γ above zero, the time was at least 4.3 at Kibaga, 3.1 at Bomu and 3.0 at Kaa when the initial count was set to the LOD (2.0 log CFU/g), and 5.8, 4.2 and 4.0 when it was set to 1.0 log CFU/g (Figure 10d; Table 6).

Sampling plans, ranking and classification of markets

With a between-sample SD of 0.37 log CFU/g, the two-class plan accepted a lot with a probability of 0.95 at a true mean count of 2.15 log CFU/g and with a probability of 0.05 at 2.95 log CFU/g, and the three-class plan did so at 2.68 and 3.32 log CFU/g (Figure 11a). At the market means, the probability of acceptance under the two-class plan was 0.998 at Rumuchiorlu, 0.984 at Omagwa, 0.965 at Omahunwa, 0.769 at Station, 0.706 at Egwi, 0.558 at Igbo and Ulakwo, 0.476 at Chokocho and 5×10^{-5} at Okomoko. Under the three-class plan, it was 1.000 at Omagwa, Omahunwa and Rumuchiorlu, 0.999 at Station, 0.997 at Egwi, 0.989 at Igbo and Ulakwo, 0.979 at Chokocho and 0.019 at Okomoko (Figure 11b; Table 6). With non-detects bounded at the LOD, the probabilities of acceptance were 0.984 and 1.000 for the two plans.

The composite hazard score was highest at Chokocho (0.554), followed by Egwi (0.386), Okomoko (0.353), Station (0.350), Igbo (0.348), Kaa (0.250), Aluu (0.240) and Bomu (0.240), and it was lowest at Kpor (0.000; Figure 11c). Across 20,000 random weight sets, Chokocho ranked among the top three markets in 72.2% of the sets, Egwi in 50.8%, Station in 47.3%, Igbo in 36.7%, Okomoko in 36.1%, Kaa in 29.2%, Bomu in 16.1% and Aluu in 11.5%, whereas the other markets did so in no more than 0.1% of the sets. Chokocho ranked first in 49.8% of the sets, Station in 20.9%, Egwi in 14.8%, Okomoko in 12.9% and Kaa in 1.6%, and the median ranks were 2 for Chokocho, 3 for Egwi, 4 for Igbo and 5 for Okomoko and Station. Chokocho ranked first and Kpor ranked last when non-detects were set to 0 (Chokocho 0.655, probability of ranking among the top three 0.817) and when they were set to the LOD (Chokocho 0.530, probability 0.661). The order of the second to fifth markets changed with the substitution: Egwi, Okomoko, Igbo and Station when non-detects were set to 0, and Egwi, Station, Igbo and Okomoko

when they were set to the LOD. Chokocho and Station were classified as Priority action, ten markets (Omagwa, Omahunwa, Rumuchiorlu, Igbo, Okomoko, Ulakwo, Egwi, Kibaga, Bomu and Kaa) as Monitor and three markets (Aluu, Isiokpo and Kpor) as Low concern (Figure 11c; Table 6).

Sensitivity to values below the limit of detection

Setting the sub-LOD market means for THB (Kpor) and LAB (Station and Kaa) to 2.0 log CFU/g gave, for THB, Welch's $F(2, 7.46) = 4.80$ ($p = 0.046$) and $H = 8.24$ ($p = 0.016$) and, for LAB, Welch's $F(2, 7.30) = 0.39$ ($p = 0.690$) and $H = 0.25$ ($p = 0.884$). Treating the Rumuchiorlu value for staphylococci as censored gave detections in 2, 5 and 1 markets of Ikwerre, Etche and Ogoni (Fisher-Freeman-Halton $p = 0.068$), a Peto-Prentice χ^2 of 16.03 ($p < 0.001$), a Tobit slope on pH of −0.167 ($p = 0.258$), an odds ratio of 0.677 ($p = 0.329$) and a Kendall's τ-b with pH of −0.26 ($p = 0.222$). Lowering the censoring limit to 1.0 log CFU/g gave Peto-Prentice χ^2 values of 16.21 for staphylococci ($p < 0.001$) and 9.66 for fungi ($p = 0.010$).

Acidity of garri among areas and markets

The pH of the Ogoni markets tended to be higher than that of the Ikwerre and Etche markets. The ten Ikwerre and Etche markets had mean values of 3.65 to 4.40 (Table 2), which is consistent with the fall in pH and the rise in titratable acidity that occur during fermentation (Afoakwa *et al.,* 2010). Four of the five Ogoni markets had mean values of 5.50 to 7.30, so the garri sold there was less acidic. Fermentation and pressing influence the lactic acid content of garri (Escobar *et al.,* 2021), and Kostinek *et al.,* (2005) reported that strains of *Lactobacillus plantarum* produced acid better and faster than strains of *Leuconostoc fallax* or *Lactobacillus fermentum* in a fermenting mash for garri in Benin. A shortened fermentation, or one led by slower acid producers, could therefore leave a less acidic product. The present data cannot test either explanation, because the duration of fermentation, the titratable acidity and the starter flora were not recorded.

The strength of the area contrast deserves a measured reading. The omnibus tests gave $p = 0.031$ (Welch) and $p = 0.026$ (Kruskal-Wallis), and the Games-Howell tests gave $p = 0.044$ and 0.045 for Ogoni against Ikwerre and Etche, but the Holm-adjusted Dunn tests gave $p = 0.053$ for both contrasts. The conclusion that Ogoni garri had a higher pH therefore rests on only five markets per area, and the evidence lies at the margin of conventional significance. The spread within Ogoni also argues against a single area-wide process. Kpor (4.20) resembled the markets of Ikwerre and Etche, whereas Station (7.30) and Kaa (7.05) exceeded neutrality, so that the market means spanned 3.10 pH units among the five markets, and the SD of 0.71 at Kaa indicates that vendors in one market sold garri of different acidity. Variation of this kind would be compatible with the differences in the quality of handmade garri that followed from the roasting and dewatering parameters adopted by operators (Dahdouh *et al.,* 2021), although that study did not report pH, and with the conclusion that the production and handling of market garri in southern Nigeria were not standardised (Ogiehor *et al.,* 2007). Olanbiwoninu *et al.,* (2026) likewise listed the absence of standardised production protocols among the challenges of Nigerian fermented foods.

Samples within a market accounted for only 2.5% of the variance in pH, whereas areas accounted for 67.6% and markets within areas for 29.9%. Three samples per market therefore described the acidity of most markets reasonably well, although the SD of 0.71 at Kaa shows that one market was variable, and the main uncertainties were the small number of markets per area and the unrecorded processing history. Although area accounted for most of the variance in pH, acidity at the point of sale could not be predicted from the area alone, because Kpor was acidic and Station was not, which supports measuring it directly.

Total heterotrophic bacteria and lactic acid bacteria

Total heterotrophic bacteria (THB) were most numerous in Ikwerre (market means 3.07 to 5.91 log CFU/g; Table 2) and least numerous in Ogoni (1.50 to 3.10, the lowest value, at Kpor, being below the LOD), although the Ogoni garri had the highest pH. If acidity were the main control, the opposite arrangement would be expected. The association between pH and THB was negative but not significant (Kendall's τ-b = −0.33, $p = 0.101$; regression slope −0.288, $p = 0.218$), and the negative cross-validated Q^2 (−0.093) shows that a model with pH predicted THB worse than the overall mean. A small effect of pH in either direction is therefore compatible with the data (analytic 95% CI for the slope −0.77 to 0.19) but is not demonstrated, and the observed slope was opposite in direction to that expected if acidity

restricted THB. The difference among areas itself is only moderately supported: the Kruskal-Wallis test (p = 0.016) and the Games-Howell comparison of Ikwerre with Ogoni (p = 0.039) were significant, whereas Welch's analysis of variance was borderline (p = 0.051) and became significant (p = 0.046) only when the Kpor value was set to the LOD. Samples within markets accounted for 27.7% of the variance, which is more than for pH and is compatible with counts that depend on handling and storage as well as on the product, although neither was recorded.

A general medium recovers organisms of several kinds, and the colonies on nutrient agar need not have been lactic acid bacteria. In a sequencing study of abacha, fufu and garri, Proteobacteria dominated garri and *Pseudomonas* was its dominant genus (Dike *et al.,* 2022). Sequencing also detects DNA from dead cells, so it cannot be equated with culturable counts, but it supports the view that THB in the garri sequenced were not mainly lactic acid bacteria. The present counts point the same way in Ikwerre (THB 4.27 and LAB 2.59 log CFU/g) but not in Ogoni, where the LAB mean (2.68) exceeded the THB mean (2.49), and at Kpor LAB (4.70) greatly exceeded THB (1.50), so the share of LAB among THB cannot be inferred from these plate counts. A high THB count would not by itself signal a hazard, because the aerobic colony count is an indicator of quality and not of safety, and dried foods are not routinely examined for it (UKHSA, 2024). The higher counts in Ikwerre therefore indicate a greater microbial load, which may reflect the conditions of handling and storage, but they do not by themselves indicate pathogen risk.

Lactic acid bacteria (LAB) did not differ among areas (p = 0.749 for Welch's analysis of variance and 0.885 for the Kruskal-Wallis test), the area component of variance was 0.0%, and markets within areas accounted for 78.8%. This result was unchanged when the two market means below the LOD were set to 2.0 log CFU/g (p = 0.690 and 0.884). Lactic acid bacteria dominate the fermenting mash (Kostinek *et al.,* 2005), but the granules are roasted after fermentation and pressing (Escobar *et al.,* 2021), so the counts in finished garri could reflect survival and recontamination more than the fermentation itself. The lactic acid bacteria isolated from cassava mash during a controlled fermentation belonged to *Lactobacillus*, *Weissella*, *Leuconostoc* and *Lactococcus* (Ahaotu *et al.,* 2017), and strains differ in their rate of acid production (Kostinek *et al.,* 2005), so an equal LAB count can accompany a different acidity.

Without adjustment for area, no significant association between LAB and pH was found (slope −0.303, p = 0.076, Q^2 = −0.023; τ-b = +0.01, p = 0.999), whereas after adjustment for area the slope was −0.909 (p < 0.001, Q^2 = 0.359; Table 3). The two results describe different patterns between and within areas: the areas differed in pH but not in LAB, and within areas a higher pH was accompanied by fewer LAB. The within-area pattern is mechanistically plausible, because LAB produce the acid during fermentation, but a low pH could also favour the survival of acid-tolerant LAB after roasting, so the direction of the association cannot be established, and it rests mainly on three Ogoni markets. Kpor combined the lowest Ogoni pH (4.20) with the highest LAB count (4.70), and Station (7.30) and Kaa (7.05) combined the highest pH values with LAB means below the LOD. The bootstrap interval of the adjusted slope (−1.11 to 0.70) was much wider than the analytic interval (−1.33 to −0.49) and included zero, so the adjusted association is fragile.

These data cannot show whether LAB suppressed staphylococci, because the design was cross-sectional and the correlation between the two groups was weak and not significant (τ-b = −0.13, p = 0.552). Growth of *Staphylococcus aureus* in milk was inhibited once a commercial starter culture reached a critical density (Le Marc *et al.,* 2009), and LAB and their bacteriocins have been studied for the biocontrol of *S. aureus* in dairy foods, although the antagonistic network against its biofilms remains poorly understood at the molecular level (Emiliano *et al.,* 2024). Both lines of work concerned dairy systems and not a dry roasted product, so they indicate a mechanism and not a prediction for garri.

Occurrence of staphylococci

Staphylococci were reported in 60.0% of the markets (9 of 15; 95% CI 32.3 to 83.7%), or in 53.3% (8 of 15; 95% CI 26.6 to 78.7%) when the Rumuchiorlu value, which was below the LOD, is treated as censored, at market mean log counts equivalent to 56 to 2,512 CFU/g. The interval is wide, and a market-level frequency is not equivalent to a sample-level prevalence. For orientation, a meta-analysis of food studies from seven African countries gave a pooled prevalence of *Staphylococcus aureus* of 27.8% in raw foods and 25.1% in ready-to-eat foods, with heterogeneity above 97% (Paudyal *et al.,*

2017). Detection in a majority of markets is therefore not clearly out of line with regional experience, although only 8.6% of the studies in that meta-analysis examined foods of plant origin, and the present counts refer to coagulase-confirmed staphylococci and not to *S. aureus*. Staphylococci were also among the bacterial genera isolated from 300 market samples of garri (Ogiehor *et al.,* 2007), among the dominant phylotypes in the combined bacterial communities of abacha, fufu and garri (Dike *et al.,* 2022), and among the aerobic bacteria recovered from cassava mash during a controlled fermentation (Ahaotu *et al.,* 2017). In lafun, a dry fermented cassava flour, *S. aureus*, *Aspergillus* spp. and *Escherichia coli* predominated in all samples, and a control prepared in the laboratory carried a lower microbial load than samples from processing sites and markets (Adebayo-Oyetoro *et al.,* 2013). These reports are compatible with the entry of staphylococci into garri through the mash and through handling after processing, and the present design could not separate the two routes.

The contrast among areas depended on the statistic. Detection frequency did not differ significantly (Fisher-Freeman-Halton $p = 0.066$; 3 of 5 markets in Ikwerre, 5 of 5 in Etche and 1 of 5 in Ogoni), whereas the censored-data comparison, which uses the detected counts and treats non-detects as censored values and not as substituted values (Shoari & Dubé, 2018), did (Peto-Prentice $\chi^2 = 16.03$, permutation $p < 0.001$). The two results are compatible, because the second test uses more information. Fisher's exact test, which conditions on the margins, is also less powerful than unconditional alternatives in small samples (Lydersen *et al.,* 2009), and a policy of using the $N - 1$ chi-squared test when the smallest expected count is at least 1 performed better than the traditional rule (Campbell, 2007), although those studies addressed 2 × 2 tables and not a 3 × 2 table.

The more cautious reading is that staphylococci were detected more often and at higher counts in Etche than in Ogoni, with Ikwerre in between, although only the omnibus censored-data test was significant and no pairwise contrast was tested (Kaplan-Meier medians 2.55 log CFU/g in Etche, 1.75 in Ikwerre and below the LOD in Ogoni). That reading depends on four Ogoni markets without detection, whose counts could lie anywhere below 100 CFU/g and so cannot be distinguished from the counts of 56 to 126 CFU/g at the three Ikwerre markets with detections.

Detection was not significantly associated with pH (Kendall's τ-b = −0.27, $p = 0.203$; Tobit slope −0.163, $p = 0.237$; odds ratio 0.633 per pH unit, 95% CI 0.247 to 1.384, $p = 0.253$; Table 3), and the cross-validated AUC of 0.44 indicates that pH did not predict detection better than chance in these 15 markets. The result held when the Rumuchiorlu value was treated as censored (odds ratio 0.677, $p = 0.329$). Staphylococci were detected in all five acidic markets of Etche and in only one of the less acidic markets of Ogoni, but also in only three of the equally acidic markets of Ikwerre, and the single Ogoni detection was at Station, which had the highest pH (7.30). Freshly sold dry garri is a poor medium for bacterial growth, because its water activity was as low as 0.587 initially in one study of trade garri, although it rose to 0.934 after three months of storage (Samuel & Ugwuanyi, 2014), so counts in the freshly sold dry product probably reflect contamination and survival more than growth. The absence of an association with pH therefore does not show that acidity is irrelevant to the risk after soaking, which is the question addressed in Section 4.4.

All nine markets with detections fell into the borderline category for coagulase-positive staphylococci in ready-to-eat foods (Table 2), if garri that is soaked and eaten without cooking is regarded as ready to eat, and the guidance cautions that enterotoxin can be present even when counts are satisfactory or borderline (UKHSA, 2024). Counts in garri were lower than those in a soft cheese, where mean counts of 3.3 to 6.7 log CFU/g were taken to indicate poor hygiene practices during production (Silva *et al.,* 2021), and only Okomoko (3.40 log CFU/g) reached the lower end of that range. Cheese is, however, a moist product in which staphylococci grow, so the comparison indicates scale only and is not a hygiene criterion for garri.

The identity of the organisms remains uncertain. The tube coagulase test alone had a specificity of 11% with human plasma and 7% with sheep plasma for *S. aureus*, as judged by *nuc* PCR, among isolates that were positive in at least two of three phenotypic tests (Kateete *et al.,* 2010). Of the coagulase-positive staphylococci recovered from 20 breaded chicken products, only three strains belonged to *S. aureus* (Pepe *et al.,* 2006). Species other than *S. aureus* can nevertheless be enterotoxigenic, as shown by *Staphylococcus intermedius* from animals and humans (Becker *et al.,* 2001) and, among coagulase-negative staphylococci, by isolates from Nigerian fermented foods (Fowoyo & Ogunbanwo, 2016). The counts here may therefore overestimate *S. aureus* while including other organisms that could produce toxin.

Growth potential and threshold exceedance of staphylococci

The growth analysis was a scenario analysis built on assumed cardinal values, and it should be read as such. The assumed minimum pH of 4.0 to 4.5 is consistent with growth of *S. aureus* at pH 4.5 when water activity was 0.915 to 0.96 at 13 to 19 °C (Valero *et al.,* 2009), but 4.5 was the lowest pH in that study, so growth at lower values could be neither confirmed nor excluded. The boundary between growth and no growth also depends on the solute that lowers water activity and on the presence of preservatives (Stewart *et al.,* 2002), so a single minimum pH should not be assumed to apply to every food. The model further used the pH of a 1:10 suspension as the pH of soaked garri, which may differ from the pH at the concentration at which garri is actually soaked. The pH values of the Ikwerre and Etche markets (3.65 to 4.40) and of Kpor (4.20) lay below the pH range tested by Valero *et al.,* (2009), which was 4.5 to 7.5, whereas those of Kibaga, Station, Bomu and Kaa (5.50 to 7.30) lay within it, so predictions for the first group are extrapolations. The assumed optimum of 7.0 is also slightly above the optimum of 6.5 for earliest growth reported in the same study, so the values of γ near neutral pH (Station and Kaa) may be slightly overestimated.

The model separated the markets where staphylococci were found from the markets where they could grow. Staphylococci were detected in all five Etche markets, but the relative growth rate γ was zero at three of them (Igbo, Okomoko and Chokocho) and small at Ulakwo (0.035) and Egwi (0.103). In Ogoni, γ was 0.695 to 1.000 at Kibaga, Station, Bomu and Kaa (Table 6), where staphylococci were detected only at Station. This inverse arrangement matters for interpretation. If the garri from Kibaga, Bomu and Kaa carried staphylococci below 100 CFU/g, soaking could allow growth; with the initial count set to the LOD, the model gave a time to 5 log CFU/g of at least 4.3 (Kibaga), 3.1 (Bomu) and 3.0 (Kaa) times the one-log growth time at optimum pH. Absence of detection therefore cannot be read as absence of risk. Water activity was not measured here. Because it rose to as much as 0.934 during three months of storage of trade garri at room temperature (Samuel & Ugwuanyi, 2014), and growth of *S. aureus* has been recorded at 0.867 at pH 7.0 and 19 °C (Valero *et al.,* 2009), growth during storage cannot be excluded for the Ogoni garri with a pH near 7 (Kaa and Station), and the evidence is less direct for Kibaga (pH 5.50) and Bomu (pH 6.45).

In the nine markets with detections, the mean count was 1.60 to 3.25 log units below the screening threshold of 5 log CFU/g, and the probability that one sample exceeded it was 1.05×10^{-3} at Chokocho, 6.96×10^{-5} at Okomoko and 3.38×10^{-5} at Egwi (Table 6). These tail probabilities rest on a normal distribution fitted to three samples per market, so they are very uncertain, and they describe the dry product and not the soaked product. The threshold lies below the population of about $10^{6.5}$ CFU/mL at which enterotoxin began to accumulate in milk (Fujikawa & Morozumi, 2006), and it is far below the roughly 8×10^{8} CFU/g of *S. aureus* in mashed potato implicated in an outbreak (Jørgensen *et al.,* 2005). In a broth model fitted at pH 5.0 to 7.0, the probability of production of enterotoxin A by *S. aureus* depended jointly on water activity, pH and temperature (Ding *et al.,* 2016). In broth and skim milk, undissociated lactic acid slowed the growth of *S. aureus* and the production of enterotoxin A, but significant toxin was still produced during incubation of up to 14 days, by which time the initial pH had changed (Rosengren *et al.,* 2013), so a low starting pH is a barrier whose strength cannot be read from pH alone. Enterotoxins tolerate heat, proteolytic enzymes and a wide pH range (Cieza *et al.,* 2024), and in an extensive outbreak linked to low-fat milk, enterotoxin A remained active although the staphylococci had been destroyed by heat (Asao *et al.,* 2003). A low viable count at the time of testing therefore does not exclude the presence of preformed toxin if the staphylococci had grown earlier, for example before the product was heated or dried, although no data on toxin or on earlier counts were available here. A challenge test with garri from Kibaga, Station, Bomu and Kaa soaked at a defined temperature would test the prediction of the model directly.

Fungi and their relation to pH

Fungi were detected in all ten Ikwerre and Etche markets (2.10 to 3.16 log CFU/g) and in none of the five Ogoni markets. Fungi are normal members of the flora of market garri. Six fungal genera were isolated from 300 market samples (Ogiehor *et al.,* 2007); ten species were identified in trade garri, and the range of species increased with water activity (Samuel & Ugwuanyi, 2014); and low-moisture ready-to-eat foods from Nigerian markets, including a cassava-based snack, carried diverse moulds, with contamination linked partly to practices before and after processing (Ezekiel *et al.,* 2020). The unusual finding is therefore the lack of

detectable fungi (below 100 CFU/g) in Ogoni, and it requires an explanation.

The higher pH of the Ogoni garri is the obvious candidate, and the statistics point towards it. In Firth regression, the odds of detection fell as pH rose (odds ratio 0.172 per pH unit, profile 95% CI 0.0006 to 0.618; Table 3), the Tobit slope was −0.516, and censored Kendall's τ-b was −0.42 (p = 0.045). Three observations argue against a causal reading. First, Kpor (pH 4.20) was the most acidic Ogoni market, yet no fungi were detected there, whereas fungi were detected at Aluu (4.10) and Ulakwo (4.30), so the absence of detection in Ogoni was not explained by pH alone. Second, spoilage fungi from bakery products, grown on media of pH 4.4 to 7.4 with and without weak-acid preservatives, spoiled the media sooner at higher pH and higher water activity, and only *Eurotium* species grew at a water activity of 0.80 (Suhr & Nielsen, 2004), which makes inhibition by near-neutral pH unlikely, although these were bakery substrates and not garri. Third, area and pH were confounded, because the four markets with a pH above 4.40 were all in Ogoni. An area-level difference in storage, handling or protection from moisture is a plausible alternative explanation, consistent with reports that the range of fungi in garri increases with water activity (Samuel & Ugwuanyi, 2014) and that fungal contamination of low-moisture foods in Nigerian markets depends on practices before and after processing (Ezekiel *et al.,* 2020), but the present data cannot test it. Bulk moisture does not obviously supply the explanation, because the Ogoni composite (8.50 g/100 g) lay between the Ikwerre (7.48) and Etche (8.94) composites, but moisture was recovered by difference from one composite per area, and water activity, the more relevant variable, was not measured.

The inference is also statistically fragile. The Kendall association did not survive adjustment across ten pairs (q = 0.293). The likelihood-ratio test of the Tobit slope (p = 0.002) disagreed with its Wald interval (−1.04 to 0.01), and the slope changed from −0.516 to −1.107 when the censoring limit was lowered to 1.0 log CFU/g. The wide Firth interval reflects near-complete separation, for which penalised likelihood is a suitable method (Heinze, 2006), but Firth regression pulls predicted probabilities towards 0.5 (Puhr *et al.,* 2017), so the odds ratio was preferred to predicted probabilities. Tobit regression can perform at least as poorly as ordinary least squares when the variance is not constant (Austin *et al.,* 2000), and the leave-one-out AUC of 0.82 is of limited weight because cross-validated estimates can be highly variable or biased in small samples (Braga-Neto & Dougherty, 2004; Vabalas *et al.,* 2019). The data are therefore compatible with an association between low pH and fungal detection that is fragile and confounded with area, and they do not demonstrate an effect of pH.

The presence of fungi does not by itself imply a mycotoxin hazard. Twenty-one mycotoxins were quantified in garri from five agroecological zones of Nigeria, and the regulated ones were within the applicable maximum levels, although the risk assessment flagged aflatoxins (Olorunnado *et al.,* 2024). Exposure to regulated mycotoxins from 373 dried cassava products was judged minimal (Abass *et al.,* 2017). Aflatoxins were nevertheless detected in market garri from southern Nigeria, with an average occurrence rate of 17.5% (Ogiehor *et al.,* 2007), so a mycotoxin hazard from toxigenic fungi cannot be excluded. Mycotoxins were not measured here, and the fungal counts cannot be translated into toxin concentrations.

Faecal coliforms and the infection risk scenario

Faecal coliforms were detected in one market only, Chokocho, at 141 CFU/g, and the confidence interval for the frequency of detection (0.2 to 31.9%) shows how little a single positive market constrains the prevalence. Low-water-activity foods do not support the growth of vegetative pathogens such as *Salmonella*, and a significant risk may arise when contamination takes place after a lethal processing step (Podolak *et al.,* 2010). Dry garri is therefore unlikely to support multiplication of faecal organisms, and the detection at Chokocho may reflect contamination after roasting, although roasting conditions were not examined here. Vegetative enteric bacteria can nevertheless survive in dry matrices: *Salmonella* survives for long periods in low-moisture foods (Podolak *et al.,* 2010), *Salmonella* strains declined by 3 to 6 log CFU over 30 days on surfaces at 49% relative humidity (Lin *et al.,* 2023), and some foodborne pathogens survive in low-moisture foods for months to years (Acuff *et al.,* 2023), so a positive result could also reflect earlier contamination that persisted. These studies concerned *Salmonella* or foodborne pathogens in general, and the survival of faecal coliforms in garri was not examined here. In a study of ten food types sold by vendors and in restaurants, one of which was garri, geometric mean coliform counts of the foods were above accepted limits, although garri was not reported separately, and 79.6% of 98 coliform isolates grew at 44

°C (Nkere *et al.,* 2011). By contrast, faecal coliforms were not detected (below 100 CFU/g) at 14 of the 15 markets here, which is consistent with localised contamination, although three samples per market and an LOD of 100 CFU/g cannot distinguish localised contamination from a more general hygiene problem.

A colony count at 44.5 °C on EMB agar is not proof of faecal origin or of *Escherichia coli*. The elevated-temperature method recovers organisms of environmental as well as enteric origin (Leclerc *et al.,* 2001), although in freshwater the mean proportion of *E. coli* among thermotolerant coliforms was 84.3% (Hachich *et al.,* 2012). In recreational waters, relationships between indicators and pathogens were weak and inconsistent and depended on detection frequency, shedding and fate (Korajkic *et al.,* 2018), which is why the pathogenic fraction f was treated as a scenario variable and not estimated.

The annual infection risk reached 10^{-4} at a pathogenic fraction of about one in a million (1.01×10^{-6} at the Chokocho count and 1.42×10^{-6} at the LOD). Pathogenic *E. coli* occur in some market foods in Africa, so a pathogenic fraction of this order cannot be dismissed, although the evidence is indirect. *Escherichia coli* was isolated from 15.5% of 207 retail produce samples in Botswana, and the *eae* gene was detected in 1.5% of the samples (Bywater *et al.,* 2024). Shiga toxin-producing *E. coli* were isolated from 61 of 180 samples of beef and street-vended meat products in Lagos (Fayemi *et al.,* 2021). These figures refer to samples and not to the fraction of *E. coli* that is pathogenic, and the pathotypes differ from the enteroinvasive reference pathogen used here. Dose-response parameters also differ among strains, because an outbreak strain of *E. coli* O157:H7 was considerably more infectious than the strains in other published dose-response studies of that serotype (Teunis *et al.,* 2004), so the true risk at a given f could differ from that estimated.

The benchmark deserves the same caution. An infection risk of 10^{-4} per person per year is a common position in national drinking-water guidelines, where it refers to a reference waterborne pathogen, and it is not a food standard; an annual average can also conceal short periods of heightened risk (Signor & Ashbolt, 2009). The same level has been applied to the probability of illness, and not of infection, in a risk assessment of a water distribution system in Pakistan (Jamal *et al.,* 2020), so the endpoint must be stated. The approximate beta-Poisson function can deviate from the exact function at low doses (Teunis & Havelaar, 2000), but the relative difference here did not exceed 6.4×10^{-6}, so the approximation had a negligible effect on the point estimates. For scale, a model of *Salmonella* in pecans predicted a baseline of one case per 775,193 servings, about 1.3×10^{-6} per serving (Farakos *et al.,* 2017b), which is within a factor of five of the infection probability per serving computed here at $f = 10^{-6}$ (2.72×10^{-7}), although the pathogen, the endpoint and the food differ. The constant daily dose is a further simplification, because the doses of *Salmonella* ingested by adult owners handling dry pet food spanned 3 log CFU per exposure event in an exposure model (Lambertini *et al.,* 2015).

The LOD for faecal coliforms was 5.85 log units above the risk-based pathogen concentration of 1.42×10^{-4} CFU/g, which is one cell per 7.0 kg of garri, so the method could not detect that concentration even if every colony were a pathogenic cell. No plate count with this limit could verify compliance with the benchmark, which shifts the emphasis from testing the end product to preventing contamination. Culture-based counts remain appropriate as exposure inputs, because the data from which dose-response models were first built came from viability assays such as plate counts (Haas, 2020).

Proximate composition and moisture

Carbohydrate made up 87.25 to 89.12 g/100 g of the composites (Table 4), and ash, crude fibre, crude lipid and crude protein were each at or below 1.65 g/100 g, a composition consistent with a starch-rich product made from a root low in protein. The crude protein of 0.63 to 1.00 g/100 g was close to the 0.73% reported for garri made from unfortified cassava mash, a value that rose to about 10% with soy fortification (Ahaotu *et al.,* 2017), although the basis of expression of the present values remains to be stated and the Ikwerre value was corrected from 0.063 to 0.63 g/100 g and awaits confirmation. The moisture of 7.48 to 8.94 g/100 g was lower than the 11.11% and 10.81% found in yellow and white garri within 24 h of purchase from markets in south-eastern Nigeria (Samuel & Ugwuanyi, 2014). Whether the difference reflects drier products, the interval between purchase and analysis or an error in the recovered values is unclear. Recovery by difference reproduces the original moisture only if carbohydrate was calculated from it, so the values should be confirmed against the original determinations.

The same study recorded a rise in moisture to 17.27% and 16.14% and in water activity to 0.934 during three months of storage at room temperature, with the number of mould species increasing as water activity rose (Samuel & Ugwuanyi, 2014). The moisture of the composites therefore describes the product at analysis, after storage at 4 °C for a period not yet stated, and not its state during later storage at room temperature, which is the period in which mould growth would be most likely. Each area was represented by one composite, so differences in composition among areas cannot be tested, and some differences were of the order of the replicate SD, as for ash at Etche (1.65 ± 0.28 g/100 g).

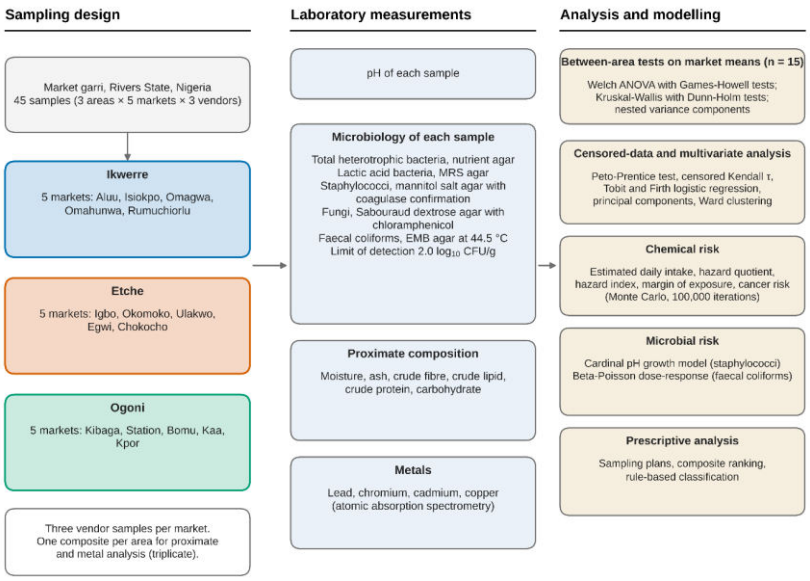
Cadmium

Cadmium dominated the chemical risk estimate and is also the least secure result. If the measured concentrations are taken at face value, 303 g of garri per day supplied 304 to 424 µg of cadmium (Table 5), which, for a 60 kg adult, gave a weekly intake 14.2 to 19.8 times the tolerable weekly intake of 2.5 µg/kg body weight set by CONTAM (2011) and a daily intake 6.1 to 8.5 times the tolerable daily intake of 0.83 µg/kg body weight (Satarug *et al.,* 2023). Satarug *et al.,* (2023) argued that kidney effects occur at urinary excretion far below the level on which conventional guidelines rest, so a stricter view of tolerable intake would not reverse the conclusion. Several observations make a high concentration conceivable. Cassava takes up cadmium from contaminated soil (Obiri *et al.,* 2006), and at dumpsites in Onne, Rivers State, cadmium in soils and in the leaves of four crops exceeded the maximum permissible level of the World Health Organization, with the greatest bioaccumulation of the metals studied in cassava leaves (Ohiagu *et al.,* 2020). Staple foods supply 40 to 60% of dietary cadmium (Satarug *et al.,* 2017), and most Finnish children aged 3 to 6 years exceeded the tolerable weekly intake from their whole diet under middle-bound assumptions (Suomi *et al.,* 2018). Exceeding the tolerable weekly intake is therefore not in itself implausible, although neither study shows that one staple can supply several times that intake to an adult. Anthropogenic sources of cadmium include industrial emissions, mining and agricultural practices (Laoye *et al.,* 2025), and potentially toxic elements in vended garri have been attributed to production processes, atmospheric dust and packaging (Enyoh *et al.,* 2023), although the abstract of that study reports no cadmium values.

The magnitude of the concentrations is the difficulty (Figure 8). The measured values were 100 to 140 times the cadmium concentration of cassava tubers from Ogoniland, which was 0.01 mg/kg in all samples at all three sites (Peters *et al.,* 2018), 21.7 to 38.4 times the concentration expected from that value after dewatering under the assumptions in Section 2.5, and 372 to 1,750 times the concentrations in food crops from an oil-impacted community (Akinkpelumi *et al.,* 2026), or about 80 to 480 times if those crop values are on a fresh weight basis and are corrected by the same factor. Dewatering alone cannot reconcile the values, because the assumed concentration factor was only 3.6 to 4.6, and a tuber value expressed on a dry weight basis would make the expected concentration lower still. The assessment of Ogoniland documented extensive hydrocarbon contamination (United Nations Environment Programme [UNEP], 2011), and in crops from oil-polluted farmland in Gokana, lead and chromium exceeded limits of the World Health Organization, whereas the abstract gives no cadmium value (Nwaichi *et al.,* 2014). Cassava grown near abandoned mining sites in Ebonyi State contained very high concentrations of other metals, such as 889 mg/kg of lead (Orji *et al.,* 2025), but the origin of the garri sold in the present markets was not established, so a point source of cadmium where the cassava was grown cannot be confirmed or excluded.

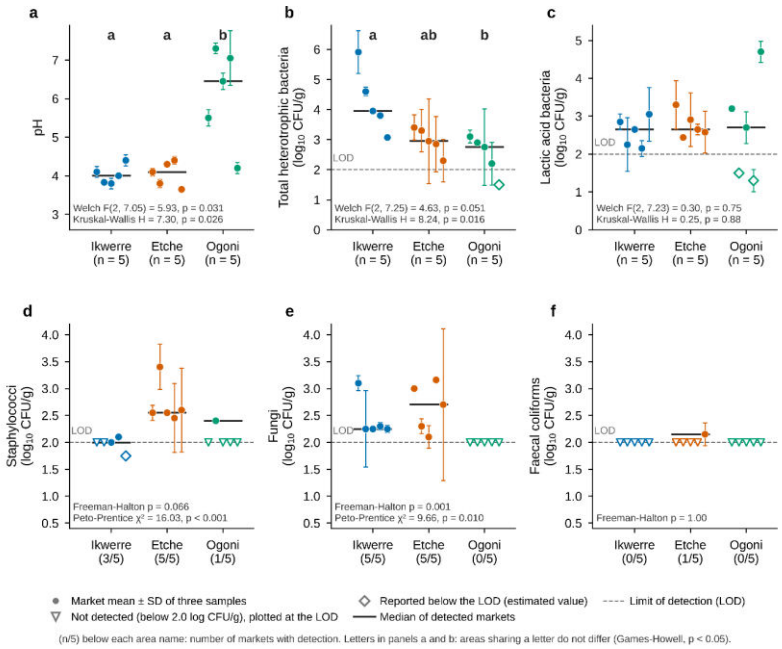
An analytical explanation, such as bias or contamination introduced in the laboratory, therefore deserves equal weight. The replicate SDs were small at Etche (0.004 mg/kg) and Ogoni (0.006 mg/kg) and larger at Ikwerre (0.141 mg/kg), but replication shows precision and not accuracy, and a constant bias from reagents, calibration or background absorption would not be revealed by replicate determinations. The study of food crops from the oil-impacted community used graphite furnace AAS with reagent blanks, certified reference materials and spike recoveries of 92 to 107% (Akinkpelumi *et al.,* 2026), and published AAS methods for cadmium have stated the sample preparation, the detection or quantification limit and the spike recovery and, for graphite furnace AAS, the background correction (Akamatsu *et al.,* 2012; Kim, 2004). Confirmation of the present values with a certified reference material, reagent blanks and spike recovery, and with a second technique, should precede any exposure-based advice.

Figure.1 Study Design, Laboratory Measurements and Analyses



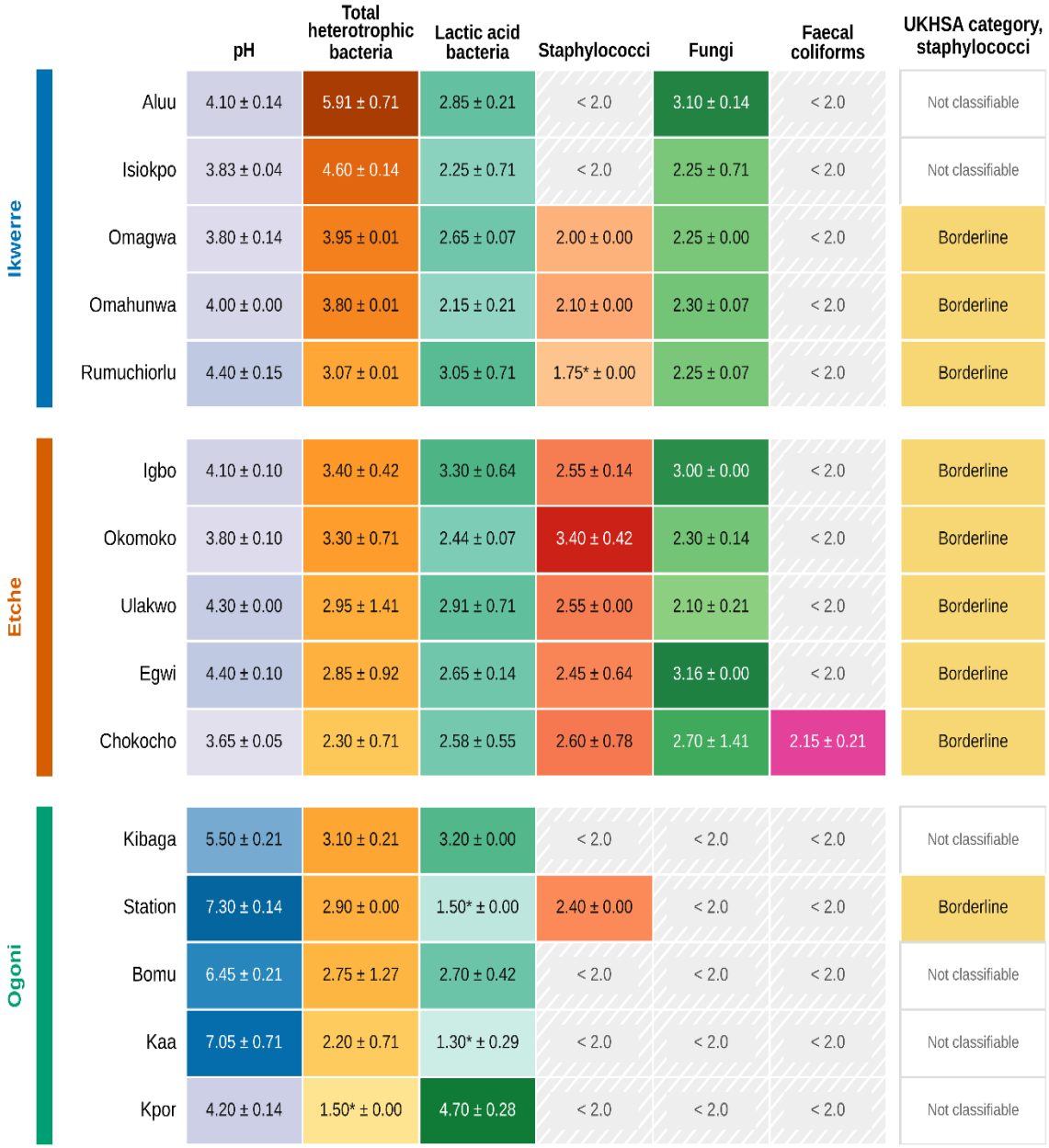
Note. Forty-five garri samples (three areas, five markets per area and three vendors per market) were analysed for pH and five microbial groups. One composite per area (analysed in triplicate) was used for proximate composition and metals. SD, standard deviation; LOD, limit of detection; CFU, colony-forming units; MRS, de Man, Rogosa and Sharpe; EMB, eosin methylene blue.

Figure.2 Distributions of pH and Microbial Counts in Garri by Area



Note. Points are market means, and error bars are the SD of three samples. Panels show pH (a), total heterotrophic bacteria (b), lactic acid bacteria (c), staphylococci (d), fungi (e) and faecal coliforms (f) in Ikwerre, Etche and Ogoni (five markets each). Horizontal lines mark the median of the markets with detection. Open triangles show markets without detection, plotted at the limit of detection (LOD; 2.0 log CFU/g), and open diamonds show values reported below the LOD. Letters in panels a and b are Games-Howell groupings (areas sharing a letter did not differ at $p < 0.05$). Numbers in brackets under the area names in panels d to f give the markets with detection among the five sampled. The statistics are Welch's analysis of variance, the Kruskal-Wallis test, the Fisher-Freeman-Halton exact test and the Peto-Prentice test. CFU, colony-forming units; SD, standard deviation.

Figure.3 Market Means of pH and Microbial Counts in Garri

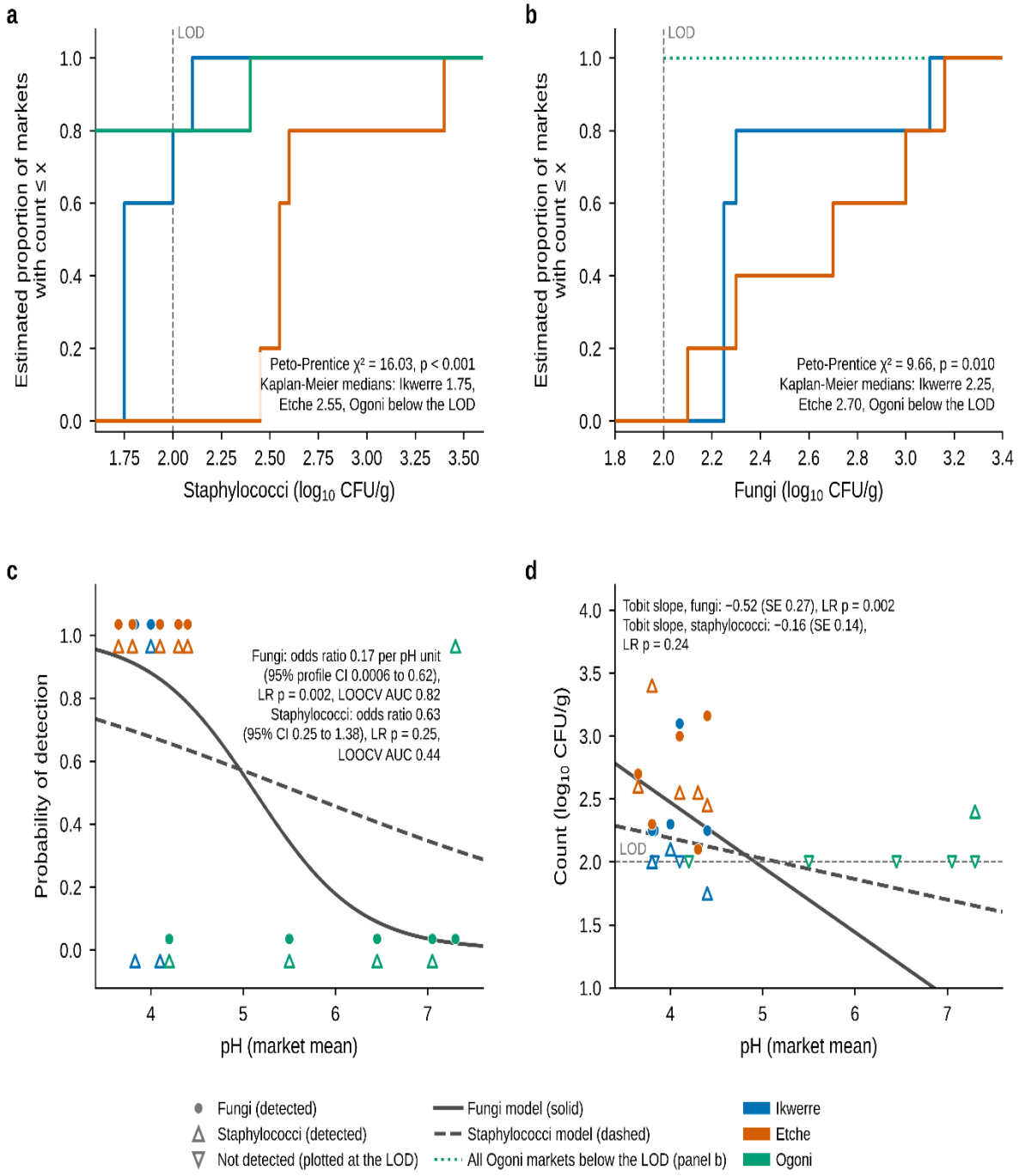


		pH	Total heterotrophic bacteria	Lactic acid bacteria	Staphylococci	Fungi	Faecal coliforms	UKHSA category, staphylococci
Ikwerre	Aluu	4.10 ± 0.14	5.91 ± 0.71	2.85 ± 0.21	< 2.0	3.10 ± 0.14	< 2.0	Not classifiable
	Isiokpo	3.83 ± 0.04	4.60 ± 0.14	2.25 ± 0.71	< 2.0	2.25 ± 0.71	< 2.0	Not classifiable
	Omagwa	3.80 ± 0.14	3.95 ± 0.01	2.65 ± 0.07	2.00 ± 0.00	2.25 ± 0.00	< 2.0	Borderline
	Omahunwa	4.00 ± 0.00	3.80 ± 0.01	2.15 ± 0.21	2.10 ± 0.00	2.30 ± 0.07	< 2.0	Borderline
	Rumuchiorlu	4.40 ± 0.15	3.07 ± 0.01	3.05 ± 0.71	1.75* ± 0.00	2.25 ± 0.07	< 2.0	Borderline
Etche	Igbo	4.10 ± 0.10	3.40 ± 0.42	3.30 ± 0.64	2.55 ± 0.14	3.00 ± 0.00	< 2.0	Borderline
	Okomoko	3.80 ± 0.10	3.30 ± 0.71	2.44 ± 0.07	3.40 ± 0.42	2.30 ± 0.14	< 2.0	Borderline
	Ulakwo	4.30 ± 0.00	2.95 ± 1.41	2.91 ± 0.71	2.55 ± 0.00	2.10 ± 0.21	< 2.0	Borderline
	Egwi	4.40 ± 0.10	2.85 ± 0.92	2.65 ± 0.14	2.45 ± 0.64	3.16 ± 0.00	< 2.0	Borderline
	Chokocho	3.65 ± 0.05	2.30 ± 0.71	2.58 ± 0.55	2.60 ± 0.78	2.70 ± 1.41	2.15 ± 0.21	Borderline
Ogoni	Kibaga	5.50 ± 0.21	3.10 ± 0.21	3.20 ± 0.00	< 2.0	< 2.0	< 2.0	Not classifiable
	Station	7.30 ± 0.14	2.90 ± 0.00	1.50* ± 0.00	2.40 ± 0.00	< 2.0	< 2.0	Borderline
	Bomu	6.45 ± 0.21	2.75 ± 1.27	2.70 ± 0.42	< 2.0	< 2.0	< 2.0	Not classifiable
	Kaa	7.05 ± 0.71	2.20 ± 0.71	1.30* ± 0.29	< 2.0	< 2.0	< 2.0	Not classifiable
	Kpor	4.20 ± 0.14	1.50* ± 0.00	4.70 ± 0.28	< 2.0	< 2.0	< 2.0	Not classifiable

Cells show the market mean ± SD of three vendor samples (log_{10} CFU/g for microbial counts). Hatched cells: not detected (below 2.0 log CFU/g).
* Value reported below the limit of detection. UKHSA categories for coagulase-positive staphylococci: satisfactory < 20, borderline 20 to 10^4, unsatisfactory > 10^4 CFU/g. Markets without detection cannot be classified because the method limit of detection (100 CFU/g) exceeds the satisfactory limit.

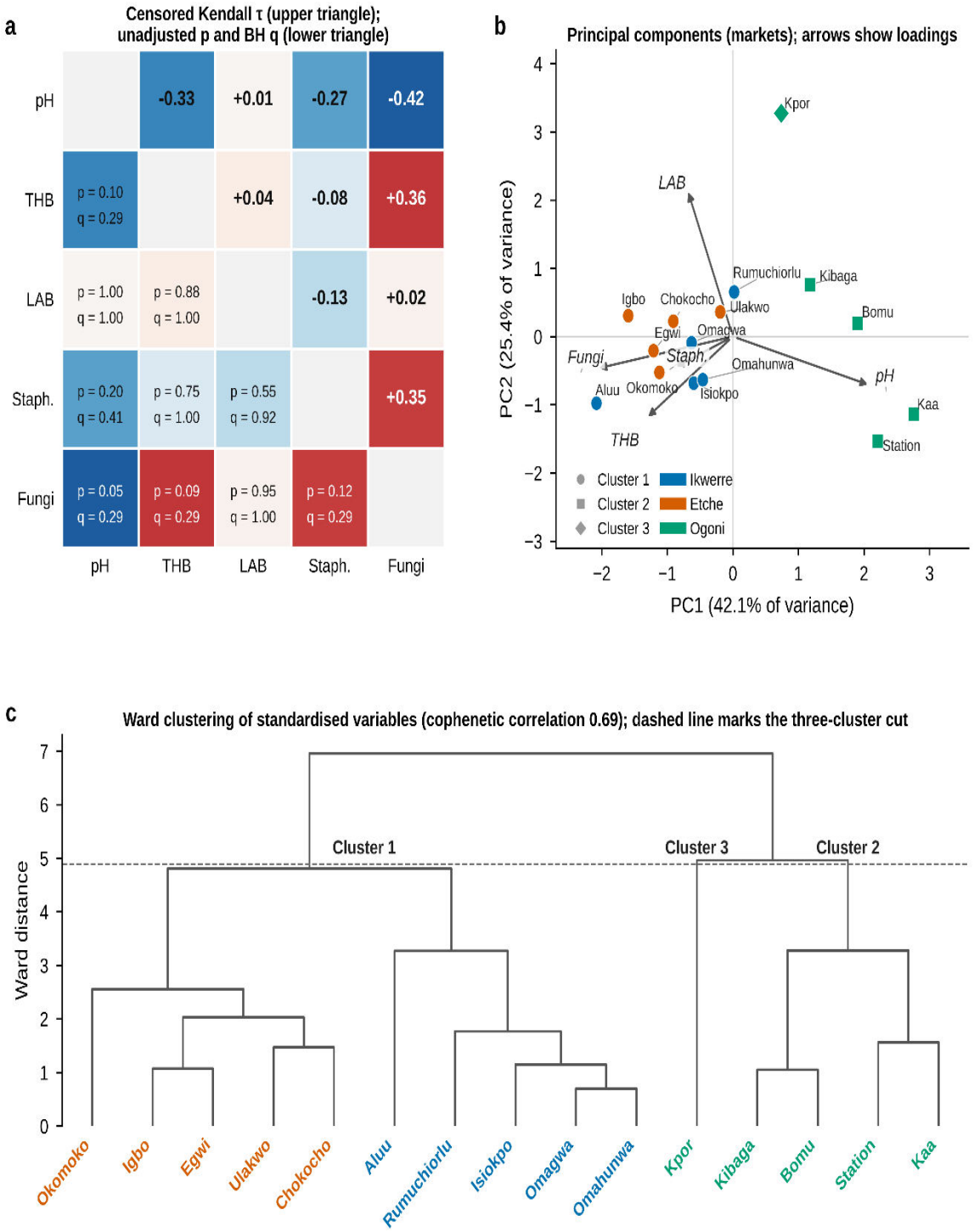
Note. Cells show the mean ± SD of three vendor samples per market (log_{10} CFU/g for counts). Hatched cells indicate no detection (below 2.0 log CFU/g), and asterisks mark values reported below the LOD. The last column gives the category for coagulase-positive staphylococci in ready-to-eat foods (UKHSA, 2024): satisfactory, less than 20 CFU/g; borderline, 20 to 10^4 CFU/g; unsatisfactory, more than 10^4 CFU/g. Markets without detection could not be classified, because the LOD of the method (100 CFU/g) exceeds the satisfactory limit. CFU, colony-forming units; LOD, limit of detection; SD, standard deviation.

Figure.4 Censored-Data Comparisons and Models of Fungal and Staphylococcal Occurrence



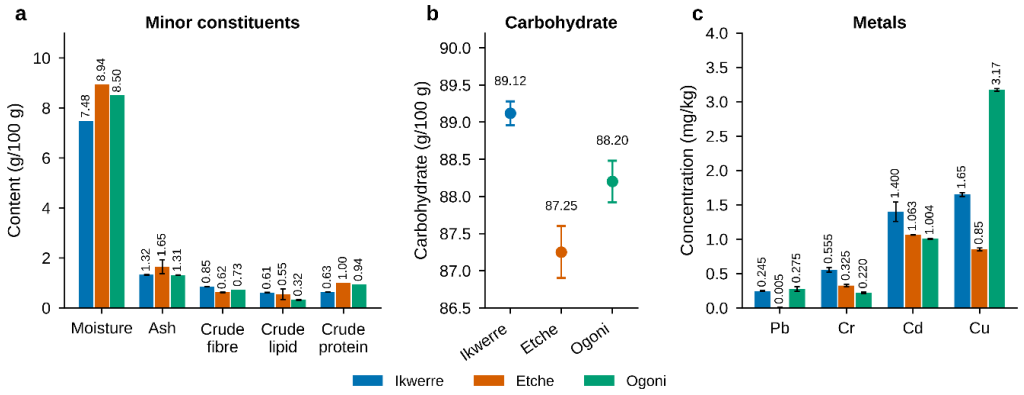
Note. Panels a and b show Kaplan-Meier estimates of the distribution of staphylococcal (a) and fungal (b) counts among the five markets of each area after flipping of the left-censored values; the dashed vertical line is the LOD, and the dotted line in panel b shows that all Ogoni markets were below the LOD. Panel c shows Firth penalised logistic regression of detection on market mean pH (curves), with markets with detection plotted at 1 and markets without detection at 0. Panel d shows Tobit regression lines of counts on pH, with markets without detection plotted at the LOD. Circles and solid lines refer to fungi, and triangles and dashed lines refer to staphylococci. Blue, orange and green symbols denote Ikwerre, Etche and Ogoni. AUC, area under the receiver operating characteristic curve; LOOCV, leave-one-out cross-validation; LR, likelihood ratio; SE, standard error.

Figure.5 Association Matrix, Principal Components and Clustering of Markets



Note. Panel a shows censored Kendall's τ-b among pH and the four counts (upper triangle) with unadjusted *p* values and Benjamini-Hochberg *q* values (lower triangle). Panel b is a biplot of the first two principal components of the standardised market means; arrows show variable loadings, colours show areas and symbols show Ward clusters. Panel c is the Ward dendrogram, and the dashed line marks the three-cluster cut. Non-detects were set to $\log_{10}$ (LOD/2) = 1.70 for panels b and c. THB, total heterotrophic bacteria; LAB, lactic acid bacteria; Staph., staphylococci.

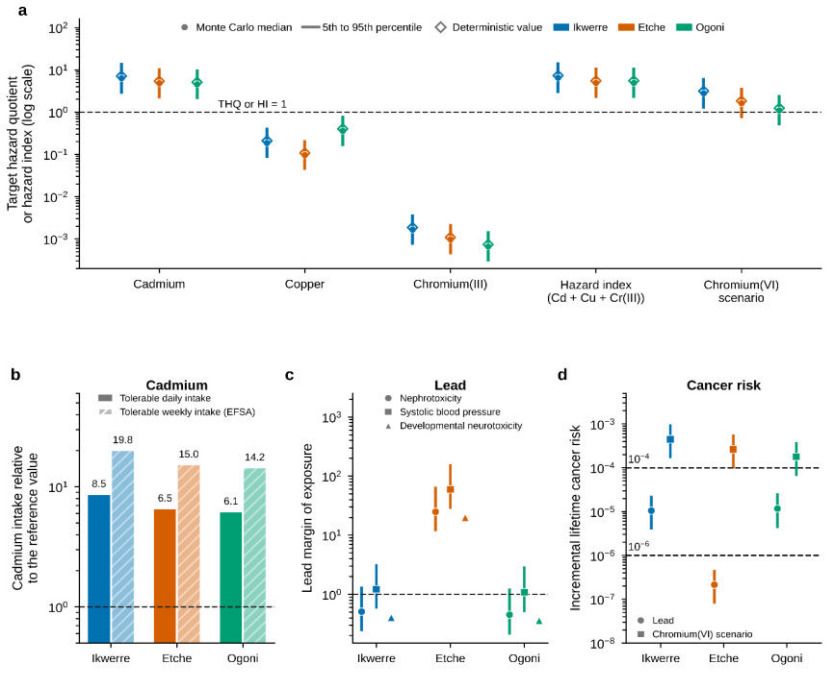
Figure.6 Proximate Composition and Metal Concentrations of the Area Composites



Bars and points show the composite mean; whiskers show the standard deviation of replicate determinations. Moisture was reported without a standard deviation.

Note. Panel a shows moisture, ash, crude fibre, crude lipid and crude protein (g/100 g), panel b shows carbohydrate (g/100 g), and panel c shows lead, chromium, cadmium and copper (mg/kg). Bars and points show the mean of triplicate determinations of one composite per area, and whiskers show the SD of the replicate determinations. Moisture was recovered by difference (Section 2.9) and has no SD. SD, standard deviation.

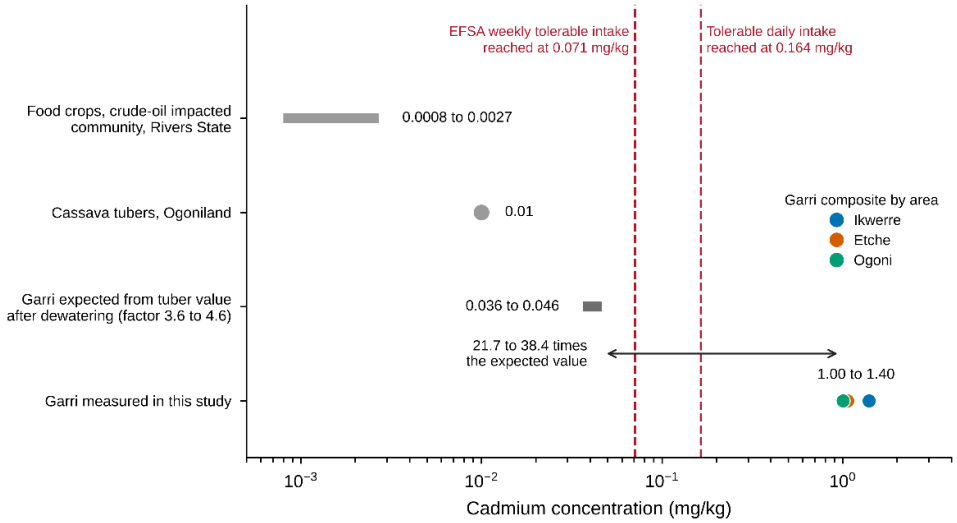
Figure.7 Dietary Chemical Risk of Garri Consumption by Area



Panels b to d: markers show deterministic values; vertical lines show Monte Carlo 5th to 95th percentile ranges where simulated (100,000 iterations).
Dashed lines: a hazard quotient or margin of exposure of 1, and cancer risks of 10^{-6} and 10^{-4}.

Note. Panel a shows target hazard quotients (THQ) of cadmium, copper and chromium(III), the hazard index (HI) and the THQ in the chromium(VI) scenario. Panel b shows cadmium intake relative to the tolerable daily intake and to the tolerable weekly intake of the European Food Safety Authority. Panel c shows the lead margin of exposure for three end points, and panel d shows the incremental lifetime cancer risk of lead and of chromium(VI) in the worst-case scenario. Markers show deterministic values, and vertical lines show Monte Carlo 5th to 95th percentile ranges (100,000 iterations) where simulated. Dashed lines mark a hazard quotient or margin of exposure of 1 and cancer risks of 10^{-6} and 10^{-4}.

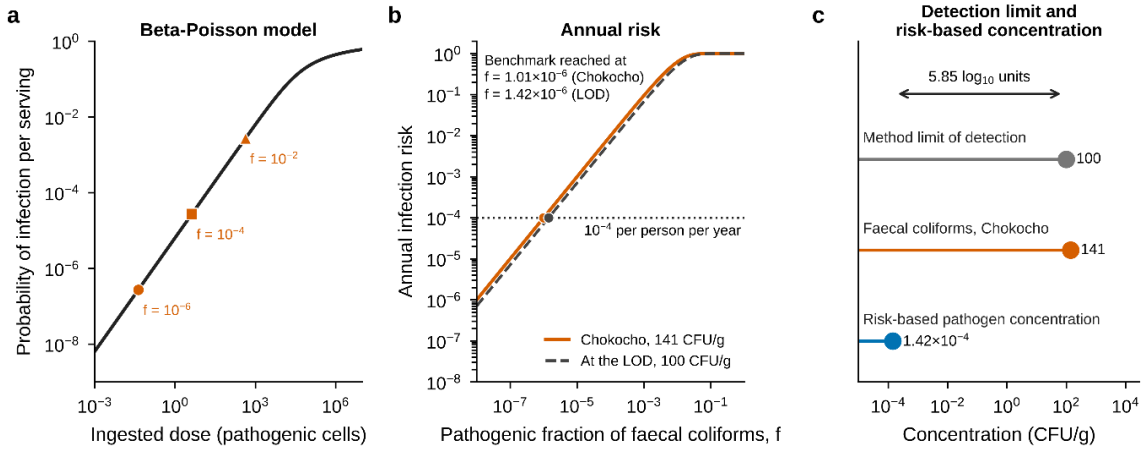
Figure.8 Measured Cadmium Concentrations Compared with Reported Values and Intake Thresholds



Dashed lines mark the concentration at which 303 g of garri per day supplies the EFSA tolerable weekly intake (2.5 µg/kg body weight per week) or the tolerable daily intake (0.83 µg/kg body weight per day) for a 60 kg adult. Expected garri concentration is the tuber value multiplied by the dewatering factor, derived from an assumed fresh-root dry matter of 20 to 25% and the measured garri moisture of 7.5 to 8.9%.

Note. The figure shows the cadmium concentration (mg/kg, logarithmic scale) of garri measured in this study, of garri expected from the tuber value after dewatering (factor 3.6 to 4.6), of cassava tubers from Ogoniland (Peters *et al.,* 2018) and of food crops from an oil-impacted community in Rivers State (Akinkpelumi *et al.,* 2026). Dashed lines mark the concentration at which 303 g per day supplies the tolerable weekly intake of the European Food Safety Authority or the tolerable daily intake to a 60 kg adult. The dry matter of fresh roots (20 to 25%) is an assumption.

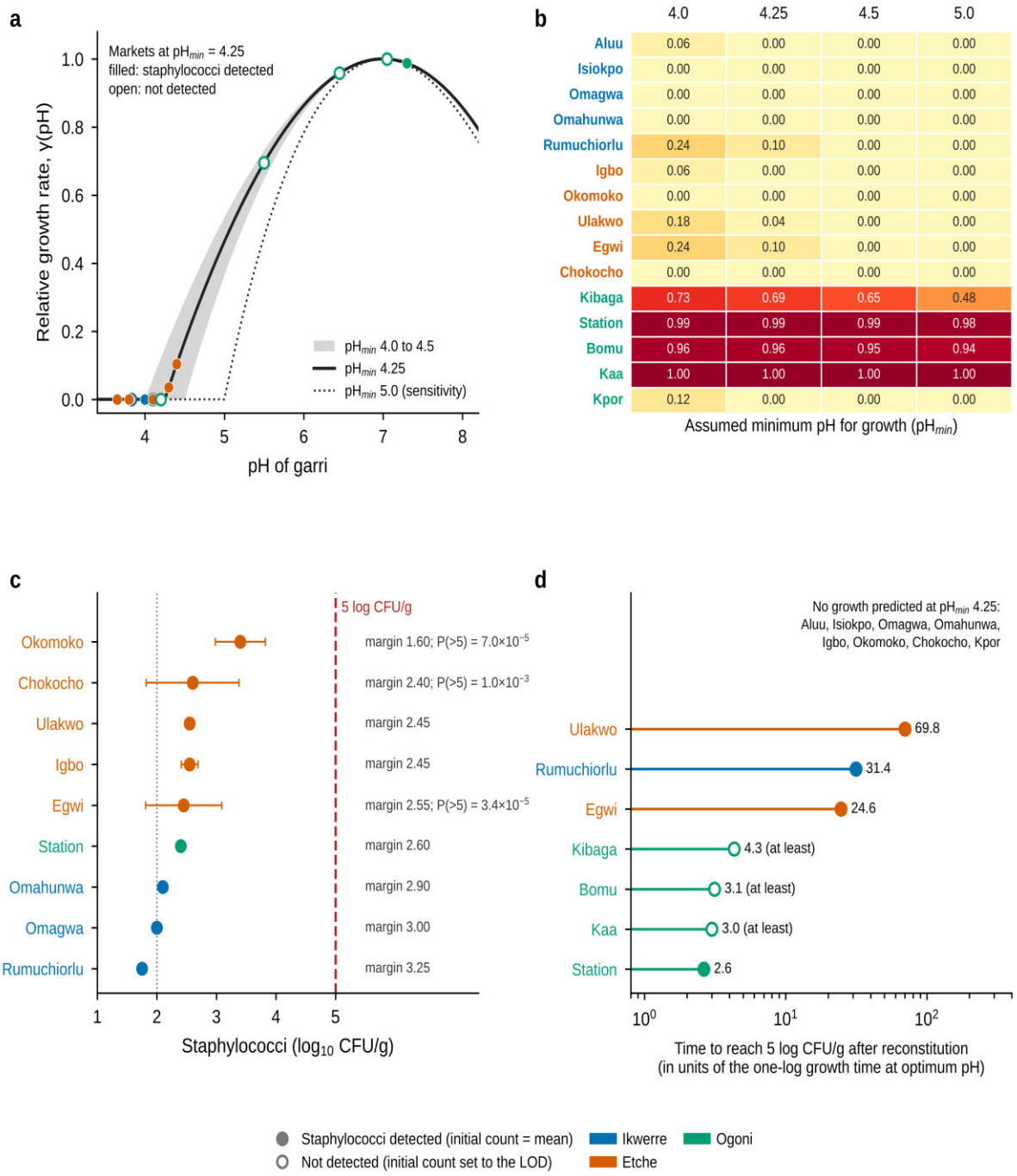
Figure.9 Infection Risk from Faecal Coliforms under the Beta-Poisson Model



erving: 303 g of garri (dry mass) eaten unheated each day. Pathogen dose = count × 303 g × f. Dose-response parameters: α = 0.155, N_{50} = 2.11 × 10^6 (enteroinvasive *Escherichia coli*

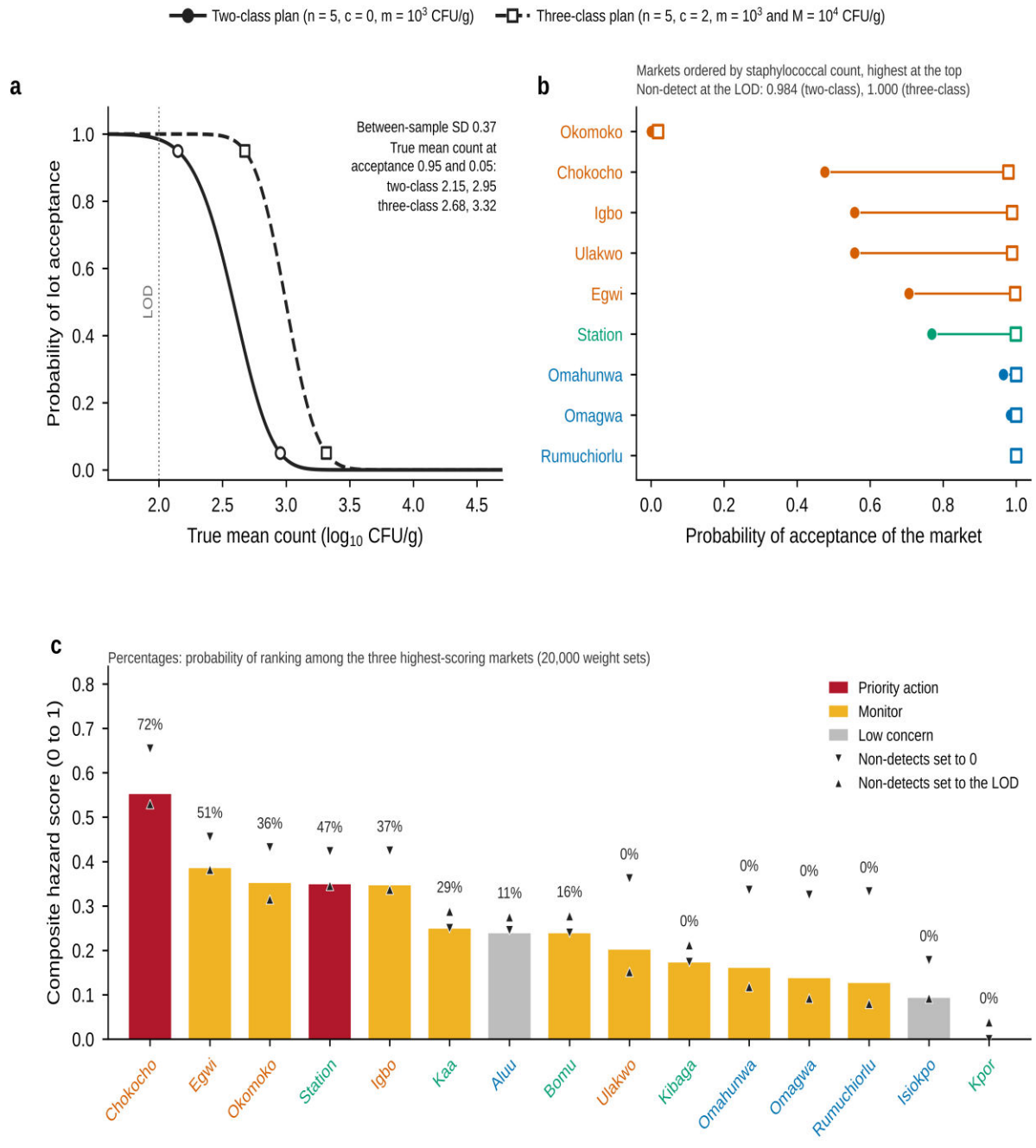
Note. Panel a shows the probability of infection per serving as a function of the ingested dose of pathogenic cells, with scenarios of the pathogenic fraction *f* of faecal coliforms. Panel b shows the annual infection risk as a function of *f* at the Chokocho count (141 CFU/g) and at the LOD (100 CFU/g); the dotted line marks 10^{-4} per person per year. Panel c compares the LOD, the Chokocho count and the risk-based pathogen concentration. A serving of 303 g of dry garri was eaten daily without heating, with α = 0.155 and N_{50} = 2.11 × 10^6 for enteroinvasive *Escherichia coli*. CFU, colony-forming units; LOD, limit of detection.

Figure.10 Growth Potential, Threshold Margin and Time to Threshold of *Staphylococci*



Note. Panel a shows the relative growth rate γ as a function of pH for a minimum pH for growth of 4.25 (line), 4.0 to 4.5 (band) and 5.0 (dotted line), with the markets plotted as points. Panel b shows γ for each market under four assumed minimum pH values. Panel c shows the market mean ± SD of staphylococci in the markets with detection relative to the screening threshold of 5 log CFU/g, with the margin and, where nonzero, the probability that a sample exceeds the threshold. Panel d shows the time to reach 5 log CFU/g after reconstitution, in units of the one-log growth time at optimum pH; open circles are lower bounds for markets without detection (initial count set to the LOD). Markets are labelled by area colour (Ikwerre, blue; Etche, orange; Ogoni, green). CFU, colony-forming units; LOD, limit of detection.

Figure.11 Operating Characteristics of Sampling Plans and Ranking of Markets



Axis labels are coloured by area (Ikwerre, blue; Etche, orange; Ogoni, green). Bars use the main analysis, in which non-detects were set to $\log_{10}$ 50 CFU/g (1.70).

Note. Panel a shows the probability that a lot is accepted by a two-class plan (n = 5, c = 0, m = 10^3 CFU/g) and a three-class plan (n = 5, c = 2, m = 10^3 and M = 10^4 CFU/g) as a function of the true mean log count, with markers at acceptance probabilities of 0.95 and 0.05. Panel b shows the probability of acceptance of each market with detections, computed at its mean count (circles, two-class plan; squares, three-class plan). Panel c shows the composite hazard score (0 to 1) of the 15 markets, the percentage of 20,000 random weight sets in which the market ranked among the top three, and the rule-based class (colour); triangles show the score with non-detects set to 0 (downward) or to the LOD (upward). The plan limits are illustrative. CFU, colony-forming units; LOD, limit of detection.

Table.1 Input Parameters of the Dietary Chemical Risk Assessment, the Microbial Risk Assessment and the Prioritisation Analysis

Parameter	Symbol	Value or distribution	Unit	Source
Exposure				
Garri intake	IR	Lognormal; mean 0.303, coefficient of variation 50%[a]	kg/day	(Olorunnado *et al.,* 2024)[a]
Body weight	BW	Normal; mean 60, SD 10, truncated at 40 and 100[a]	kg	Assumption
Metal concentration	*C*	Lognormal; area mean and SD of replicates (Section 3.6)	mg/kg	This study
Serving mass of garri (dry mass)	*M*	303	g	(Olorunnado *et al.,* 2024)[b]
Exposures per year	*n*	365	per year	Assumption
Toxicity				
Oral reference dose, cadmium	RfD	1×10^{-3}	mg/kg bw/day	(US EPA, n.d.-a)
Oral reference dose, copper	RfD	4×10^{-2}	mg/kg bw/day	(Taylor *et al.,* 2023)
Oral reference dose, chromium(III)	RfD	1.5	mg/kg bw/day	(US EPA, n.d.-b)
Oral reference dose, chromium(VI)[c]	RfD	9×10^{-4}	mg/kg bw/day	(US EPA, 2024)
Oral slope factor, chromium(VI)[c]	CSF	0.16	$(\text{mg/kg bw/day})^{-1}$	(US EPA, 2024)
Cancer slope factor, lead	CSF	8.5×10^{-3}	$(\text{mg/kg bw/day})^{-1}$	(Office of Environmental Health Hazard Assessment [OEHHA], n.d.)
Benchmark dose lower limit, lead, nephrotoxicity	BMDL	0.63	µg/kg bw/day	(CONTAM, 2010)
Benchmark dose lower limit, lead, systolic blood pressure	BMDL	1.50	µg/kg bw/day	(CONTAM, 2010)
Benchmark dose lower limit, lead, developmental neurotoxicity	BMDL	0.50	µg/kg bw/day	(CONTAM, 2010)
Tolerable daily intake, cadmium	TDI	0.83	µg/kg bw/day	(Satarug *et al.,* 2023)
Tolerable weekly intake, cadmium	TWI	2.5	µg/kg bw/week	(CONTAM, 2011)
Microbial risk of faecal coliforms				
Faecal coliform concentration	C_{FC}	141 (Chokocho mean) and 100 (LOD)	CFU/g	This study
Pathogenic fraction of faecal coliforms	*f*	10^{-7} to 1 (scenario)	Proportion	Scenario
Beta-Poisson shape	α	0.155	Dimensionless	(Center for

parameter				Advancing Microbial Risk Assessment [CAMRA], n.d.)
Median infectious dose	N_{50}	2.11×10^6	Cells	(CAMRA, n.d.)
Benchmark annual infection risk	NA	10^{-4}	Per person per year	(Signor & Ashbolt, 2009)
Staphylococci				
Screening threshold	NA	5.0	log CFU/g	(Cai *et al.,* 2023)
Minimum pH for growth	pH_{min}	Uniform, 4.0 to 4.5 (central value 4.25)[a]	pH units	Assumption[d]
Optimum pH for growth	pH_{opt}	7.0[a]	pH units	Assumption
Maximum pH for growth	pH_{max}	9.6[a]	pH units	Assumption
Sampling plans and plausibility check				
Plan limits, staphylococci[e]	*m*, *M*	10^3 and 10^4	CFU/g	Illustrative
Between-sample SD, staphylococci	σ	0.37	log CFU/g	This study[f]
Dry matter of fresh cassava roots	NA	20 to 25[a]	%	Assumption
Cadmium in cassava tubers, Ogoniland	NA	0.01	mg/kg	(Peters *et al.,* 2018)

Note. SD, standard deviation; bw, body weight; LOD, limit of detection; NA, not applicable; TDI, tolerable daily intake; TWI, tolerable weekly intake. [a]Distribution shape, spread or value assumed in the absence of data for Rivers State. [b]The mean daily intake was treated as one serving of dry garri per day. [c]Worst-case scenario in which all chromium is assumed to be hexavalent. [d]Growth of *Staphylococcus aureus* was observed at pH 4.5 at high water activity (Valero *et al.,* 2009). [e]Illustrative limits, not a published criterion for garri. [f]Pooled within-market SD of staphylococcal counts.

Table.4 Replicate Means of Proximate Composition and Metal Concentrations in the Area Composites

Variable	Unit	Ikwerre	Etche	Ogoni
Proximate composition				
Moisture[a]	g/100 g	7.48	8.94	8.50
Ash	g/100 g	1.32 ± 0.01	1.65 ± 0.28	1.31 ± 0.01
Crude fibre	g/100 g	0.85 ± 0.01	0.62 ± 0.01	0.73 ± 0.00
Crude lipid	g/100 g	0.61 ± 0.01	0.55 ± 0.21	0.32 ± 0.02
Crude protein	g/100 g	0.63 ± 0.01[b]	1.00 ± 0.00	0.94 ± 0.00
Carbohydrate	g/100 g	89.12 ± 0.16	87.25 ± 0.35	88.20 ± 0.28
Metals				
Lead	mg/kg	0.245 ± 0.007	0.005 ± 0.000[d]	0.275 ± 0.035
Chromium	mg/kg	0.555 ± 0.035	0.325 ± 0.021[c]	0.220 ± 0.010
Cadmium	mg/kg	1.400 ± 0.141	1.063 ± 0.004	1.004 ± 0.006
Copper	mg/kg	1.65 ± 0.03	0.85 ± 0.02	3.17 ± 0.02

Note. Values are the mean ± SD of triplicate determinations on one composite per area [state whether the results are expressed on a fresh-weight or a dry-weight basis]. [a]Moisture was recovered by difference (Section 2.9) and has no SD [original moisture values to be inserted]. [b]Corrected from 0.063 g/100 g (decimal error in the source table). [c]Corrected from 90.325 mg/kg (decimal error in the source table). [d]May be close to the detection limit of the method [detection limit to be stated]. All corrections are described in Section 2.9.

Table.5 Dietary Chemical Risk of Garri Consumption by Area: Deterministic and Probabilistic Estimates

Quantity	Ikwerre	Etche	Ogoni
Deterministic estimates (intake 0.303 kg/day, body weight 60 kg)			
Cadmium intake (µg/day)	424	322	304
Cadmium intake (% of TDI)	852	647	611
Cadmium intake (multiple of TWI)	19.8	15.0	14.2
THQ, cadmium	7.07	5.37	5.07
THQ, copper	0.21	0.11	0.40
THQ, chromium(III)	0.0019	0.0011	0.0007
Hazard index	7.28	5.48	5.47
THQ, chromium(VI) scenario[a]	3.11	1.82	1.23
Lead MOE, nephrotoxicity	0.51	24.95	0.45
Lead MOE, systolic blood pressure	1.21	59.41	1.08
Lead MOE, developmental neurotoxicity	0.40	19.80	0.36
ILCR, lead	1.05×10^{-5}	2.15×10^{-7}	1.18×10^{-5}
ILCR, chromium(VI) scenario[a]	4.48×10^{-4}	2.63×10^{-4}	1.78×10^{-4}
Monte Carlo simulation (100,000 iterations), median (5th to 95th percentile)			
Hazard index	6.50 (2.82 to 14.92)	4.90 (2.17 to 11.13)	4.90 (2.17 to 11.13)
Probability that hazard index > 1 (%)	99.99	99.93	99.93
THQ, cadmium	6.31 (2.74 to 14.51)	4.81 (2.13 to 10.92)	4.54 (2.01 to 10.31)
THQ, copper	0.19 (0.08 to 0.42)	0.10 (0.04 to 0.22)	0.36 (0.16 to 0.81)
THQ, chromium(III)	0.0017 (0.0007 to 0.0038)	0.0010 (0.0004 to 0.0022)	0.0007 (0.0003 to 0.0015)
THQ, chromium(VI) scenario[a]	2.79 (1.22 to 6.36)	1.63 (0.71 to 3.73)	1.11 (0.49 to 2.51)
Lead MOE, nephrotoxicity	0.57 (0.25 to 1.29)	27.86 (12.26 to 63.03)	0.51 (0.22 to 1.19)
Probability that MOE < 1, nephrotoxicity (%)	87.0	0.0	90.5
Lead MOE, systolic blood pressure	1.35 (0.60 to 3.07)	66.33 (29.20 to 150.08)	1.22 (0.52 to 2.83)
Probability that MOE < 1, systolic blood pressure (%)	27.2	0.0	35.1
ILCR, lead	9.41×10^{-6} (4.16×10^{-6} to 2.14×10^{-5})	1.92×10^{-7} (8.50×10^{-8} to 4.37×10^{-7})	1.05×10^{-5} (4.50×10^{-6} to 2.44×10^{-5})
ILCR, chromium(VI) scenario[a]	4.01×10^{-4} (1.76×10^{-4} to 9.16×10^{-4})	2.35×10^{-4} (1.03×10^{-4} to 5.37×10^{-4})	1.59×10^{-4} (6.99×10^{-5} to 3.62×10^{-4})
Probability that ILCR > 10^{-4}, chromium(VI) scenario[a] (%)	99.7	95.5	82.3
Spearman correlation of the hazard index with the inputs			
Intake rate	0.926	0.944	0.944
Body weight	−0.293	−0.300	−0.300
Cadmium concentration	0.184	0.008	0.011
Chromium concentration	0.005	0.006	0.006
Copper concentration	0.0000	−0.0005	−0.0005

Note. THQ, target hazard quotient; MOE, margin of exposure (benchmark dose lower limit divided by the estimated daily intake); ILCR, incremental lifetime cancer risk; TDI, tolerable daily intake; TWI, tolerable weekly intake. Reference values are listed in Table 1. The simulation sampled the intake rate, the body weight and the metal concentrations (Table 1); percentile ranges therefore express consumer variability and the replicate SD of one composite per area, and not uncertainty about the true concentration. [a]Worst-case scenario in which all chromium is hexavalent.

Table.2 Market Means of pH and Microbial Counts with Tukey Groupings and UKHSA Categories

Market	pH	THB	LAB	Staphylococci	Fungi	Faecal coliforms	Staphylococci (CFU/g)	UKHSA category†
Ikwerre								
Aluu	4.10 ± 0.14^{de}	5.91 ± 0.71^{a}	2.85 ± 0.21^{b}	ND	3.10 ± 0.14	ND	ND	Not classified
Isiokpo	3.83 ± 0.04^{de}	4.60 ± 0.14^{ab}	2.25 ± 0.71^{bcd}	ND	2.25 ± 0.71	ND	ND	Not classified
Omagwa	3.80 ± 0.14^{de}	3.95 ± 0.01^{abc}	2.65 ± 0.07^{bc}	2.00 ± 0.00^{b}	2.25 ± 0.00	ND	100	Borderline
Omahunwa	4.00 ± 0.00^{de}	3.80 ± 0.01^{bc}	2.15 ± 0.21^{bcd}	2.10 ± 0.00^{b}	2.30 ± 0.07	ND	126	Borderline
Rumuchiorlu	4.40 ± 0.15^{d}	3.07 ± 0.01^{bcd}	3.05 ± 0.71^{b}	$1.75 \pm 0.00^{*b}$	2.25 ± 0.07	ND	56	Borderline
Etche								
Igbo	4.10 ± 0.10^{de}	3.40 ± 0.42^{bcd}	3.30 ± 0.64^{b}	2.55 ± 0.14^{ab}	3.00 ± 0.00	ND	355	Borderline
Okomoko	3.80 ± 0.10^{de}	3.30 ± 0.71^{bcd}	2.44 ± 0.07^{bcd}	3.40 ± 0.42^{a}	2.30 ± 0.14	ND	2,512	Borderline
Ulakwo	4.30 ± 0.00^{de}	2.95 ± 1.41^{bcd}	2.91 ± 0.71^{b}	2.55 ± 0.00^{ab}	2.10 ± 0.21	ND	355	Borderline
Egwi	4.40 ± 0.10^{d}	2.85 ± 0.92^{bcd}	2.65 ± 0.14^{bc}	2.45 ± 0.64^{ab}	3.16 ± 0.00	ND	282	Borderline
Chokocho	3.65 ± 0.05^{e}	2.30 ± 0.71^{cd}	2.58 ± 0.55^{bc}	2.60 ± 0.78^{ab}	2.70 ± 1.41	2.15 ± 0.21	398	Borderline
Ogoni								
Kibaga	5.50 ± 0.21^{c}	3.10 ± 0.21^{bcd}	3.20 ± 0.00^{b}	ND	ND	ND	ND	Not classified
Station	7.30 ± 0.14^{a}	2.90 ± 0.00^{bcd}	$1.50 \pm 0.00^{*cd}$	2.40 ± 0.00^{ab}	ND	ND	251	Borderline
Bomu	6.45 ± 0.21^{b}	2.75 ± 1.27^{bcd}	2.70 ± 0.42^{bc}	ND	ND	ND	ND	Not classified
Kaa	7.05 ± 0.71^{ab}	2.20 ± 0.71^{cd}	$1.30 \pm 0.29^{*d}$	ND	ND	ND	ND	Not classified
Kpor	4.20 ± 0.14^{de}	$1.50 \pm 0.00^{*d}$	4.70 ± 0.28^{a}	ND	ND	ND	ND	Not classified

Note. Values are the mean ± SD of three vendor samples per market, in $\log_{10}$ CFU/g except for pH and the column of staphylococcal counts in CFU/g. ND, not detected (reported as below the LOD of 2.0 log CFU/g); THB, total heterotrophic bacteria; LAB, lactic acid bacteria; ANOVA, analysis of variance; HSD, honestly significant difference. Superscript letters give Tukey groupings at $\alpha = 0.05$, from the highest (a) to the lowest mean; markets that share a letter do not differ. Groupings are from one-way ANOVA of the 15 market means for pH ($F(14, 30) = 93.93$; HSD 0.66), THB (7.41; 2.01) and LAB (10.53; 1.27), and of the nine markets with detection for staphylococci ($F(8, 18) = 4.88$; HSD 1.05). Counts of fungi did not differ among the ten markets with detection ($F(9, 20) = 1.93$, $p = 0.106$). *Mean reported below the LOD and retained as reported (Section 2.9). †Category for coagulase-positive staphylococci in ready-to-eat foods (UKHSA, 2024): satisfactory, less than 20 CFU/g; borderline, 20 to 10^4 CFU/g; unsatisfactory, more than 10^4 CFU/g. Markets without detection were not classified, because the LOD of the method (100 CFU/g) exceeds the satisfactory limit.

Table.3 Regression and Logistic Models of Counts and Detection in Relation to pH

Outcome	Model	Term	Estimate (SE)	95% CI	Bootstrap 95% CI	*p*	Fit statistics
Ordinary least squares regression of market mean count on pH							
THB	OLS	pH slope	−0.288 (0.223)	−0.77 to 0.19	−0.63 to −0.02	0.218	R^2 = 0.114; Q^2 = −0.093
LAB	OLS	pH slope	−0.303 (0.157)	−0.64 to 0.04	−0.52 to 0.37	0.076	R^2 = 0.222; Q^2 = −0.023
LAB	OLS with area	pH slope, adjusted for area	−0.909 (0.191)	−1.33 to −0.49	−1.11 to 0.70	< 0.001	R^2 = 0.676; Q^2 = 0.359
Tobit regression of counts on pH (censoring limit in log CFU/g)							
Fungi	Tobit, limit 2.0	pH slope	−0.516 (0.267)	−1.04 to 0.01	NA	0.002	LR = 9.51; σ = 0.456
Fungi	Tobit, limit 1.0	pH slope	−1.107 (0.437)	−1.96 to −0.25	NA	< 0.001	LR = 16.00; σ = 0.680
Staphylococci	Tobit, limit 2.0	pH slope	−0.163 (0.141)	−0.44 to 0.11	NA	0.237	LR = 1.40; σ = 0.560
Staphylococci	Tobit, limit 1.0	pH slope	−0.360 (0.278)	−0.90 to 0.18	NA	0.189	LR = 1.73; σ = 1.132
Firth penalised logistic regression of detection on pH							
Fungi	Firth logistic	Odds ratio per pH unit	0.172	0.0006 to 0.618	NA	0.002	LR = 9.22; AUC = 0.82; Brier = 0.091 (null 0.253)
Staphylococci	Firth logistic	Odds ratio per pH unit	0.633	0.247 to 1.384	NA	0.253	LR = 1.31; AUC = 0.44; Brier = 0.286 (null 0.273)

Note. n = 15 markets for all models. SE, standard error; CI, confidence interval; OLS, ordinary least squares; THB, total heterotrophic bacteria; LAB, lactic acid bacteria; LR, likelihood-ratio statistic; AUC, leave-one-out cross-validated area under the receiver operating characteristic curve; Brier, leave-one-out Brier score; NA, not applicable. Q^2 is the leave-one-out cross-validated coefficient of determination. The OLS confidence interval is analytic, and the bootstrap interval is the percentile interval of resampled markets. The Tobit interval is the Wald interval (estimate ± 1.96 SE), and the p value is from the likelihood-ratio test of the slope. The Firth interval is the profile penalised-likelihood interval, and the p value is from the likelihood-ratio test. The adjusted model has four coefficients (intercept, pH and two area indicators).

Table.6 Growth Potential, Threshold Exceedance, Sampling-Plan Acceptance and Ranking of the 15 Markets

Market	pH	γ^a	*P*(growth)[b]	Staphylococci	*P*(> 5 log)[c]	Time to 5 log[d]	P_a, two-class[e]	P_a, three-class[e]	Score[f]	Top three (%)	First (%)	Class
Ikwerre												
Aluu	4.10	0.000	0.20	ND	NA	NA	0.984[g]	1.000[g]	0.240	11.5	0.0	Low concern
Isiokpo	3.83	0.000	0.00	ND	NA	NA	0.984[g]	1.000[g]	0.094	0.0	0.0	Low concern
Omagwa	3.80	0.000	0.00	2.00	0	NA	0.984	1.000	0.139	0.0	0.0	Monitor
Omahunwa	4.00	0.000	0.00	2.10	0	NA	0.965	1.000	0.162	0.0	0.0	Monitor
Rumuchiorlu	4.40	0.103	0.80	1.75	0	31.4	0.998	1.000	0.128	0.0	0.0	Monitor
Etche												
Igbo	4.10	0.000	0.20	2.55	0	NA	0.558	0.989	0.348	36.7	0.0	Monitor
Okomoko	3.80	0.000	0.00	3.40	6.96×10^{-5}	NA	5×10^{-5}	0.019	0.353	36.1	12.9	Monitor
Ulakwo	4.30	0.035	0.60	2.55	0	69.8	0.558	0.989	0.202	0.1	0.0	Monitor
Egwi	4.40	0.103	0.80	2.45	3.38×10^{-5}	24.6	0.706	0.997	0.386	50.8	14.8	Monitor
Chokocho	3.65	0.000	0.00	2.60	1.05×10^{-3}	NA	0.476	0.979	0.554	72.2	49.8	Priority action
Ogoni												
Kibaga	5.50	0.695	1.00	ND	NA	≥ 4.3	0.984[g]	1.000[g]	0.174	0.0	0.0	Monitor
Station	7.30	0.987	1.00	2.40	0	2.6	0.769	0.999	0.350	47.3	20.9	Priority action
Bomu	6.45	0.958	1.00	ND	NA	≥ 3.1	0.984[g]	1.000[g]	0.240	16.1	0.0	Monitor
Kaa	7.05	1.000	1.00	ND	NA	≥ 3.0	0.984[g]	1.000[g]	0.250	29.2	1.6	Monitor
Kpor	4.20	0.000	0.40	ND	NA	NA	0.984[g]	1.000[g]	0.000	0.0	0.0	Low concern

Note. ND, not detected; NA, not applicable. Staphylococci are the market mean in log CFU/g. [a]Relative growth rate at the central minimum pH for growth of 4.25 (pH_{opt} 7.0, pH_{max} 9.6; assumed). [b]Proportion of 100,000 draws of the minimum pH (uniform, 4.0 to 4.5) with a growth rate above zero. [c]Probability that a sample exceeds 5 log CFU/g, from a normal distribution with the market mean and SD. [d]Time to reach 5 log CFU/g after reconstitution, in units of the one-log growth time at optimum pH, from the market mean count; for markets without detection, a lower bound from an initial count at the LOD (2.0 log CFU/g). [e]Probability of acceptance at the market mean count, with a between-sample SD of 0.37 log CFU/g; two-class plan, $n = 5$, $c = 0$, $m = 10^3$ CFU/g; three-class plan, $n = 5$, $c = 2$, $m = 10^3$ and $M = 10^4$ CFU/g (illustrative limits). [f]Mean of four criteria scaled from 0 to 1 (growth rate, staphylococci, faecal coliforms and fungi), with non-detects set to log(LOD/2) = 1.70; top three and first, percentage of 20,000 random weight sets in which the market ranked among the three highest or first. [g]Bounded at the LOD for markets without detection. Class, rule-based class defined in Section 2.8.

The conclusion depends mainly on which concentration is correct, and also on the assumption that the 303 g eaten each day is dry garri. At the concentration expected from the tuber value (0.036 to 0.046 mg/kg), this intake would, over a week, supply about half to two-thirds of the tolerable weekly intake of a 60 kg adult, whereas at the measured concentrations it supplied 14 to 20 times that intake.

The probabilistic analysis does not remove this uncertainty. The hazard index exceeded 1 in 99.93% to 99.99% of iterations (Table 5), but the simulated variability came from assumed distributions of intake and body weight and from the replicate SD of one composite per area. The hazard index correlated with the intake rate (Spearman $\rho = 0.93$ to 0.94) and with body weight ($\rho = -0.29$ to -0.30) but only weakly with the cadmium concentration ($\rho = 0.008$ and 0.011 in Etche and Ogoni and 0.18 in Ikwerre), whose simulated spread reflected only the replicate SD. The 5th to 95th percentile ranges (2.82 to 14.92 in Ikwerre and 2.17 to 11.13 in Etche and Ogoni) therefore express assumed consumer variability and not the much larger uncertainty about the concentration. In a comparison of ten sensitivity methods applied to a food safety risk model, most methods ranked the key inputs similarly (Patil & Frey, 2004), and a second, model-independent method, such as analysis of variance or scatter plots, would be a useful check.

Lead, copper and chromium

The margin of exposure of lead for nephrotoxicity was 0.51 in Ikwerre and 0.45 in Ogoni and fell below 1 in 87.0% and 90.5% of the iterations (Table 5), whereas the Etche composite (0.005 mg/kg, which may be close to the detection limit) gave a margin of 24.95. For systolic blood pressure, the margins in Ikwerre and Ogoni were slightly above 1 (1.21 and 1.08) and fell below 1 in 27.2% and 35.1% of the iterations. A margin below 1 shows that the intake exceeds the benchmark dose lower limit and does not predict disease. Conversely, a margin above 1 does not establish safety, because these exposure levels are not reference health standards and no safety threshold can be established for lead (Malavolti *et al.,* 2020). The intake from garri alone (1.24 µg/kg body weight per day in Ikwerre and 1.39 in Ogoni) was eight to nine times the mean dietary intake of 0.155 µg/kg body weight per day estimated for adults in Northern Italy (Malavolti *et al.,* 2020), and it exceeded the mean dietary intake of residents of Guangzhou (0.25 and 0.28 µg/kg body weight per day in adults and 0.34 and 0.44 in children and adolescents), whose margins of exposure indicated a potential health risk for children (Song *et al.,* 2024). In the Niger Delta, lead exposure of children from fish and meat was above or close to the benchmark dose lower limit for developmental neurotoxicity in all six areas studied (Okoye *et al.,* 2021). The lead result therefore adds a staple food to the dietary sources of lead reported for the region, and the studies cited suggest that children, who were not modelled here, may be the group of greatest concern.

Unlike cadmium, the lead concentrations in Ikwerre and Ogoni did not conflict with regional tuber data, whereas the Etche value was lower than those data would predict. The range reported for tubers from Ogoniland, 0.01 to 0.09 mg/kg pooled across three crops (Peters *et al.,* 2018), corresponds to about 0.036 to 0.42 mg/kg in garri after the concentration factor in Section 3.8. This range included the Ikwerre and Ogoni values (0.245 and 0.275 mg/kg) but not the Etche value (0.005 mg/kg), which lay within the range of 0.0028 to 0.0118 mg/kg reported for food crops from an oil-impacted community (Akinkpelumi *et al.,* 2026) but below it if the same factor is applied (about 0.010 to 0.055 mg/kg). The concentration factor is assumed and the tuber range is pooled, so this agreement is suggestive and not confirmatory. The roughly 50-fold difference between Etche and the other two areas rests on single composites and cannot be attributed to an area effect.

Copper posed little concern for the modelled 60 kg adult (target hazard quotient 0.11 to 0.40; Table 5) against the oral reference dose of 0.04 mg/kg body weight per day, which is the value best supported by evidence on gastrointestinal effects and on copper deficiency (Taylor *et al.,* 2023). Children were not modelled, however, and the target hazard quotients of copper exceeded 1 for children eating food crops from an oil-impacted community (Akinkpelumi *et al.,* 2026). The concentrations (0.85 to 3.17 mg/kg) were of the same order as the mean of 0.94 mg/kg reported for 61 samples of garri from Liberia (Awoyale *et al.,* 2018) and lower than the 7.99 to 9.37 mg/kg in those food crops, in which copper was attributed to agrochemicals (Akinkpelumi *et al.,* 2026).

Chromium was measured as total chromium. With the reference dose of chromium(III), the hazard quotient was below 0.002, whereas, under the scenario in which all chromium was hexavalent, the quotient was 1.23 to 3.11

and the incremental lifetime cancer risk exceeded 10^{-4} in 82.3% to 99.7% of the iterations (Table 5). The scenario is an upper bound. Hexavalent chromium is genotoxic and carcinogenic, whereas trivalent chromium can be considered essential, so speciation is needed in dietary exposure assessment (Chung, 2024), and organic matter in foods can reduce hexavalent chromium to the trivalent form (Hamilton *et al.,* 2018). Because detections of chromium in foods are infrequent and speciation data are limited, chromium was excluded from a screening tool for heavy metals in the diet (Wong *et al.,* 2022). The concentrations here (0.220 to 0.555 mg/kg) were within the range of 0.20 to 0.84 mg/kg reported for tubers from Ogoniland, pooled across three crops (Peters *et al.,* 2018), but below the range of about 0.73 to 3.9 mg/kg expected in garri after the concentration factor in Section 3.8, so the comparison does not confirm the accuracy of the analysis, and speciation remains the main unresolved factor. In shellfish from artisanal oil mining areas of Nigeria, the total cancer risks of cadmium and chromium exceeded the range accepted by the US Environmental Protection Agency (Chris *et al.,* 2023); the present study estimated a cancer risk for chromium(VI) but not for cadmium.

Sampling plans, ranking and classification of markets

The operating characteristics show what the illustrative plans could separate. With a between-sample SD of 0.37 log CFU/g, the two-class plan distinguished lots with mean counts of 2.15 and 2.95 log CFU/g (acceptance probabilities of 0.95 and 0.05), and the three-class plan distinguished those of 2.68 and 3.32 log CFU/g. Okomoko (3.40 log CFU/g) was the only market at whose mean count either plan would reject a lot with high probability (acceptance probabilities of 5×10^{-5} and 0.019; Table 6). A lot with the mean count of Chokocho would be rejected by the two-class plan with a probability slightly above one half (acceptance probability 0.476), whereas the three-class plan would accept a lot at the mean count of any market other than Okomoko with a probability of at least 0.978. These figures describe the plans and not the garri. The limits are illustrative, the SD was pooled from the markets with detections, and a market is a collection of lots from different vendors and not a single lot. Contamination that is heterogeneous or localised increases the uncertainty of a sampling result (Jongenburger *et al.,* 2015), and microbiological criteria discriminate defective lots but have limitations (Pérez-Lavalle *et al.,* 2020), so acceptance by a plan is not proof that a hazard is absent. A plan based on staphylococci also gives no information on the faecal coliforms of Chokocho, so each organism would need its own criterion and method.

Chokocho had the highest composite score (0.554; Table 6) and the most stable position at the top of the ranking: it was among the top three markets in 72.2% of the weight sets and first when non-detects were set to 0 or to the LOD. The stability has limits. Chokocho was first in only 49.8% of the weight sets, and, because it was the only market with faecal coliforms, it received the maximum scaled value for that criterion, which contributed 0.25 to its score. Okomoko, Station and Igbo (0.353, 0.350 and 0.348) were practically indistinguishable, their median ranks were 5, 5 and 4, and their order changed with the treatment of non-detects, so no ordering among them is supported. The score also ranks the markets against one another after each criterion has been scaled from 0 to 1, and it does not measure absolute risk. Bevilacqua *et al.,* (2023) described the advantages and disadvantages of Risk Ranger, one of several commonly used risk assessment tools. Because the order of the present markets depended on the weights and on the substitution of non-detects, both dependencies were reported here.

The plans, the score and the classes answered different questions, and they did not always agree. Okomoko had the highest staphylococcal count (3.40 log CFU/g) and the lowest acceptance probabilities, but its pH of 3.80 lay below every assumed minimum pH for growth, and it was classified as Monitor. Station had a lower count (2.40 log CFU/g) and was accepted with probabilities of 0.769 and 0.999, but its pH of 7.30 placed it in Priority action. The classes also omitted fungi, so Aluu, which ranked seventh by score (0.240) entirely through its fungal count (3.10 log CFU/g), was classified as Low concern. Ten of the 15 markets fell into Monitor, so the classes discriminated little among markets. The rules are screening rules defined by the authors, and their growth criterion, a pH above 4.5, is the upper end of the assumed range of minimum pH, whereas the score used the central value of 4.25. The classes therefore indicate where inspection should begin and do not identify safe markets.

Strengths and limitations

The study has three strengths. The hierarchical design of areas, markets and vendor samples allowed the variance

of pH, THB and LAB to be partitioned, and for pH the partition showed that areas and markets within areas accounted for 97.5% of the variance. Non-detects were treated as left-censored observations in the area comparisons, associations and regressions, substitution was used only in the multivariate and ranking analyses and was tested in sensitivity analyses, and the LOD served as an explicit bound in the sampling-plan, growth and infection-risk scenarios, in agreement with advice against relying on substitution (Helsel, 2006; Shoari & Dubé, 2018). The assumptions of the exposure and growth models were stated, the growth results were examined over a range of assumed minimum pH values and initial counts, and the inputs that drove the simulated hazard index were identified by rank correlation.

The limitations arise from the design, the measurements and the statistical and modelling choices. The proximate composition and the metals were measured on one composite per area, so differences among areas in those variables could not be tested, and each market mean of a microbial variable rested on three vendor samples. Results for individual vendors were not available, so every analysis, including the partition of variance, was reconstructed from the market means and SDs. Processing history may have differed among areas and markets, and because the duration of fermentation, the roasting conditions and the storage time were not recorded and water activity and titratable acidity were not measured, its effects could not be separated from those of area, so the associations with pH are descriptive and do not show causes. Only adults were considered in the exposure models, and no biomarker or illness data were available, so the risk estimates are outputs of models and not observations of harm.

The measurements impose further limits. Staphylococci were coagulase-confirmed and not identified to species, and the faecal coliforms were not confirmed as *Escherichia coli*. The LOD of 100 CFU/g is five times the satisfactory limit of 20 CFU/g for coagulase-positive staphylococci in ready-to-eat foods (UKHSA, 2024), so a market without detection could not be classified, and applying these categories at all assumes that garri soaked and eaten without cooking is a ready-to-eat food. For faecal coliforms, the LOD was 5.85 log units above the concentration at which the modelled annual risk reached the benchmark (Section 4.6), so non-detection at 14 markets gives no assurance, and no pathogen, staphylococcal enterotoxin or mycotoxin was measured directly. Four market means lay below the LOD, although one colony on a plate of the lowest dilution already corresponds to the LOD, so their origin requires confirmation. They were retained as reported, and their influence on the area comparisons and the staphylococcal models was examined in sensitivity analyses, but not their influence on the classes, in which Rumuchiorlu was placed in Monitor only because of its value of 1.75 log CFU/g. The pH was measured in a 1:10 suspension and may differ from the pH of garri soaked for eating, and the metals were measured without documented quality control (Section 4.8). The source tables also required correction: moisture was recovered by difference because the recorded values duplicated those of ash, and two decimal-place errors, in crude protein for Ikwerre and chromium for Etche, were corrected (Section 2.9); these values await confirmation against laboratory records.

The statistical and modelling choices also have limits. With 15 markets, tests at the market level have little power, and several results lay at the margin of significance or changed with the test used, as for pH among areas (Section 4.1) and fungi in relation to pH (Section 4.5). The exposure model assumed a normal body weight with a mean of 60 kg and an SD of 10 kg, truncated at 40 and 100 kg, treated the national mean adult intake of 0.303 kg/day as dry garri, although the basis of the metal results remains to be confirmed, and assumed a lognormal intake with a coefficient of variation of 50%. This coefficient is lower than the 83% implied by the cassava intake of 940 ± 777 g/day (raw fresh weight) reported for women in Akwa Ibom (De Moura *et al.,* 2015). A constant conversion from raw to dry weight would not change the coefficient, but that survey covered women only and all cassava foods, mainly garri or foofoo, so the two values are not directly comparable. If intake varies as widely as in that survey, the true spread of exposure would be wider than modelled, and because the hazard quotients and the hazard index are proportional to intake, the spread of risk would widen in proportion. The growth model described the effect of pH alone, in units of the one-log growth time at optimum pH, without lag, temperature, water activity or competing organisms, and its screening threshold of 5 log CFU/g came from a cheese model. The other assumptions (the cardinal pH values, the dry matter of fresh roots, the pathogenic fraction, the 365 exposures per year, the benchmark and the illustrative plan limits) are listed in Table 1. The cardinal pH values, the dry matter of fresh roots, the pathogenic fraction and the frequency of consumption should be replaced by

measured values in later work, and the benchmark and the plan limits by criteria agreed for garri.

In conclusion, the causes of the variation in the pH of market garri should be sought in practices shared within areas and markets rather than in those of individual vendors. The cadmium concentrations, which dominated the chemical risk estimate, are inconsistent with regional crop data and must be verified with certified reference materials before they are used for exposure-based advice. Later surveys should record fermentation, roasting and storage conditions, measure water activity and titratable acidity, and use methods with a detection limit below the satisfactory limit for staphylococci together with enrichment-based detection of pathogens, because the present plating method could neither show that any market was satisfactory nor exclude faecal contamination at levels relevant to infection risk.

Author Contributions

Lasbry Nnodim: conceptualisation, methodology, investigation, formal analysis, writing (original draft) and writing (review and editing) [

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How to cite this article:

Lasbry Chidi Nnodim, Felicia Oluwatoyin Osakuade, Stella Awaji-Iroyem Aaron and Anayo Frank Orji. 2026. Acidity, Microbial Hazards and Cadmium Exposure in Market Garri from Rivers State, Nigeria: A Probabilistic Chemical and Microbial Risk Assessment. *Int.J.Curr.Microbiol.App.Sci.* 15(10): 349-391.
doi: https://doi.org/10.20546/ijcmas.2026.1510.038