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Spatial distribution and predictive risk of perpetuation of non-typhoidal salmonellosis in poultry farms and human communities: meta-analysis of data from Nigeria

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Abstract

To gain insight into the common pathogenic, bacterial zoonosis represented by Salmonella infections in poultry and humans, we acted to determine salmonellosis prevalence in poultry and humans in Nigeria mapping hotspots. Using multi-sourced data, we conducted a meta-analysis to determine national and sub-national prevalence of salmonellosis in poultry from 2000 until 2020. Bayesian spatial joint modelling was used to map Non-Typhoidal Salmonella (NTS) infections in humans and poultry using climatic and demographic predictor variables. With the overall prevalence in poultry at 31.6%, the highest state-level prevalence rates were seen in Ogun (70.2%), Lagos (61.8%), Zamfara (58.2%) and Bauchi (57.1%). The North-West, South-West and South-South regions of Nigeria have the highest regional-level prevalence in poultry amounting to 38.5%, 36.9% and 33.6%, respectively. Thirteen states have higher than the average national prevalence (31.6%). While we found a negative association between NTS in humans and in poultry, the prevalence of diarrhoea in humans positively predicted salmonellosis in poultry. Not surprisingly, poultry populations positively predicted salmonellosis in other poultry populations. Higher numbers of human cases were predicted in the North, with more poultry cases in the South and in some North-Eastern states. The observed human NTS-poultry salmonellosis correlation is counterfactual to logic and plausibility as high poultry density and contamination in poultry are expected to predict human infection. The outcome pointed to under-reporting linked to self-treatment, under-testing in the public health and veterinary laboratory and lack of uniform primary healthcare services, particularly in under-served areas of Nigeria. Salmonellosis continues to be a serious burden, and provision of better health data is needed.

Key words: non-typhoidal *Salmonella*; spatial distribution; food-borne zoonoses; gastro-enteritis; Nigeria.

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Introduction

Salmonellosis is a pathogenic, bacterial zoonosis that continues to impact human and animal health substantially (Ao *et al.*, 2015; World Health Organization - WHO, 2015). *Salmonella* has a large number of identified serovars (> 2600) and its species are broadly divided into typhoidal and non-typhoidal *Salmonella* (NTS) (Gal-Mor *et al.*, 2014; Sanni *et al.*, 2022). Both typhoidal and NTS cause widespread food-borne, diarrhoeal diseases globally; in complicated situations, even Invasive NTS (iNTS) can occur leading to major problems, such as sepsis (Batz *et al.*, 2012; Gal-Mor *et al.*, 2014; Ao *et al.*, 2015). In the West African sub-region, salmonellosis ranks as 20 out of the 30 prioritized zoonoses (Goryoka *et al.*, 2021). Though it is a ubiquitous health problem, recent attempts at prioritizing zoonoses in Nigeria have resulted in a view of the disease as a moderate zoonosis ranking low in severity and epidemic potential. However, although ranking high to moderate with regard to burden of disease, it is felt to be controllable by the health services, with socio-economic impact and a 0.50 score on a maximum scale of 1.00 (Ihekweazu *et al.*, 2021). In Nigeria, the human prevalence of salmonellosis and associated gastroenteritis may range from 5.7 - 16.3% (Ihekweazu *et al.*, 2021; Akinyemi *et al.*, 2021), with approximately 1.9% of *Salmonella* bacteraemia cases (Akinyemi *et al.*, 2021). The farm-level prevalence of NTS in poultry ranges from 39.7 – 48.3% (Fagbamila *et al.*, 2017; Jibril *et al.*, 2020; Ihekweazu *et al.*, 2021), but individual poultry bird-level prevalence may be less. Akinyemi and colleagues (2021) have earlier reported that a total of 53 *Salmonella* serotypes have been identified in humans in Nigeria including 39 associated with *Salmonella*-bacteraemia and 31 associated with *Salmonella*-related gastroenteritis. For instance, an estimate for the year 2020 in Nigeria indicated that NTS is grossly under-appreciated because experts perceived it not to be a significant burden and not rapidly fatal. Still, it can potentially cause 325,731 cases and 1,043 human deaths in a single year, with a Disability-Adjusted Life Year (DALYs) of 37,321 (Sanni *et al.*, 2023). Its economic burden with respect to humans was estimated at USD 473,982,068 and for poultry at USD 456,905,311 for the year 2020 alone (Sanni *et al.*, 2023). Similarly, *Salmonella* spp. is the first-ranked, food-borne pathogen in the US, with a high economic impact including heavy Quality-Adjusted Life Year (QALY) losses (Batz *et al.*, 2011; Ihekweazu *et al.*, 2021).

The human and poultry population dynamics in Nigeria and elsewhere come with the increasing need for enormous animal-sourced foods, especially in large cities. This situation has led to the multiplication of rural, peri-urban and urban farming, primarily focussing on poultry and pigs (Federal Ministry of Agriculture and Rural Development - FMARD, 2022; Omodele *et al.*, 2014). Although some statutory guidelines and acts regulate the poultry industry, which most large-scale commercial operations may adhere to, many backyard poultry, semi-commercial farms, informal hatcheries, opaque operators in the poultry value chain and vendors in outlets and informal markets may not comply fully with hygiene and biosecurity protocols. Non-adherence to these protocols may portend a significant but inadvertent source of risk for the horizontal and vertical transmission of *Salmonella* pathogens in the course of their operations (Awojulugbe, 2019; Oloso *et al.*, 2020; Mokgophi *et al.*, 2021; FAO, EU, CIRAD, 2022). Apart from salmonellosis from animal-sourced foods, NTS in humans may originate from fruits, seeded vegetables and other produce (Interagency Food Safety Analytics Collaboration, 2022). In Nigeria, NTS is primarily spread through contaminated food products, particularly poultry, due to substandard handling and poor biosecurity. Cross-contamination during processing, inadequate cooking, and the use of untreated manure in agriculture exacerbate the transmission risk (Sanni *et al.*, 2022; Hambolu *et al.*, 2024; Mugabe *et al.*, 2024; Sanni *et al.*, 2024a). While the veterinary services monitor looking for zoonotic outbreaks, detection is often reactive rather than preventive, and monitoring resources are limited, especially in rural areas. Control strategies, when implemented, focus on isolation, hygiene education and, in some cases, culling (Jibril *et al.*, 2020; Ihekweazu *et al.*, 2021; Meseko *et al.*, 2021; Okafor, 2024). In humans, the use of antimicrobials for treating acute diarrhoea in Nigeria lacks uniform regulation and remains largely uncoordinated. Although guidelines do exist within clinical practice, adherence is inconsistent, especially in rural areas. Many practitioners continue to administer antimicrobials without adequate diagnostic confirmation, often as a presumptive treatment (Efunshile *et al.*, 2019; Sekoni *et al.*, 2022; Udoh *et al.*, 2024). The Federal Ministry of Health and the Nigerian Centre for Disease Control have released some guidelines, recommending supportive therapy for diarrhoea and antimicrobial use only when specific pathogens are confirmed or highly suspected (NCDC, 2017 a,b). However, these recommendations face significant implementation challenges due to limited resources, insufficient awareness, and inconsistent supply chains (Eneh *et al.*, 2024). In fact, there is no dedicated legislation specifically targeting NTS in Nigeria. However, broader regulatory frameworks such as the Nigerian Animal Disease (Control) Act and the National Livestock Transformation Plan touch on various aspects of zoonotic disease control (Federal Republic of Nigeria - FRN, 1988; FMARD, 2021; Sanni *et al.*, 2024a). These frameworks do not address NTS specifically, but outline measures aimed at limiting the spread of zoonotic diseases more generally. Moreover, the Veterinary Council of Nigeria (VCN) and other regulatory bodies promote biosecurity practices on farms that indirectly contribute to salmonellosis control, though efforts remain inadequately enforced (Agbaje *et al.*, 2021; Sanni *et al.*, 2024a). The economic burden of NTS in Nigeria, including productivity losses, healthcare costs and export limitations, is significant and can exceed USD 930,000,000 in a single year. Poultry producers affected by *Salmonella* outbreaks face financial strain from animal mortality, lowered productivity and market disruptions (WHO, 2015; Arias-Granada *et al.,* 2021; Sanni *et al.*, 2023; Kim *et al.*, 2024). Outbreaks also increase healthcare costs due to hospitalizations and treatment expenses for humans. Comprehensive economic data specific to Nigeria are sparse, though regional estimates suggest that food-borne illnesses, including salmonellosis, cost the agricultural sector millions annually (Sanni *et al.*, 2024a; Sanni *et al.*, 2024b).

To mitigate the scenario described above, at least in the animal food value chain, the knowledge and understanding of the spatial and temporal distribution of hotspot risks of *Salmonella*, particularly the poultry-associated ones, can assist pre-emptive planning and predictive disease intelligence to control the disease and reduce the disease. Such information could also be useful for scenario planning elsewhere, particularly, for countries with similar poultry industry profiles. In this work, historical and peer-reviewed information as well as grey literature from multiple data sources were utilized to map the current situation of salmonellosis in poultry and predict the risk of poultry-associated salmonellosis in Nigerian poultry, including possible zoonotic transmission to humans. The outcome may assist the health authorities to focus on informed decisions and provide tools for controlling and reducing the burden of salmonellosis in poultry and humans.

Materials and Methods

Study site

The study covered all of Nigeria, a large West-African country, with a mid-2020 human population of 208,327,405 and a poultry population of 224,326,708 (FMARD, 2020; United Nations, Department of Economic and Social Affairs - UN-DESA, 2022; Sanni *et al.*, 2023).

Data sources

A search based on extensive data and peer-reviewed document from 2000 to 2020 on poultry and human salmonellosis in Nigeria was conducted using available tools and following preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) guidelines (Moher *et al.*, 2015). Applying the *Publish or Perish* software (https://harzing.com/) and using the search term '*Salmonella*', 'poultry' and 'Nigeria', relevant papers published between January 2000 and December 2020 were retrieved from the following websites: 1. Crossref (1,000 papers), Google Scholar (200 papers), OpenAlex (689 papers), PubMed (34 papers) and Semantic Scholar (1,004 papers). An additional search aiming to find papers that may have been missed during the original search was conducted on scholar websites (Scopus and Web of Science) by artificial intelligence (AI)-linked research database applications: i) Dimensions (https://app.dimensions.ai/discover/publication) and ii) Connected Papers (https://www.connectedpapers.com/). All publications were screened using the PRISMA-P principles and 77 publications were retained. All duplicates and non-qualifying publications were removed.

All full-text search results from the previously mentioned databases, including abstracts, were reviewed and independently screened for inclusion or exclusion. Any article that mentioned *Salmonella* in humans and/or poultry in Nigeria was recruited for full review. Prevalence data for inclusion were based on the use of bacteria culture on humans (blood or stool) or poultry (faeces, dust, environmental and pathological samples) to obtain *Salmonella* isolates or on other validated tests. All direct human typhoidal isolates were excluded from the analysis since only poultry-related *Salmonella* were of interest. Articles that did not mention Nigeria specifically and studies simply comparing findings from other territories with previous studies from Nigeria were also excluded to prevent duplications. All relevant articles were retrieved and thoroughly reviewed using these inclusion and exclusion criteria.

All data from previously validated and peer-reviewed meta-analysis Excel spreadsheets (Neyeloff et al., 2012) were filtered and entered into a new spreadsheet (*Supplementary material 1*), but not until they had been individually checked, validated and accepted. The final state-level prevalence of salmonellosis in poultry was obtained from the literature and laboratory records determining the latest national prevalence and used to produce a forest plot (Neyeloff *et al.*, 2012). All calculations are reflected in the *Supplementary material 2*. Outcome (effect size, es) was calculated using the formula: the number of events divided by the number of subjects (D = B/C). Standard Error (SE) was derived by the formula: E = D/SQRT(D*C) as done by Neyeloff et al. (2012).

For human NTS cases, hospital records, laboratory data and peer-reviewed records were used. Sixteen of the 36 states + the Federal Capital Territory (FCT) did not have empirical spatial prevalence data. To bridge this data gaps, the 2018 Nigeria Demographic and Health Survey (NDHS) data on diarrhoea were filtered and used in addition, since this source covered all the states of the country including those without NTS prevalence data (Uzochukwu & Onwujekwe, 2004; Adeyemi *et al.*, 2021; Sanni *et al.*, 2024). The mean farm-level salmonellosis prevalence in poultry and human NTS in Nigeria from 2000 to 2020 was obtained based on the peer-reviewed data review above. Any report covering any of the following isolates previously found in Nigeria was included: *S. gallinarum, S. paratyphi, S. typhimurium, S. enteritidis, S. pullorum, S. agama, S. hiduddify, S. virchow, S. mbandaka, S. muenster, S. derby, S. haifa, S. bredeney, S. onireke* and *S. havana*. Four Nigerian states (Ondo, Osun, Yobe, and Jigawa) did not have any empirical prevalence data for poultry. For each of the four states, the national average was used as a proxy for the prevalence of salmonellosis in poultry.

Mapping of salmonellosis in poultry and NTS in humans

To develop a prediction map of state-level salmonellosis in poultry and NTS in humans, the following eco-climatic variables (minimum/ maximum environmental temperatures, elevation and relative humidity), economic ones and population data (poultry and human) were integrated into the prevalence analyses. Data were cross-validated through consultations with experts and subject matter specialists, and direct data confirmation with technical experts at the sub-national FMARD offices (FMARD, 2020) as done previously (Sanni *et al.*, 2023). The human population data were obtained from UN-DESA (2022).

Geospatial modelling

For the geospatial modelling, the outcome variables were the prevalence of salmonellosis in humans and poultry. The total number of positive samples out of those from people presenting at hospitals or laboratories were used as the level of salmonellosis prevalence in humans. The predictor variables used were those mentioned above under Mapping (Table 1).

To analyse the relationship between the outcome variables and the predictors, we developed a Bayesian joint model that includes predictors and spatial random effects. There are several advantages to this modelling approach. The predictors were used to account

Table 1. The variables used in the study.

No.	Predictor	Description	Resolution	Reference
1.	Temperature	The minimum and maximum	2.5 minutes (21 km^2 at the equator) temperatures in 2020 averaged by state and recorded in Celsius degrees	Fick & Hijmans, 2017; Harris *et al.*, 2020
2.	Elevation	Height above the mean sea level averaged by state and measured in meters	1.5 by 1.5 degrees	CGIAR-CSI, 2024
3.	Relative humidity	Measured for 2020 and averaged by state and expressed as percentage	0.5 by 0.5 degrees	NASA, 2024
	Precipitation	Any type of water reaching the surface of the Earth averaged by state and measured in millimeters	2.5 minutes (21 km^2 at the equator)	Fick & Hijmans, 2017; Harris et al., 2020
4.	Poultry population	The number of poultries available per state	State-wise	FMARD, 2020
5.	Human population density	Number of people in 2019 and projected by state	State-wise	NBS, 2000; UN-DESA, 2022
6.	Diarrhoea prevalence	The prevalence of diarrhoea in each state	State-wise	FRN, 2019

CGIAR-CSI, Consultative Group for International Agricultural Research- Consortium for Spatial Information; NASA, the US National Aeronautics And Space Administration; FMARD, Ministry of Agriculture and Rural Development; NBS, National Bureau of Statistics; UN-DESA, United Nations, Department of Economic and Social Affairs; FRN, Federal Republic of Nigeria.

for known risk factors as well as to improve the precision of the predicted prevalence map, especially for states where data on salmonellosis in humans were not available. Also, the joint modelling approach allowed us to borrow strength across the two outcomes to improve local prediction. This was achieved through the specification of the shared spatial random effect. For human data, let Y_h denote the number of cases of salmonellosis isolates and m_h the number of people sampled. The probability distribution for the outcome is binomial and we write $Y_h \sim$ binomial $(_{mh}, p_h)$, where p_h is the prevalence of salmonellosis in humans. For the poultry data, let Y_p denote the salmonellosis prevalence in poultry. The probability distribution for the outcome is Beta and we write $Y_p \sim$ Beta(a, b) with mean $E[Y_p] = a/a+b = \mu_p$. Our model for p_h and μ_p is given by the equations: (Eqs):

$$\text{logit}(p_h) = \beta_{0h} + \beta_{1h}\log(\text{hpop}) + \beta_{2h}\text{diar} + \beta_{3h}\text{elev} + \beta_{4h}\text{maxtemp} + \beta_{5h}\text{mintemp} + \beta_{6h}\text{RH} + S \quad \text{(Eq.1)}$$

$$\text{logit}(\mu_p) = \beta_{0p} + \beta_{1p}\log(\text{ppop}) + \alpha S \quad \text{(Eq.2)}$$

Table 2. Mean empirical prevalence of salmonellosis in poultry by state in the period 2000-2020.

State	No.	Event	Sample size	Outcome	SE	Confidence interval	Rate	Confidence interval
Abia	1	58	240	0.242	0.032	0.179, 0.304	24.167	6.220, 54.553
Anambra	2	102	220	0.464	0.046	0.374, 0.554	46.364	8.998, 101.725
Ebonyi	3	110	259	0.425	0.040	0.345, 0.504	42.471	7.937, 92.879
Enugu	4	84	458	0.183	0.020	0.144, 0.223	18.341	3.922, 40.603
Imo	5	57	412	0.138	0.018	0.102, 0.174	13.835	3.592, 31.262
Akwa-Ibom	6	48	366	0.131	0.019	0.094, 0.168	13.115	3.710, 29.940
Bayelsa	7	30	310	0.097	0.018	0.062, 0.131	9.677	3.463, 22.818
Cross-river	8	206	374	0.551	0.038	0.476, 0.626	55.080	7.522, 117.682
Edo	9	352	786	0.448	0.024	0.401, 0.495	44.784	4.678, 94.246
Delta	10	43	150	0.287	0.044	0.201, 0.372	28.667	8.568, 65.902
Rivers	11	11	22	0.500	0.151	0.205, 0.795	50.000	29.548, 129.548
Ekiti	12	4	50	0.080	0.040	0.002, 0.158	8.000	7.840, 23.840
Ogun	13	92	131	0.702	0.073	0.559, 0.846	70.229	14.351, 154.809
Ondo	14	114	384	0.297	0.028	0.242, 0.351	29.688	5.450, 64.825
Osun	15	114	384	0.297	0.028	0.242, 0.351	29.688	5.450, 64.825
Oyo	16	81	366	0.221	0.025	0.173, 0.270	22.131	4.820, 49.082
Lagos	17	21	34	0.618	0.135	0.353, 0.882	61.765	26.417, 149.947
Kogi	18	15	102	0.147	0.038	0.073, 0.221	14.706	7.442, 36.854
Niger	19	29	98	0.296	0.055	0.188, 0.404	29.592	10.770, 69.954
Nasarawa	20	305	3170	0.096	0.006	0.085, 0.107	9.621	1.080, 20.323
Kwara	21	18	100	0.180	0.042	0.097, 0.263	18.000	8.316, 44.316
Benue	22	117	688	0.170	0.016	0.139, 0.201	17.006	3.081, 37.093
Plateau	23	314	854	0.368	0.021	0.327, 0.408	36.768	4.067, 77.603
Taraba	24	96	500	0.192	0.020	0.154, 0.230	19.200	3.841, 42.241
Borno	25	130	525	0.248	0.022	0.205, 0.290	24.762	4.257, 53.780
Adamawa	26	39	196	0.199	0.032	0.137, 0.261	19.898	6.245, 46.041
Bauchi	27	12	21	0.571	0.165	0.248, 0.895	57.143	32.332, 146.617
Gombe	28	3	11	0.273	0.157	-0.036, 0.581	27.273	30.862, 85.407
Yobe	29	114	384	0.297	0.028	0.242, 0.351	29.688	5.450, 64.825
FCT	30	16	98	0.163	0.041	0.083, 0.243	16.327	8.000, 40.653
Jigawa	31	114	384	0.297	0.028	0.242, 0.351	29.688	5.450, 64.825
Kaduna	32	162	809	0.200	0.016	0.169, 0.231	20.025	3.084, 43.133
Kano	33	21	45	0.467	0.102	0.267, 0.666	46.667	19.960, 113.293
Katsina	34	12	39	0.308	0.089	0.134, 0.482	30.769	17.409, 78.948
Kebbi	35	17	48	0.354	0.086	0.186, 0.523	35.417	16.836, 87.669
Sokoto	36	30	62	0.484	0.088	0.311, 0.657	48.387	17.315, 114.089
Zamfara	37	32	55	0.582	0.103	0.380, 0.783	58.182	20.159, 136.523
Multistate-NG	38	570	1267	0.450	0.019	0.413, 0.487	44.988	3.693, 93.670
Summary				0.316	0.005	0.307, 0.326	31.634	0.921, 64.190

FCT, Federal Capital Territory (Abuja); Note that for this analysis, there was no literature available for the prevalence of salmonellosis in poultry for Ondo, Osun, Yobe and Jigawa; hence the national average was used for those four states.

where β_h and β_p are the regression coefficients for prevalence in humans and poultry, respectively; log(hpop) and log(ppop) the log of human and poultry populations, respectively; diar, elev, max-temp, mintemp and RH the diarrhoea prevalence, elevation, maximum temperature, minimum temperature and relative humidity, respectively; S the shared spatial random effects accounting for the spatial autocorrelation structures for prevalence in humans and poultry; and α the scaling parameter regulating the shared spatial effect. The shared spatial effect S is modelled using the Intrinsic Conditional Autoregressive (iCAR) specification (Besag *et al.*, 1991) such that $S \sim N(0, T(D - W)]^{-1})$, where W is the spatial adjacency matrix; D a diagonal matrix with the number of neighbours of each state; and T the precision parameters. To arrive at the set of predictors in Eq 1 and Eq2, we performed model selection procedures. We used the best subset approach to identify the most relevant predictors. The best subset selection method evaluates all possible combinations of predictors (16,384) and selects the subset of predictors that provides the best fit to the data. We evaluated all possible models and selected the model with the best fit based on the Watanabe-Akaike Information Criteria (WAIC), where the model with the least WAIC is considered the best. The geospatial model was fitted using an integrated nested Laplace approximation (INLA) approach (Rue *et al.*, 2009), which is implemented in R package R-INLA (https://www.r-inla.org/).

Results

When the empirical and predicted prevalence of poultry salmonellosis and human NTS were calculated, 158,222 biological samples (mainly stools and blood) were retained based on data from 77 publications. This yielded 8,279 positive isolates originating from humans and poultry. With regard to the latter, a total of 3,693 *Salmonella* spp. isolates from 14,402 samples were retained from the 77 publications giving an overall empirical prevalence of salmonellosis in poultry of 31.6% with differing state-level prevalence. While the states Ekiti, Nasarawa and Bayelsa showed 8.0%, 9.6% and 9.7%, respectively, Ogun, Lagos, Zamfara and Bauchi had 70.2%, 61.8%, 58.2% and 57.1% respectively (Table 2). In the North-West, South-West and South-South geopolitical zones the highest regional-level prevalence were 38.5%, 36.9%, and 33.6%, respectively (Table 3). Based on the forest plot, 13 states, three regions and the multi-state evaluation were higher than the national average of 31.6% (Figure 1, Table 3).

Salmonellosis in poultry manifests primarily as fowl typhoid and pullorum disease (WOAH, 2018). where there was missing data in humans, the NDHS data for diarrhoea were used as a proxy. For poultry-level data, only four states (Ondo, Osun, Gombe and

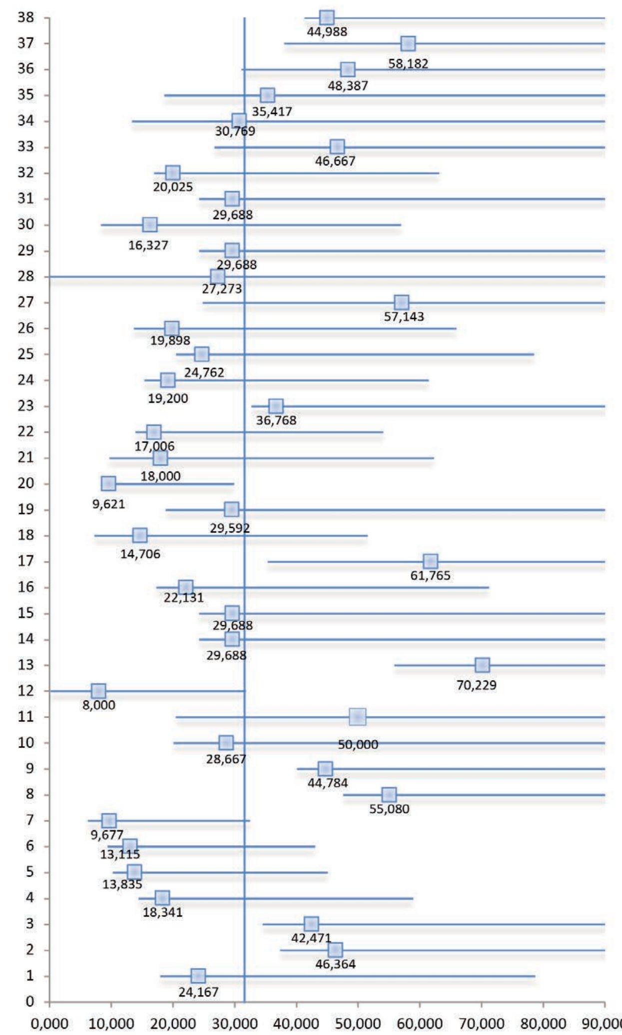

Figure 1. Forest plot of empirical prevalence of non-typhoidal salmonellosis (NTS) in poultry in the different states of Nigeria, 2000-2020. 1, Abia; 2, Anambra; 3, Ebonyi; 4, Enugu; 5, Imo; 6, Akwa-Ibom; 7, Bayelsa; 8, Cross-River; 9, Edo; 10, Delta; 11, Rivers; 12, Ekiti; 13, Ogun; 14, Ondo; 15, Osun; 16, Oyo; 17, Lagos; 18, Kogi; 19, Niger; 20, Nasarawa; 21, Kwara; 22, Benue; 23, Plateau; 24, Taraba; 25, Borno; 26, Adamawa; 27, Bauchi; 28, Gombe; 29, Yobe; 30, FCT; Abuja; 31, Jigawa; 32, Kaduna; 33, Kano; 34, Katsina; 35, Kebbi; 36, Sokoto; 37, Zamfara; 38, Multistate. Note that for this analysis; there was no literature available for the prevalence of Salmonellosis in poultry for Ondo; Osun; Yobe and Jigawa; hence; the national average was used for those four states.

Table 3. Summary of mean prevalence in Nigeria of salmonellosis in poultry per region and poultry population dynamics in the period 2000-2020.

Geopolitical zones (regions), Nogeria	Regional prevalence	Poultry population dynamics 2020*		
		Indigenous	Exotic	Estimated total
South-East	29.04	8,682,064	22,439,738	30,933,716
South-South	33.55	2,466,606	11,757,575	4,224,181
South-West	36.92	3,347,106	23,388,375	26,735,481
North-Central + FCT	20.29	9,691,867	22,726,618	32,418,485
North-East	29.66	10,130,102	11,044,134	21,174,236
North-West	38.45	20,484,256	28,697,419	49,181,675

Poultry population data were from the Federal Ministry of Agriculture and Rural Development (see reference FMARD, 2020); FCT, Federal Capital Territory (Abuja).

Jigawa) (10.8%) lacked data, hence the national average of poultry salmonellosis was used for those states (see Figure 2).

Based on the empirical spatial map of the prevalence of NTS and diarrhoea in humans and salmonellosis in poultry, some interesting patterns were observed. Only 21 of the 37 states (including the FCT) had NTS data for humans but 33 of them had data for poultry (Figure 2A,B). The prevalence varied widely between states, with those in the South-West, North-West and South-South regions displaying higher endemicity than the three other regions, a pattern consistent with the predicted map generated from the spatial analysis (Figure 2A,B). The scatter plots indicated that the prevalence of NTS in humans was negatively associated with salmonellosis in poultry, but prevalence of diarrhoea in humans was positively associated with salmonellosis in poultry. Furthermore, the reported prevalence of NTS in humans was negatively associated with diarrhoea in humans, while prevalence of NTS in poultry was positively associated with other poultry populations (Figure 2C–F).

Based on the predicted mapping, the burden of NTS in humans appeared to be more intense in the southern part of the country, especially in Ekiti, Ondo, Bayelsa, Rivers, Cross Rivers, Akwa Ibom, Abia, Edo and Delta states, whereas the infection with poultry salmonellosis was more prevalent in the North and in selected southern states (Oyo, Ogun, Lagos, Imo, Edo, Anambra, Enugu and Ebonyi) (Figures 3A,B). The empirical versus the predicted prevalence of NTS in humans and salmonellosis in poultry showed a strong correlation. While the correlations were smoother for poultry, it was 'wavy' for humans (*Supplementary Figures 1a,b*). The parameter estimates of the model are displayed in Table 4. Human population, diarrhoea prevalence, elevation, maximum temperature, minimum temperature and relative humidity were found to be negatively associated with the prevalence of NTS in humans, while the poultry population was positively associated with the prevalence of NTS in poultry.

Discussion

This work, re-evaluating the prevalence of salmonellosis in poultry in Nigeria from 2000 until 2020 based on data from different sources, reveals that the national prevalence of salmonellosis in poultry 30% with differing prevalence among states. This is a major challenge for the industry, while the health authorities have yet to give the disease in humans and poultry the attention it deserves. It appears that states and regions in the country with dense human populations, many periurban poultry-related facilities, such as day-old chick hatcheries and distribution services, tend to have higher prevalence compared to areas with relatively sparse populations.

The resulting patterns of correlation analyses are a source of concern. In the empirical analysis, human NTS was negatively associated with salmonellosis in poultry; it is known that NTS is a food-borne zoonosis, with the disease linked to contaminated poultry threatening to get into the human food chain (Ao *et al.*, 2010; Batz *et al*., 2012). It can thus be expected that increasing numbers of human cases will present in the hospitals as more poultry cases are detected. However, the negative correlation found by us contradicts this view. The likely reason is that many cases of acute self-limiting gastrointestinal illnesses, possibly caused by many NTS infections never being reported to the health authorities and/or bypassing laboratory testing. The ensuing low record (Baba *et al.*, 2013; Enabulele & Awunor, 2016; Rockers & McConnell, 2017) is reinforced because only 21 states have peer-reviewed records out of the 37 distinct sub-national health-related authorities. Indeed, it is unlikely that there has been no real human NTS cases in those non-reporting states. In addition, primary healthcare services may not reach under-served areas of the country or may be delivering poor or inadequate services as reported by Makinde *et al*. (2018) and Adelabu *et al.* (2022). Furthermore, abuse of antimicrobials to treat acute diarrhoea is common nationwide. Anecdotal evidence reveals that diarrhoea is initially treated with metronidazole (Flagyl) or tetracycline, or some mix of complementary or home remedies, with hospital follow-up only in unresolved cases. Even in the resolved cases, many patients do not complete the course of medication, a fact that often goes unreported and without diagnostic follow-up (Uzochukwu & Onwujekwe, 2004; Omolase *et al.*, 2007; Adeyemi *et al.*, 2021; Wegbom *et al.*, 2021). This may have been responsible for the observed negative correlation between NTS prevalence and diarrhoea in humans. Interestingly infection and transmission of *S. gallinarum* and *S. enteritidis* in poultry farms (Sirdar *et al.*, 2012; Neogi *et al.*, 2020).

We are aware that Nigeria currently does not have a dedicated NTS control program. General biosecurity measures and poultry vaccination efforts are promoted through initiatives under the National Livestock Transformation Plan (NLTP) and other zoonot-

Table 4. Model data estimates.

Parameter	Mean	95% Credible interval	
Intercept (humans)	92.194	88.526	95.861
Intercept (poultry)	-4.713	-7.859	-1.509
Human population (humans)	-0.690	-0.690	-0.631
Poultry population (poultry)	0.257	0.049	0.462
Diarrhoea prevalence (humans)	-15.465	-16.410	-14.519
Elevation (humans)	-0.010	-0.010	-0.009
Maximum temperature (humans)	-1.442	- 1.532	-1.352
Minimum temperature (humans)	-1.197	- 1.271	-1.122
Relative humidity (humans)	-0.103	-0.117	-0.089
Precision of spatial effect	22,170.89	1,625.219	84,938.150
Scaling parameter (poultry)	1.00	0.379	1.62
Precision of poultry observation	9.16	5.773	13.790)

ic control frameworks, but these are not specifically targeted at *Salmonella* spp. (Tasie *et al.*, 2020; Akpabio *et al.*, 2023; Sanni *et al.*, 2024a). Some states, especially those with larger poultry industries, have seen some success in managing outbreaks due to more stringent veterinary oversight and greater private sector engagement. Poultry associations and cooperatives in some regions have occasionally partnered with government agencies to enhance farmer awa, we found the reverse direction of this kind of infection, *i.e.*, diarrhoea in humans being a positive predictor for salmonellosis in poultry (Figure 2D). It is not surprising that Nigerian states with high poultry populations, *i.e.*, those with huge open poultry markets, large numbers of hatcheries and other similar facilities, also have a high predicted likelihood of prevalence of poultry salmonellosis. Previous studies have confirmed that biological and anthropogenic risk factors, including the age of the birds, flock size, feed, hygienic condition of the farm and environmental determinants, may drive farm-level reness and training, often through workshops and extension services (Anosike *et al.*, 2018; Endacott *et al.*, 2021; Njoga *et al.*, 2021; Ikeogu *et al.*, 2024). We encourage the widespread adoption of these positive practices to mitigate the impact of NTS. It should also be noted that there is no structured vaccination program targeting NTS exist

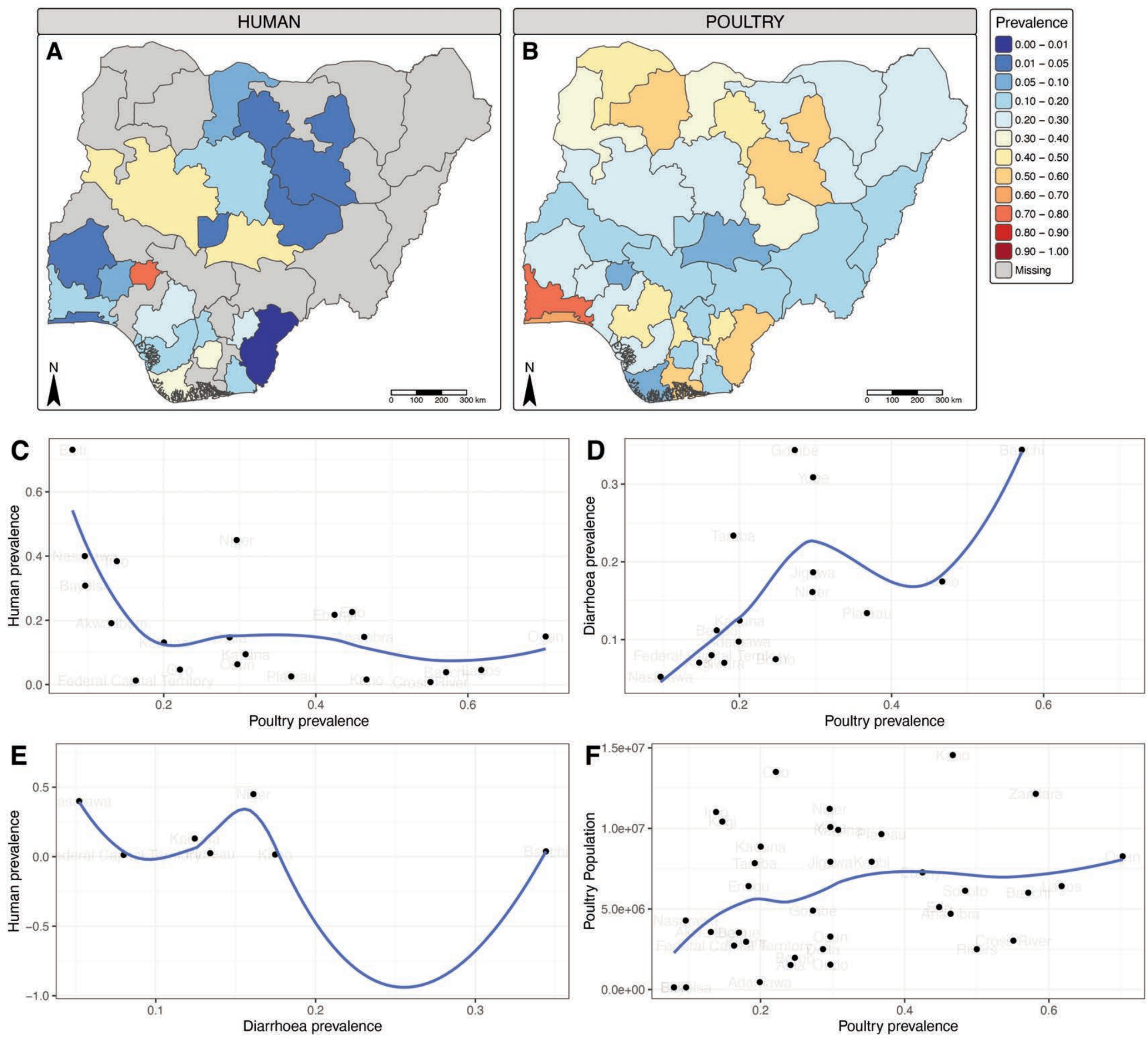

Figure 2. State-level empirical prevalence of poultry salmonellosis and Non-Typhoidal Salmonellosis (NTS) in humans based on historical and peer-reviewed data, 2000-2020. **A**) Prevalence of NTS in humans based on hospital records and peer-reviewed publications; **B**) Prevalence of salmonellosis in poultry based on peer-reviewed publications and laboratory records; **C**) Correlation analysis of poultry versus human salmonellosis prevalence; **D**) Correlation analysis of poultry salmonellosis versus human diarrhoea prevalence; **e**) Correlation analysis of reported human salmonellosis versus human diarrhoea prevalence; **F**) Correlation analysis of poultry population versus poultry salmonellosis prevalence.

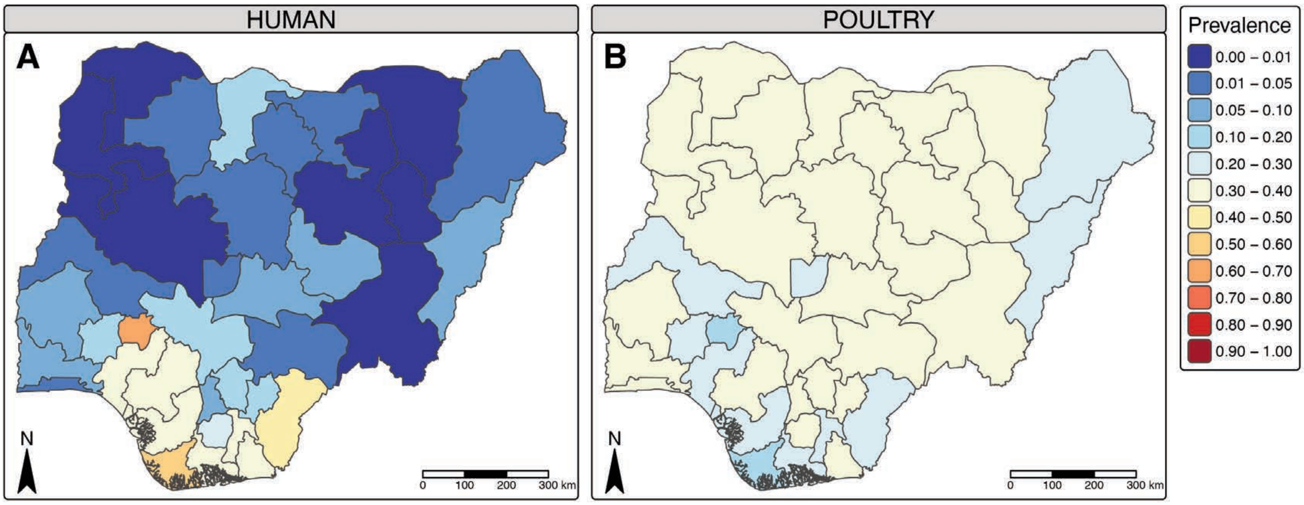

Figure 3. Predicted non-typhoidal salmonellosis (NTS) in humans and salmonellosis in poultry. (**A**) Predicted prevalence of NTS in humans; (**B**) Prevalence of salmonellosis in poultry.

in Nigeria, primarily due to cost and logistical barriers. However, vaccination is used occasionally on larger commercial farms where veterinary oversight is more consistent but smallholder farmers often lack the resources for such measures (Alders *et al.*, 2007; Ishola, 2012; Anosike *et al.*, 2018; Sanni *et al.*, 2022; Ouma *et al.*, 2023). With few incentives or subsidies available, adoption of improved regimes remains limited across much of the country.

Strengs and limitations

We experienced lack of data on NTS, which may be due to various reasons: i) high poverty rate; ii) lack of health information; iii) poor healthcare delivery in the under-served areas of the country; iv) lack of robust laboratory services; v) abuse of antimicrobials before the cause of diarrhoea is determined; and vi) lack of or seeking hospitalization only when diarrhoea refused to resolve following care at home (Uzochukwu & Onwujekwe, 2004; Adeyemi *et al.*, 2021; Sanni *et al.*, 2024). It would in this situation have been useful to carry out correlation analysis geared at comparing the prevalence of salmonellosis (and diarrhoea) in humans versus poultry populations.

The lack of comprehensive health data, both in humans and poultry (livestock) and especially for mildly symptomatic illnesses like diarrhoea, was a challenge for this study that must be addressed by the relevant health authorities. We utilized proxy data where the needed data were not available immediately and this may cause some degree of overestimation or underestimation in the model parameters. First, the cause of such lack must be established and actions triggered to address them. Efforts to promote health-seeking behaviour in cases of NTS gastroenteritis, and increase hospital visits, adequate risk communication and community engagement must be supported. This will have a consequential positive effect on robust and systemized health data collection, collation, and availability. Even, where data exist, the quality and consistency of the data are questionable. It will be important to set a standard template to collect all diarrheic-related data, and back it up with laboratory confirmation to make future works based on quantitative epidemiology more robust.

This work emphasizes the need for integrated and sustained health surveillance for salmonellosis and other diarrhoeagenic diseases in humans and animals. The government needs to invest in and maintain such activities to reduce the burden of NTS in humans and salmonellosis in poultry (Sanni *et al.*, 2023, 2024). In addition, improving the laboratory capacity to detect, confirm, and report NTS cases in humans and animals regularly is necessary It is recommended that the national One Health platforms and One Health actors contribute to and be part of driving such an integrated approach to disease surveillance, outbreak prevention, management, and control. The main advantage of our joint modelling approach is the ability to borrow strength across the two outcomes to improve prediction. It also allowed us to include potential risk factors for the two outcomes. This method can be extended to numerous diseases. Pavani *et al.* (2023) used this approach to jointly model dengue and chikungunya, while Johnson *et al.* (2022) used a similar approach to model outcomes arising from multiple diagnostic tools.

Conclusions

This work draws attention to the continued burden of NTS in humans and poultry in Nigeria, highlighting states with a high disease burdens among human and poultry populations. There are considerable data gaps in hospital, clinical and laboratory records and surveillance data. Real efforts at disease reduction, control and eradication in poultry and humans would benefit from robust and comprehensive data supporting these efforts.

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Online supplementary materials

Sheet 1. Prevalence of poultry salmonellosis and non-typhoidal salmonellosis in Nigeria
Sheet 2. Meta-analyses and forest plot of poultry salmonellosis2000 – 2020 in Nigeria
Forest plot for sheet 2
Sheet 3. Figure 1: Correlation analysis of empirical vs predicted prevalence of NTS in humans and salmonellosis in poultry. a) Empirical vs predicted prevalence of NTS in humans; b) Empirical vs predicted prevalence of salmonellosis in poultry.
Included literature

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