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Richard Nyoni

richardmauluka@gmail.com

Lilongwe University of Agriculture and Natural Resources

Tionge Chunda

Mzuzu University

Gilbert Banda

Center for Community Empowerment Initiatives

Marko Chiumia

Center for Community Empowerment Initiatives

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Heterogeneous Pathways to Rabies Prevention: Household-Level Determinants and Dog Owner Profiles of Vaccination Uptake

Authors: *Richard Nyoni[13], Tionge Chunda[2], Gilbert Banda[3], Marko Chiumia[3]

[1]Lilongwe University of Agriculture and Natural Resources (LUANAR), Environment and Natural Resource Management Department, Lilongwe, Malawi
richardmauluka@gmail.com **(Corresponding Author)**
[2]Mzuzu University (MZUNI), Department of Biological Sciences, Mzuzu, Malawi.
tiongechunda948@gmail.com
[3]Center for Community Empowerment Initiatives (CCEI), Mzuzu, Malawi. gilbertbanda@cceimw.org
[3]Center for Community Empowerment Initiatives (CCEI), Mzuzu, Malawi. markochiuma@cceimw.org

Abstract

Dog-mediated rabies remains a persistent public health challenge in many low- and middle-income countries, despite the availability of effective vaccines and global commitments to eliminate the disease through mass dog vaccination. Achieving and sustaining the recommended 70% vaccination coverage is complicated by substantial heterogeneity in dog ownership, management practices, and access to veterinary services, across urban and rural settings. This study investigates household-level determinants of dog vaccination and explores heterogeneity in rabies knowledge and vaccination behaviour among dog-owning households in Mzimba District, Malawi. Using secondary cross-sectional survey data from 682 households, the study combines count data regression and latent class analysis to examine factors influencing the number of dogs vaccinated per household and to identify distinct dog-owner typologies. The Negative Binomial Regression results indicate that urban residence, higher educational attainment, training in responsible dog ownership, larger dog ownership size, and prior vaccination behaviour significantly increase household vaccination uptake, whereas rabies knowledge alone does not independently predict vaccination. Latent Class Analysis revealed three distinct owner profiles: *low-awareness moderate-prevention owners, prevention-oriented moderately aware owners,* and *high-awareness high-risk multidog owners*. These clusters differ markedly in dog population structure, knowledge levels, and vaccination outcomes, highlighting mismatches between awareness and practice in some groups. In summary, the findings demonstrate that household-level configurations and behavioural patterns play a critical role in shaping vaccination outcomes. Tailored, context-sensitive rabies control strategies that integrate education, behaviour-focused training, and structural support are essential to improve vaccination coverage and advance dog-mediated rabies elimination.

1 Introduction

Dog-mediated rabies remains a major and persistent public health problem in many low- and middle-income countries, where domestic dogs constitute the principal reservoir and source of human infection (Tiwari et al, 2021). Despite the availability of effective vaccines for both humans and animals, rabies continues to cause an estimated tens of thousands of human deaths annually, with the overwhelming majority attributable to bites from infected dogs in endemic settings (Campbell, 2023; Hampson et al, 2015). In response, global and national elimination strategies have converged on a central operational target: achieving and sustaining at least 70% vaccination coverage in dog populations to interrupt transmission and ultimately eliminate dog-

mediated rabies (Taylor, 2017; Truong et al, 2025). This threshold, which is derived from epidemiologic theory and empirical experience, has become a cornerstone of rabies control policy worldwide (Zha et al, 2025).

However, achieving and maintaining this level of coverage in practice has proven far more challenging than suggested by theoretical models (Rupprecht et al, 2020; Fahrion et al, 2017; Haselbeck, 2021). Empirical evidence from diverse geographic, cultural, and ecological settings, including Bali, Flores (Indonesia), Namibia, Sierra Leone, Algeria, and Burkina Faso, consistently demonstrates that vaccination coverage is highly heterogeneous within and between communities, even in areas where mass dog vaccination campaigns have been implemented repeatedly over multiple years (Arief et al, 2017; Mshelbwala, 2024;Laibane et al, 2021; Wera et al, 2015; Tenzin et al, 2024; Kardjadj et al, 2019). While reported average coverage may approach or even exceed the recommended threshold at the district or regional level, these aggregate figures often conceal the presence of persistent pockets of under vaccinated dogs, which can sustain viral transmission and precipitate outbreaks (Castillo et al, 2024). Such heterogeneity has been repeatedly identified as a key obstacle to rabies elimination and suggests that conventional monitoring approaches may obscure critical structural drivers of risk (Ferguson et al, 2025; Ferguson et al, 2015).

This unevenness in vaccination coverage cannot be fully explained by logistical shortcomings alone, such as insufficient vaccine supply or campaign frequency (AL-Eitan, 2025). Rather, a growing body of evidence indicates that underlying differences in dog ownership, management practices, and human–dog relationships play decisive roles in shaping both exposure risk and program reach (Obara, 2025; Mshelbwala). Importantly, these differences are not adequately captured by analyses that focus exclusively on individual dogs or individual owners as independent units of observation. Instead, decisions regarding how many dogs to keep, how they are managed, whether they are allowed to roam freely, and whether and when they receive preventive health care are typically made at the household level. As such, the household represents a critical yet underutilized analytic unit for understanding heterogeneity in rabies-related outcomes.

Household-level surveys conducted across rabies-endemic regions consistently document substantial variation in dog ownership patterns. These include differences in dog numbers per household, human:dog ratios, age and sex composition of dog populations, modes of acquisition, and levels of confinement or roaming (Arief et al, 2017; Tenzin et al, 2024; Kardjadj et al, 2019). Such variation is pronounced along the urban–rural continuum, reflecting broader differences in livelihoods, settlement patterns, land use, and access to services. Rural households often keep more dogs per household, maintain lower human:dog ratios, and rely more heavily on dogs for functional purposes such as guarding property, protecting livestock, hunting, or herding (Laibane et al, 2021; Tenzin et al, 2024; Kardjadj et al, 2019). In contrast, urban households tend to keep fewer dogs, place greater emphasis on companionship, and impose stricter confinement practices, which are influenced by housing density, municipal regulations, and social norms (Crespin & Contreras-Abarca, 2024).

Rabies remains endemic in Malawi, with evidence indicating that domestic dogs play a major role in the transmission of the virus to other animal hosts. Molecular epidemiological investigations have shown that rabies viruses detected in dogs and livestock belong to the same Africa 1b lineage, suggesting transmission between domestic dogs and livestock. Analysis of 683 suspected rabies cases reported in Malawi between 2008 and 2021 found that 38.1% were laboratory-confirmed, of which 65.4% were canine rabies cases (Henson et al., 2023). On the other hand, several studies have assessed dog vaccination coverage in Malawi. Gibson et al. (2016) reported a vaccination coverage of 79.3% among dogs and demonstrated the potential of mobile technology to facilitate real-time data collection and coordination of large-scale vaccination campaigns. Similarly, Mazeri et al. (2018) reported dog vaccination coverage of approximately 79%. More

recently, Sanchez-Soriano et al. (2020) documented an increased vaccination coverage of 83.4%, suggesting relatively high levels of dog vaccination coverage in the study settings.

The household-level configurations have direct and multifaceted implications for rabies epidemiology. Larger numbers of dogs within a household increase the probability that at least one animal will be missed during vaccination campaigns, especially when resources are constrained (Kotze et al, 2021). Higher levels of roaming and semi confinement increase opportunities for contact between dogs, facilitating viral transmission and complicating efforts to identify and vaccinate all eligible animals. At the same time, rural households frequently face greater barriers to veterinary care, including longer distances to clinics, higher opportunity costs associated with travel, and more limited access to information about vaccination schedules or campaign timing (Laibane et al, 2021; Tenzin et al, 2024; Kardjadj et al, 2019) [7,9,10]. As a result, even when awareness of the risk of rabies exists, structural constraints may prevent households from acting on this knowledge.

Urban–rural contrasts thus play a central role in structuring dog-keeping systems and shaping rabies outcomes. Across multiple countries and study contexts, rural settings consistently present larger household dog populations, higher proportions of owned but free-roaming dogs, and lower rabies vaccination coverage than urban areas do Tenzin et al, 2024; Kardjadj et al, 2019 [9,10]. These patterns are not merely different in degree but often reflect qualitatively distinct dog-keeping regimes embedded within broader socioeconomic and ecological systems. For example, in rural communal lands, free roaming may be considered a normal and acceptable practice, whereas in urban environments, it is often discouraged or prohibited. Such contextual differences influence not only observed behaviours but also the feasibility and acceptability of intervention strategies.

Moreover, Knowledge, Attitudes, And Practices (KAPs) related to rabies are unevenly distributed across populations and settings. Numerous KAP surveys conducted in rabies-endemic regions, including Flores, Namibia, Burkina Faso, and Sierra Leone, report relatively high awareness that rabies is a fatal but preventable disease (Mshelbwala, 2024; Wera et al, 2015; Tenzin et al, 2024). However, a deeper understanding of critical issues, such as appropriate bite management, the need for Postexposure Prophylaxis (PEP), and the importance of routine vaccination of dogs, remains variable. Importantly, several studies have documented a disconnect between knowledge and behaviour: households with adequate or even high levels of rabies knowledge may still fail to vaccinate their dogs owing to financial constraints, lack of access to services, competing priorities, or perceptions that vaccination is unnecessary for certain types of dogs (Mshelbwala, 2024; Wera et al, 2015; Tenzin et al, 2024).

These findings underscore the limitations of analytical approaches that treat knowledge, attitudes, or individual sociodemographic characteristics as independent predictors of behaviour. They also highlight the need to move beyond simple urban–rural comparisons or single-factor regression analyses toward approaches capable of capturing cooccurring patterns of structure, behaviour, and context. In real-world settings, dog ownership practices, perceptions of risk, access to services, and socioeconomic conditions interact in complex ways, producing distinct configurations that may not be reducible to linear combinations of individual variables.

In recent years, a small but growing number of studies have demonstrated the value of data-driven segmentation and unsupervised methods for understanding heterogeneity in rabies-related behaviour and related domains. Rather than imposing predefined categories, these approaches seek to identify latent groupings or typologies that emerge from the data itself, reflecting common patterns across multiple dimensions. For example, latent class models applied to discrete choice experiments have been used to identify distinct household types with different preferences for rabies vaccination services, levels of

compliance, and responsiveness to incentives (Chen et al, 2023). In this work, class membership was associated with knowledge of rabies, for example, by illustrating how contextual and cognitive factors combine to shape behavioural responses to interventions.

Similarly, Q-methodology combined with Principal Component Analysis (PCA) has been employed to uncover coherent urban and rural discourses around rabies prevention, autonomy, and adherence to recommended practices (Phu, 2025). This approach reveals not only differences in knowledge levels but also fundamentally different ways in which owners conceptualize responsibility, risk, and external authority. Other studies have applied cluster analysis to KAP scores, showing that owners consistently group into recognizable profiles with distinct trajectories of vaccination behaviour over time in response to sustained intervention programmes (Truong, 2025). In addition to rabies, Multiple Correspondence Analysis (MCA) combined with clustering has been used to identify multidimensional human–dog relationship patterns on the basis of health-care histories and behavioural indicators, demonstrating the feasibility of typology construction at the household or dyad level (Canejo-Teixeira, 2019).

Collectively, these studies provide compelling evidence that latent typologies are both methodologically feasible and epidemiologically meaningful. They also demonstrated the flexibility of unsupervised approaches across different data types, including categorical, ordinal, and continuous variables. However, the scope of existing work remains limited in important respects. Most rabies-focused segmentation studies have concentrated on perceptions, preferences, or KAPs rather than on the full structure and management of dog-owning households. Conversely, studies that examine dog management and health-care patterns have often been conducted outside a rabies-specific framework or without explicit consideration of vaccination and sterilization outcomes.

No study has systematically integrated household-level rabies awareness (heard of rabies, knowledge of rabies critical signs, knowledge on recommended vaccinations per year) and training on responsible dog ownership, leaving a gap in understanding the multidimensional drivers of vaccination coverage and disease risk. This study addresses this gap by using latent variable and unsupervised methods to identify household typologies and link rabies-related awareness to vaccination outcomes, offering a holistic, context-sensitive perspective for targeted control strategies, within an explicit urban–rural comparative framework.

Existing rabies research continues to rely predominantly on regression-based approaches that estimate the marginal effects of individual predictors, such as education, dog age or sex, or distance to vaccination points (Mshelbwala et al, 2024; Mazeri et al, 2018; Mazeri et al, 2019; Kazadi et al, 2017; Bardosh et al, 2014). While such analyses have yielded valuable insights, they are inherently limited in their ability to represent the complex configurations of practices that characterize real-world dog-owning households.

It should be noted that the risk of rabies transmission and the effectiveness of control programs are unlikely to be determined by any single factor in isolation. Rather, they emerge from the interaction of multiple dimensions: the number and type of dogs kept, their degree of confinement, household perceptions of risk and responsibility, access to veterinary services, and broader urban–rural contexts. Unsupervised and latent variable methods are uniquely suited for capturing these multidimensional profiles, allowing researchers to move from lists of risk factors toward a more holistic understanding of household dog-keeping systems.

It is against this backdrop, the present line of research seeks to combine powerful methods such regression analysis and the application of unsupervised and latent variable methods, Latent Class Analysis (LCA), to household-level data on rabies awareness, dog ecology, management, and care. The primary objectives are threefold. First, the study aims to delineate distinct dog ownership typologies on the basis of structural and management characteristics observed at the household level. Second, it seeks to examine how these

typologies are distributed across urban and rural contexts, recognizing that urban–rural differences may shape not only the prevalence but also the nature of dog-keeping systems. Third, the study aims to quantify differences in rabies-related outcomes, including knowledge, vaccination coverage, and sterilization practices, across identified typologies. Nevertheless, the study firstly uses conventional methods to analyse factors that influence the number of dogs affected at the household level.

In integrating detailed household-level dog data with rabies-specific outcomes, this approach builds directly on prior empirical findings (Awoyomi et al, 2021; Misapa et al, 2024; Mulipukwa et al, 2017; Beyene et al,2018; Mshelbwala et al, 2024; Mazeri et al, 2019) while addressing a key conceptual and methodological gap in the rabies literature. In doing so, it offers the potential to inform more targeted, context-sensitive, and equitable rabies control strategies tailored to the realities of different household dog-ownership systems rather than relying on one-size-fits-all interventions.

2 Methods

2.1 Study Design and Data Collection

This study involved the primary collection of cross-sectional survey data from dog-owning households in Mzimba District, Malawi (as seen in figure 1). A structured household survey was designed specifically for this research to assess dog ownership characteristics, management practices, and rabies-related knowledge and behaviours among dog owners in urban and rural areas. The collected data were subsequently used to construct household dog ownership typologies and to examine their associations with rabies knowledge, vaccination, and sterilization outcomes across urban and rural settings.

2.2 Study Area and Urban–Rural Stratification

Mzimba District comprises both urban and predominantly rural areas, with substantial variation in dog-keeping systems, population density, and access to veterinary services. For analytical purposes, dog-owning households were stratified into urban and rural categories.

The urban stratum consisted of Mzuzu city, purposively selected as the major urban centre in the district and relevant for understanding urban dog-keeping practices and service access. Within Mzuzu, a systematic sampling approach was employed to select households, accounting for low-density and high-density residential areas to capture heterogeneity in settlement patterns and socioeconomic conditions.

The rural stratum comprised areas outside Mzuzu city. Rural sampling involved purposive selection of traditional authorities (TAs) in the northern part of Mzimba, followed by simple random sampling of

households to represent diverse rural contexts. This stratified approach ensured adequate representation of both urban and rural dog-keeping systems and allowed for meaningful comparisons between settings.

2.3 Study population and sample size

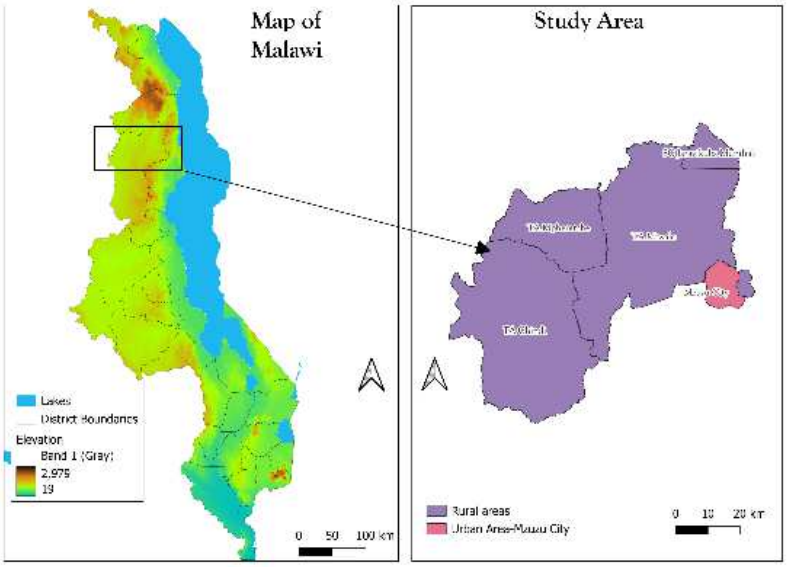


Figure 1Study area map

The study population consisted of dog owners residing within the selected urban and rural areas of Mzimba District at the time of data collection. To calculate the sample size, the study adopted the following formula by Fisher et al

$$n = \frac{Z^2 pq}{d^2}$$

Where *n* is the desired sample size, *z* is the standard normal deviate (1.96 which corresponds to 95%), *p* is the proportion of the target population (assumed to be 0.5), *q*=1-*p* and *d* is the degree of accuracy set at 0.05. To account for non-responses, 10% was added. The calculated sample size was 422. However, a total of 682 dog owners were interviewed. For qualitative perspective, the study identified government officials such as officers from the Department of Animal Health and Livestock Development (DAHLD). Local leaders were also engaged.

2.4 Data collection procedures

Data were collected via a digitally administered questionnaire implemented on electronic data-capture devices using the *KoboToolBox* platform. The questionnaire was programmed in advance to incorporate logical skips, validation checks, and range restrictions, thereby minimizing data entry errors and internal inconsistencies at the point of collection. The use of digital data facilitated real-time monitoring of fieldwork progress and enabled rapid identification of missing or inconsistent responses. The questionnaire captured information on household sociodemographic characteristics, dog population structure, ownership and management practices and other variables.

Prior to the full collection of the data used, a pilot survey was conducted to pretest the questionnaire. The pilot served multiple purposes: (i) to assess the clarity, relevance, and sequencing of questionnaire items; (ii) to identify potential sources of respondent misunderstanding; and (iii) to ensure that enumerators were competent and fully conversant with the questionnaire content and digital data collection platform.

The enumerators recruited for the study underwent structured training that covered the objectives of the survey, ethical considerations, interviewing techniques, and practical use of the digital data-collection tools. Feedback from the pilot exercise was used to refine the questionnaire and to reinforce enumerator training prior to the main survey

2.5 Statistical Analysis

2.5.1 Determinants of Dog Vaccination: Count Model

One of the preliminary objectives of this study was to examine the factors associated with the number of dogs vaccinated per household. Given that this outcome is a nonnegative count variable, count data regression techniques are considered most appropriate (Hashim et al, 2021; Schober, 2021; Pangapanga-Phiri et al 2024). Accordingly, Poisson and negative binomial regression models were identified as potential models, with model selection guided by the presence and magnitude of overdispersion, as indicated by the dispersion parameter in the model outputs (Tiara et al, 2023).

The set of explanatory variables comprises key household and dog ownership characteristics, including the sex, age, and education level of the household head, as well as the total number of household members. Variables capturing rabies-related exposure and capacity were also included, namely, awareness of rabies, training on responsible dog ownership, and a rabies knowledge index constructed by summing respondents' knowledge of recognized rabies signs. Additional covariates accounted for structural and behavioural factors, including the total number of dogs owned, the vaccination status in the previous year, the average distance to the nearest veterinary office, and whether the children were responsible for making decisions regarding dog vaccination**.** On the basis of the count models, the study uses the following model:

$$Y_{ij} = \beta_0 + \gamma_{ij} H_{ij} + \varepsilon_{ij}$$

where Y_{ij} is the dependent variable representing the number of dogs a household vaccinates and where H_{ij} is the vector of parameters hypothesized to influence dog vaccinations at the household level, which include household demographics, rabies exposure knowledge, and structural or behavioural variables. γ_{ij} represents the coefficient vector of explanatory variables, whereas ε_{ij} is the error term.

2.5.2 Latent Cluster Analysis (LCA)

Latent Cluster Analysis (LCA) is a cluster-analysis method used for identifying and creating structures from unobserved or latent subgroups, which typically rely on individual responses from multivariate data. An LCA can also be utilized as a data reduction tool when multivariate data are analysed. The mathematical model of LCA can be described as follows: Let y_j represent the element j of a response pattern y. Thus, let us establish an indicator function I ($y_j = r_j$) that equals 1 when the response to variable j equals r_j and 0 otherwise. Accordingly, following Khamis & Alanazi (2023) and Esposito et al. (2008), the probability of observing a particular vector of responses is

$$P(Y = y) = \sum_{c=1}^{c} \gamma c \prod_{j=1}^{j} \prod_{rj=1}^{Rj} P_{j.rj\backslash c}^{I(yi=rj)}$$

In the formula above, *Yc* is the probability of membership in latent class *c, and* $P_{j.rj\backslash c}^{I(yi=rj)}$ is the probability of response r_j to item j conditional on latent class c membership. In addition, y is the parameter representing a vector of class membership probabilities that sum to one, and the *p* parameters represent a matrix of item–response probabilities conditional on the latent class membership. In this analysis, the underlying latent class is the dog owner's knowledge patterns. Model fit indices (log-likelihood, AIC, and BIC) were used to select the optimal number of clusters (Auceio, 2023; Nayum, 2016).

One of the metrics used in LCA is the scoring score. The *scoring score equations* explain how each observation receives a score (or probability) of belonging to each latent class. These equations are central to how the model assigns cases to classes and how the results should be interpreted. The formula for scoring equations is given as follows Debon et al. (2023):

$$S_{ik} = \alpha_k + \sum_{j=1}^{p} \beta_{jk} X_{ij}$$

where S_{ik} is the score observation of *i* for class *k*, α_k is the class-specific intercept (class weight), β_{jk} is the coefficient of variable *j* for class *k*, X_{ij} is the value of the variable for observation *i*, and *p* is the number of variables.

Data was analysed using XLSTAT software plug-in and Stata Version 16.

2.6 Data Quality Assurance

Multiple data quality assurance measures were implemented throughout the data collection process. The completed interviews were reviewed on a regular basis to identify missing values, logical inconsistencies, or atypical response patterns. Where necessary, enumerators were provided with feedback to correct identified issues and to improve adherence to standardized interviewing procedures.

The digital data collection system further enhances the data quality by enforcing predefined response options and validation rules. These measures collectively contributed to the generation of a high-quality dataset suitable for advanced statistical analysis.

2.7 Ethical Approval

Ethical principles relating to voluntary participation, informed consent, confidentiality, and the protection of participants were followed throughout the study. Before data collection, participants were informed about the purpose of the study, what participation involved, and their right to decline participation or withdraw at any time without consequence. Oral informed consent was obtained from each participant and electronically recorded in the Computer-Assisted Personal Interviewing (CAPI) questionnaire. Participant identities were kept confidential, and findings were reported using participant categories rather than names.

3 Results

3.1 Determinants of the number of dogs a household vaccinates

Table 1 presents the results of the Negative Binomial Regression Model expressed as Incidence Rate Ratios (IRRs) for the number of dogs vaccinated per household. Reporting IRRs facilitates interpretation by indicating the multiplicative change in the expected count of vaccinated dogs associated with a one-unit change in each covariate, with other factors held constant.

On the basis of the analysis, household location is a statistically significant determinant of dog vaccination uptake. Urban households vaccinated dogs at a rate that was 1.223 times greater than that of rural households (IRR = 1.223, p <0.05), corresponding to a 22.3% greater expected number of vaccinated dogs. This finding suggests that urban residences confer advantages, potentially through improved access to veterinary services or greater exposure to vaccination campaigns. In fact, previous studies have demonstrated that immunization programs aimed at rural communities are more expensive, primarily because of the logistical costs involved in moving people and vaccines over long distances to sparsely populated areas (Wallace et al, 2019; Bardosh, 2014; Chazya, 2025).

The sex and age of the household head are not significantly associated with the number of dogs vaccinated. These results agree well with studies by Savadogo et al. (2021). However, the results contradict the findings of Dhaka et al. (2023), who reported that the age of respondents influences dog vaccinations. On the other hand, in this study, household size did not significantly influence vaccination outcomes.

The education level of the household head is a significant predictor. Households in which the head has only primary education receive dogs at a significantly lower rate than do households with other education levels (IRR = 0.806, p < 0.01). This implies a 19.4% reduction in the expected number of vaccinated dogs, highlighting the importance of educational attainment in shaping preventive or transformative animal health behaviours.

Neither training on rabies nor the rabies knowledge index is statistically significant.

In contrast, training on responsible dog ownership has a positive and statistically significant effect on vaccination outcomes. Households that received such training vaccinated dogs at a rate 1.248 times higher than untrained households did (IRR = 1.248, p < 0.01), corresponding to a 24.8% increase in the expected number of vaccinated dogs. This highlights the effectiveness of behaviour-focused training interventions.

As anticipated, the total number of dogs owned is strongly associated with vaccination counts. Each additional dog increases the vaccination rate by 17.0% (IRR = 1.170, p < 0.01), reflecting a direct relationship between dog ownership and vaccination opportunities. Vaccination history was the strongest predictor in the model. Households that vaccinated dogs in the previous year presented a vaccination rate 3.547 times higher than those that did not (IRR = 3.547, p < 0.01), indicating strong persistence in preventive behaviour and likely habitual engagement with veterinary services.

Occasionally, households seek vaccines from veterinary offices as vaccination sites. In these situations, distance to the veterinary office can influence vaccination habits, and children play an important role in taking dogs for vaccinations (Ankakwatsa et al, 2025). However, from the analysis, the average distance to the veterinary office and children's involvement in vaccination decisions are not statistically significant predictors, suggesting that these factors do not independently affect the number of dogs vaccinated once other covariates are controlled for. This may be a result of mass vaccination campaigns that government officers and other entities organize in villages.

In this study, the IRR-based results indicate that urban residence, education level, responsible dog ownership training, dog ownership size, and prior vaccination behaviour are the key drivers of household-level dog vaccination. These findings emphasize the importance of sustained vaccination programs and targeted educational interventions to improve rabies control and dog vaccination coverage. The NBRM results are presented in Table 1.

Table 1 Results of the negative binomial regression model

Dependent variable=Number of dogs vaccinated	IRR	Std. Err.	P>z	[95% Conf.	Interval]
Location (1=Urban, 0=Rural	**1.223**	**0.107**	**0.022****	**1.030**	**1.453**
Household head Sex (1=Female, 0=Male)	0.972	0.075	0.716	0.836	1.131
Age of household head	1.002	0.003	0.521	0.997	1.007
Education level (1=Primary, 0=Otherwise)	**0.806**	**0.066**	**0.008*****	**0.687**	**0.945**
Total number of household members	1.006	0.019	0.768	0.969	1.043
Training on rabies (1=Yes, 0=No)	1.098	0.265	0.699	0.684	1.761
Rabies knowledge index	0.943	0.037	0.142	0.873	1.020
Training on dog ownership (1=Yes, 0=No	**1.248**	**0.103**	**0.007*****	**1.061**	**1.468**
Total number of dogs owned	**1.170**	**0.016**	**0.000*****	**1.138**	**1.203**
Vaccinated dogs last year (1=Yes, 0=No)	**3.547**	**0.416**	**0.000*****	**2.818**	**4.465**
Average distance to vet office	0.999	0.002	0.581	0.996	1.002
Children decision to vaccine dogs (1=Yes, 0=No)	1.074	0.103	0.457	0.890	1.296
Constant	0.271	0.082	0.000	0.150	0.490

3.2 Heterogeneity among rabies and vaccination knowledge among dog owners

The study employed a LCA model to examine the variability in rabies and vaccination knowledge among dog owners. To determine the optimal number of classes, the Bayesian Information Criterion (BIC) was used (and a range of 2-5 classes was suggested). According to the information criteria summarized in Table 2, a three-class model was identified as the most suitable, offering an optimal balance between simplicity and interpretability. Standard R2 of 0.685 and Entropy 0.671 shows moderate classification performance (Weller et al., 2020). Other outputs, such as profile plots, classification characteristics and cluster profiles, are shown in Figure 2, Table 3, Table 4 and Table 5, respectively.

Table 2 Summary statistics of each model

Clusters	LL	BIC(LL)	AIC(LL)	AIC3(LL)	Number of parameters	L^2
2	-3330.206	6797.530	6702.413	6723.413	21	618.810
3	**-3278.784**	**6766.509**	**6621.567**	**6653.567**	**32**	**515.965**
4	-3250.371	6781.508	6586.743	6629.743	43	459.140
5	-3229.425	6811.438	6566.850	6620.850	54	417.247

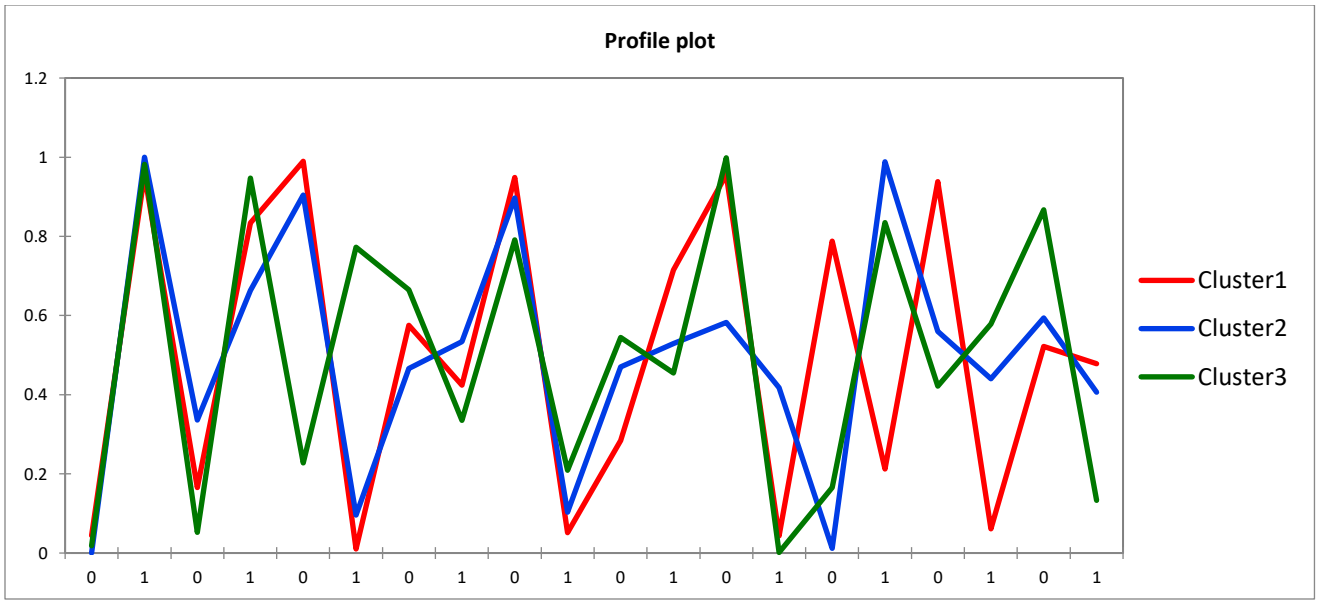


Figure 2 Profile plot

352 *Table 3 Classification characteristics*

Classification errors	Reduction of errors (Lambda)	Entropy R^2	Standard R^2	Classification Log-likelihood	Entropy	CLC	AWE	ICL_BIC
0.137	0.698	0.671	0.685	-3504.2	225.413	7008.392	7522.275	7217.334

353

354 *Table 4 Cluster profiles*

Variables	Categories	Cluster1	Cluster2	Cluster3
Cluster size		0.546	0.250	0.204
Heard rabies	0	0.044	0.000	0.018
	1	0.956	1.000	0.982
Signs aggressiveness	0	0.166	0.336	0.053
	1	0.834	0.664	0.947
Signs difficulty in swallowing	0	0.990	0.904	0.227
	1	0.010	0.096	0.773
Signs drooling	0	0.576	0.466	0.665
	1	0.424	0.534	0.335
Signs paralysis	0	0.949	0.897	0.791
	1	0.051	0.103	0.209
Signs foaming	0	0.284	0.470	0.545
	1	0.716	0.530	0.455
Signs sudden and drastic changes in temperament	0	0.956	0.583	0.998
	1	0.044	0.417	0.002
Importance of rabies	0	0.788	0.012	0.165
	1	0.212	0.988	0.835
Training on responsible dog ownership	0	0.939	0.560	0.421
	1	0.061	0.440	0.579
Number vaccinations awareness	0	0.522	0.594	0.867
	1	0.478	0.406	0.133

355 *Table 5 Description of household characteristics and other parameters accounting for the clusters*

Variable	**Cluster 1**- Low Awareness, Moderate Prevention Dog Owners	**Cluster 2-** Prevention-Oriented, Moderately Aware Dog Owners	**Cluster 3-** Highest Rabies-High Awareness, High Risk Dog Owners	**Total**	**p value**
Sex					0.226^{NS}
Male	38.4%	15.5%	15.5%	69.3%	
Female	21.2%	6.0%	3.5%	30.7%	
Age	45.3	46.2	42.6	45.0	0.360^{NS}
Location					0.211^{NS}
Rural	28.3%	13.4%	16.2%	58.0%	
Urban	31.2%	8.0%	2.8%	42.0%	
Knowledge index	2.0	2.4	2.8	2.3	0.099*
Dog structure					0.000***
Average number of dogs	2.1	1.9	2.7	2.1	

Average of male dogs	1.3	1.2	1.7	1.4	0.000***
Average number of female dogs	0.7	0.7	1.0	0.8	0.000***
Average number of puppies	0.4	0.3	0.7	0.5	0.000***
Average of adult dogs	1.6	1.6	2.0	1.7	0.000***
Average dogs vaccinated	1.3	1.4	1.1	1.3	0.000***

The cluster analysis of dog owners revealed distinct patterns in terms of rabies knowledge, dog ownership, and vaccination practices, with important implications for vaccination programs. Cluster 1, the largest group, comprised predominantly male owners with a mixed rural–urban distribution and a mean age of 45.3 years. However, nonparametric and parametric tests conducted on the sex of the household head, location, cluster group and age of the household were not statistically significant.

Nevertheless, cluster one presented the lowest level of rabies and vaccination knowledge (knowledge index = 2.0), moderate dog ownership (mean 2.1 dogs per household), and average vaccination coverage (1.3 dogs vaccinated per household), indicating community-level transmission risk despite moderate preventive practices; it was therefore labelled ***low awareness, moderate prevention dog owners***. The means were significantly different.

Cluster 2 included slightly older owners (mean age 46.2 years) concentrated in rural areas. Members of this group demonstrated moderate rabies knowledge (2.4) and the highest vaccination coverage (1.4 dogs vaccinated), despite owning fewer dogs on average (1.9 per household). This profile suggests effective engagement with rabies prevention measures, and the cluster was termed ***prevention-oriented, moderately aware dog owners*.**

Cluster 3, the smallest cluster, presented the highest level of rabies knowledge (2.8) and had the largest dog population, including more adult dogs and puppies, yet had the lowest average vaccination coverage (1.1 dogs vaccinated). This mismatch between awareness and practice highlights potential structural or access-related barriers, positioning this group as a high-risk node for rabies transmission at the human–animal–environment interface; it was therefore ***labelled high awareness, high-risk multidog owners***.

These findings demonstrate substantial heterogeneity in knowledge, behaviour, and dog ownership patterns, emphasizing the need for targeted interventions. Strategies could include educational campaigns for low-knowledge owners, reinforcement of vaccination practices among moderately aware owners, and interventions addressing structural barriers for high-risk, knowledgeable owners to optimize rabies control and reduce zoonotic transmission.

3.3 Reasons for not vaccinating Dogs

Table 6 presents the distribution of reported reasons for nonvaccination of dogs across three latent clusters of dog owners, revealing marked differences in the relative importance of informational, access-related, and dog-related constraints.

For Cluster 1 (*low awareness, moderate prevention dog owners*), non-vaccination is overwhelmingly driven by informational deficits. Lack of awareness accounts for the largest share of responses (n = 110), far exceeding all other reasons. This finding indicates that this group is constrained primarily by limited knowledge of rabies vaccination campaigns rather than deliberate refusal. Structural barriers are present but secondary, with distance to vaccination sites (n = 23) and lack of veterinary services (n = 16) reported by a smaller yet notable proportion. Dog-related constraints such as aggressive behaviour (n = 12) and other

unspecified reasons (n = 12) play a comparatively minor role. In short, this cluster appears highly responsive to improved communication and outreach strategies.

In Cluster 2 (*prevention-oriented, moderately aware dog owners*), the overall frequency of reasons for nonvaccination was substantially lower, reflecting greater engagement with preventive practices. Lack of awareness remains the most commonly cited reason (n = 14) but at a much lower level than that in Cluster 1. Distance to vaccination sites (n = 6) and aggressive dog behaviour (n = 3) emerge as moderate barriers, whereas the absence of veterinary services is not reported at all (n = 0). This pattern suggests that for this cluster, service availability is generally adequate, and the remaining gaps are related mainly to logistical convenience and residual information barriers.

Cluster 3 (*highest level of rabies awareness, high-risk dog owners)* reports the lowest absolute counts across all categories, which is consistent with high awareness levels. A lack of awareness is infrequently cited (n = 6), indicating that nonvaccination in this group is not primarily knowledge-driven. Instead, practical and situational factors—such as distance to vaccination sites (n = 2), aggressive dog behaviour (n = 2), lack of veterinary services (n = 2), and other reasons (n = 2)—are evenly represented. This dispersion suggests that despite high awareness, contextual and risk-related challenges continue to impede full vaccination coverage.

In summary, the cluster-specific patterns demonstrate that the reasons for dog nonvaccination are heterogeneous and closely linked to awareness profiles and preventive orientations. Informational barriers dominate among low-awareness owners, whereas logistical and situational constraints become relatively more important among more aware groups. These findings imply that rabies vaccination strategies should be tailored by cluster, prioritizing awareness-raising interventions for Cluster 1, service accessibility and convenience for Cluster 2, and targeted risk-management and dog-handling support for Cluster 3.

Table 6 Reasons for not vaccinating dogs

Reasons for not vaccinating	Cluster 1- Low Awareness, Moderate Prevention Dog Owners	Cluster 2-Prevention-Oriented, Moderately Aware Dog Owners	Cluster 3-Highest Rabies-High Awareness, High Risk Dog Owners
Lack of awareness	110	14	6
Vaccination site too far	23	6	2
Dog very aggressive	12	3	2
No veterinary services	16	0	2
Other reasons	12	2	2

3.4 Discussion

This study demonstrates that household dog vaccination is shaped by a combination of geographic, educational, behavioural, and dog-population characteristics, rather than by rabies knowledge alone. The NBRM identified urban residence, education level, responsible dog-ownership training, number of dogs owned, and previous vaccination behaviour as significant determinants of the number of vaccinated dogs. In parallel, the latent class analysis demonstrated substantial heterogeneity among dog-owning households, revealing that knowledge, preventive behaviour, and vaccination coverage do not necessarily move together. Taken together, these findings suggest that improving dog vaccination coverage requires interventions that address both individual behaviour and the structural conditions under which vaccination decisions are made.

3.4.1 Geographic and socioeconomic inequalities in vaccination

Household location emerged as an important determinant of vaccination, with urban households having an expected number of vaccinated dogs approximately 22% higher than rural households (IRR = 1.223). This finding is consistent with the broader understanding that access to animal-health services is often geographically unequal. The urban advantage may reflect greater proximity to veterinary services, greater exposure to organised vaccination activities, better availability of information, or lower logistical costs associated with accessing vaccination. Previous work has similarly highlighted the additional logistical and financial challenges of delivering immunisation services to dispersed rural populations, where the movement of personnel, vaccines, and other resources can substantially increase programme costs (Wallace et al., 2019; Bardosh et al, 2014; Chazya et al., 2025).

Importantly, however, the absence of a statistically significant association between average distance to a veterinary office and vaccination in the multivariable model complicates a simple interpretation of the urban–rural difference as a consequence of physical distance alone. Once other household characteristics were controlled for, distance did not independently predict the number of vaccinated dogs (IRR = 0.999, $p = 0.581$). This suggests that geographical inequity may operate through a broader set of mechanisms-including availability and timing of services, awareness of vaccination campaigns, affordability, transport, and the convenience of vaccination-rather than through distance alone. The finding is therefore particularly relevant for programme design: simply increasing the number of fixed veterinary facilities may not be sufficient if households continue to experience other access barriers.

The lack of significant associations with household-head sex, age, and household size further suggests that vaccination behaviour is not readily explained by basic demographic characteristics. The null association with sex and age is consistent with Savadogo et al. (2021), although it differs from Dhaka et al. (2023), who reported an association between respondent age and dog vaccination. Such differences may reflect variation in study populations, vaccination delivery systems, contextual norms, or how vaccination outcomes were defined. Importantly, these findings caution against targeting interventions solely on the basis of demographic characteristics when more proximal behavioural and service-related determinants may be more actionable.

3.4.2 Education, knowledge, and the knowledge–behaviour gap

Educational attainment was significantly associated with vaccination. Households whose head had primary education had an approximately 19% lower expected number of vaccinated dogs than households in the reference educational categories (IRR = 0.806, $p < 0.01$). This finding supports the proposition that formal education may influence the ability to understand preventive health messages, navigate veterinary services, or translate information into preventive action. Nevertheless, the relationship between knowledge and vaccination appears considerably more complex than a conventional knowledge-deficit model would imply.

Neither the rabies knowledge index nor receipt of rabies training was statistically associated with the number of vaccinated dogs in the regression model. More importantly, the LCA identified a group with the highest level of rabies knowledge but the lowest average vaccination coverage. Cluster 3 had a knowledge index of 2.8 and the largest dog population, yet vaccinated only 1.1 dogs per household on average. This is a particularly important finding because it challenges the assumption that increasing knowledge alone will necessarily produce higher vaccination uptake.

The apparent knowledge-practice gap is consistent with a behavioural interpretation of vaccination. Knowledge may be necessary but insufficient when households face practical barriers, competing priorities, difficulties handling dogs, inconvenient vaccination arrangements, or limitations in service availability. The results from the non-vaccination analysis reinforce this interpretation. Among the high-awareness group, lack of awareness was infrequently reported, whereas distance, lack of veterinary services, aggressive dog behaviour, and other practical considerations accounted for the remaining reasons for nonvaccination. Thus, interventions based exclusively on health education risk having diminishing returns among households that already understand the importance of rabies vaccination.

3.4.3 Responsible dog-ownership training as an actionable determinant

In contrast to general rabies training and the knowledge index, training on responsible dog ownership was positively associated with vaccination. Households receiving such training had an expected number of vaccinated dogs approximately 25% higher than households without such training (IRR = 1.248, $p < 0.01$). This distinction is important from a public health perspective. It suggests that interventions may be more effective when they move from simply communicating the dangers of rabies towards developing practical behaviours and capabilities related to dog ownership.

Responsible dog-ownership training may influence vaccination through several pathways: reinforcing routine preventive care, increasing owners' engagement with veterinary services, improving confidence in handling dogs, and embedding vaccination within a broader conception of responsible ownership. The association should nevertheless be interpreted cautiously because the analysis demonstrates an association rather than establishing that training itself caused higher vaccination uptake. Households that participate in responsible-ownership training may already differ from untrained households in motivation, access to services, or engagement with animal health. Nonetheless, the finding identifies a potentially useful intervention platform that warrants evaluation through prospective or intervention-based research.

3.4.4 The importance of previous vaccination behaviour

Previous vaccination was by far the strongest predictor in the regression model. Households that had vaccinated dogs during the previous year had an expected number of vaccinated dogs more than three times that of households that had not (IRR = 3.547, $p < 0.001$). This magnitude is substantially greater than that observed for most other determinants and suggests that dog vaccination may be characterised by behavioural persistence. Households that have successfully engaged with vaccination services may be more likely to continue doing so, potentially because vaccination becomes an established routine, owners develop familiarity with service providers, or previous vaccination reduces uncertainty about the process.

From a programme perspective, this finding suggests that maintaining existing vaccination behaviour may be as important as converting previously unvaccinated households. Preventing lapses among households that have already participated could therefore represent a relatively efficient strategy for sustaining population-level coverage. At the same time, the strong association may also indicate the existence of a relatively persistent subgroup of households that remain outside routine vaccination systems. The challenge for programmes is therefore twofold: preserve continuity among existing users while designing specific mechanisms to reach households that have never established vaccination as a routine practice.

3.4.5 Dog population size and the implications for rabies control

The positive association between the number of dogs owned and the number vaccinated (IRR = 1.170 per additional dog) might initially appear reassuring because households with larger dog populations vaccinate more dogs. However, the cluster analysis provides an important qualification. Cluster 3 contained the largest dog populations, including more adult dogs and puppies, but had the lowest average vaccination coverage.

This apparent discrepancy illustrates why absolute vaccination counts should not be interpreted as equivalent to adequate coverage. A household with many dogs can vaccinate more animals in absolute terms while still leaving a substantial proportion of its dog population unvaccinated. Larger dog-owning households may therefore represent disproportionately important targets for rabies control because they potentially contain more susceptible animals and may generate greater opportunities for onward transmission. This finding supports a shift from measuring only the number of dogs vaccinated towards monitoring vaccination completeness within households and across dog populations**.**

3.4.6 Heterogeneity among dog owners: implications for targeted interventions

One of the principal contributions of this study is the identification of three distinct owner profiles. The largest group, Cluster 1, was characterised by low awareness and moderate preventive behaviour, with a mean knowledge index of 2.0 and approximately 1.3 vaccinated dogs per household. Cluster 2 was more prevention-oriented, had moderate knowledge, and achieved the highest average vaccination level despite having fewer dogs. Cluster 3 had the highest knowledge but the lowest vaccination coverage and the largest dog populations.

These profiles indicate that dog owners should not be regarded as a homogeneous population. The reasons for non-vaccination also varied systematically across the clusters. In Cluster 1, lack of awareness was overwhelmingly the most frequently reported reason for non-vaccination, whereas distance and lack of veterinary services were secondary concerns. In Cluster 2, awareness remained the most frequently cited barrier but logistical convenience became relatively more prominent. In Cluster 3, non-vaccination was rarely attributable to lack of awareness; practical and situational constraints predominated.

This pattern has direct implications for the design of rabies vaccination programmes. A single communication strategy is unlikely to achieve equivalent effects across these groups. For low-awareness owners, community mobilisation, repeated risk communication, and notification of vaccination campaigns may be most appropriate. For prevention-oriented owners, reducing inconvenience and maintaining reliable access may yield greater benefits than additional general education. For highly knowledgeable, high-risk multidog owners, interventions should focus on service accessibility, dog-handling support, and mechanisms that facilitate complete vaccination of all eligible animals. The cluster analysis therefore provides a basis for moving from population-wide messaging towards segmented and behaviourally informed vaccination strategies.

3.4.7 Policy and public health implications

The findings have several implications for rabies elimination policy. First, vaccination strategies should explicitly address the rural–urban inequity observed in this study. The urban advantage indicates that programmes cannot assume that delivery mechanisms effective in urban settings will automatically achieve comparable coverage in rural communities. Mobile vaccination teams, community-based vaccination points,

integration with local outreach activities, and appropriately timed campaigns may help reduce access inequalities, particularly where fixed veterinary services are limited.

Second, vaccination programmes should place greater emphasis on **continuity and repeat vaccination**. The strong association between previous and current vaccination suggests that maintaining established vaccination behaviour may be an important component of sustainable rabies control. Systems that facilitate reminders, household-level vaccination records, follow-up of previously vaccinated households, and predictable annual campaigns could help preserve this continuity.

Third, public health messaging should distinguish between knowledge acquisition and behaviour change. The absence of an independent association between the knowledge index and vaccination, together with the high-awareness/low-coverage cluster, indicates that information campaigns alone are unlikely to eliminate vaccination gaps. Communication should therefore be coupled with convenient opportunities to vaccinate, practical support for dog handling, and service delivery approaches that minimise the effort required from owners.

Fourth, multidog households deserve particular attention. Because the number of dogs owned was strongly associated with vaccination counts, but the highest-risk cluster combined large dog populations with comparatively low vaccination coverage, programme monitoring should consider household-level completeness rather than vaccination counts alone. High-density dog-owning households may be particularly important targets for intensified outreach because achieving high coverage within these households could have a disproportionate effect on the susceptible dog population.

Finally, these findings support a One Health approach to rabies prevention. Dog vaccination is not merely an animal-health intervention; sustained canine vaccination reduces the risk of transmission at the human–animal interface and therefore contributes directly to human rabies prevention. Policies should consequently promote coordination among veterinary services, public health authorities, local government, community structures, and organisations involved in rabies control. Behavioural interventions should be embedded within service-delivery systems rather than implemented as stand-alone education campaigns.

4 Summary of findings

This study highlights multiple factors influencing household-level dog vaccination and reveals distinct profiles of dog owners with implications for rabies control. Urban residence emerged as a significant determinant of vaccination uptake, with households in urban areas vaccinating dogs at a rate 1.223 times higher than that of rural households, corresponding to a 22.3% increase in the expected number of vaccinated dogs. This suggests that urban households benefit from improved access to veterinary services, greater exposure to vaccination campaigns, or both, underscoring the importance of addressing geographic disparities in rabies control programs.

The education level of the household head was also a key predictor: households where the head had only primary education presented a 19.4% lower vaccination rate than did those with higher education levels. This finding aligns with evidence that educational attainment shapes preventive health behaviours, highlighting the role of knowledge, comprehension, and capacity to act on health information in promoting dog vaccination. In contrast, neither the sex nor the age of the household head, household size, rabies-specific training, nor rabies knowledge scores were independently associated with vaccination rates. These results

suggest that demographic characteristics alone are insufficient to drive vaccination behaviour and that knowledge alone may not translate into action without enabling conditions.

Behavior-focused interventions, especially training on responsible dog ownership, had a positive and significant impact, increasing vaccination rates by 24.8%. Similarly, the total number of dogs owned and prior vaccination history were strongly associated with current vaccination uptake, emphasizing the role of both opportunity and habitual engagement with veterinary services. These findings indicate that interventions that combine education, practical training, and reinforcement of vaccination habits may be more effective than knowledge dissemination alone.

The cluster analysis further contextualizes these findings by identifying heterogeneous patterns in dog ownership, knowledge, and vaccination behaviour. Cluster 1, the largest group, comprised predominantly male owners with mixed rural–urban residences, moderate dog ownership, and low rabies knowledge, representing a population at potential risk of community-level transmission despite moderate vaccination levels. Cluster 2 included older, mostly rural owners with moderate knowledge and the highest vaccination coverage, reflecting a group effectively engaging with preventive practices. Cluster 3 presented the highest level of knowledge but had the largest dog population and the lowest degree of vaccination coverage, indicating structural or access-related barriers that limit the translation of knowledge into practice and positioning this group as a high-risk node for rabies transmission.

Together, the regression and cluster analyses underscore that improving dog vaccination coverage requires multiple factors. Urban–rural disparities, low educational attainment, and structural barriers for large dog-owning households should be addressed through targeted campaigns, behaviour-focused training, and accessible veterinary services. Interventions should also account for habitual behaviours and reinforce routine vaccination practices to sustain high coverage.

Conclusion

Household-level dog vaccination is influenced by urban residence, education, responsible dog ownership training, dog ownership size, and prior vaccination behaviours, whereas demographic factors such as age, sex, and household size appear to be less important. Dog owner clusters reveal heterogeneous patterns of knowledge and behaviour, with low-knowledge owners, prevention-oriented moderate owners, and high-knowledge but high-risk multidog owners requiring distinct, targeted strategies. These findings highlight the importance of integrating education, behaviour-focused interventions, and structural support in rabies control programmes to optimize dog vaccination coverage and reduce zoonotic transmission, which is consistent with a One Health approach.

Ethics approval and consent to participate

The data collection adhered to standard ethical principles for research involving human participants. Participation was voluntary, and informed consent was obtained from all respondents prior to the interviews.

Consent for publication

All authors have approved the publication of this manuscript

Competing interests

Authors declare no competing interests

Data availability

The data supporting this study can be obtained from the corresponding author upon reasonable request

Author Contribution

Richard Nyoni wrote the main manuscript and analysed data, Tionge Chunda reviewed the manuscript, Gilbert Banda supervised the project, Marko Chiumia reviewed the manuscript.

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