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Untangling choices: how awareness and socio-economic status shape malaria vaccination decisions among Ghanaian women

Richard Kwame Ansah[1,2*], Sampson Tackie[1], Killian Asampana Asosega[1,3], Kassim Tawiah[1,3], Baaba Abassawah Danquah[1], Sampson Takyi Appiah[1], Rhodaline Abena Twum[4] and Maurice Omane-Adjepong[1]

Abstract

Malaria remains a major public health challenge in sub-Saharan Africa, making effective vaccine uptake a priority. Although individual factors such as awareness, education, and place of residence are known to influence vaccination decisions, there is a gap in understanding how these socio-economic attributes interact with social context to shape choices under peer influence. This study addresses this gap by applying the Multi-Population Curie-Weiss Model, a statistical mechanics framework, to analyse binary vaccination decisions influenced jointly by private incentives and social interactions. Data were obtained from the 2019 Ghana Malaria Indicator Survey (GMIS), which included 3,004 women. Analysis showed that 93.54% of respondents intended to vaccinate their children, whereas 6.45% did not. Among those in favour, 72.10% had received formal education, while 27.90% had not; 40.10% were aware of the malaria vaccine, whereas 56.90% were unaware. Among respondents who did not intend to vaccinate, 78.35% were educated and 21.65% were uneducated; 28.87% were aware of the vaccine, while 71.13% lacked prior awareness. In the absence of social interactions, factors such as education, vaccine awareness, and place of residence were associated with vaccination decisions. Rural women with some education demonstrated a modest increase (1.62%) in intrinsic motivation, indicating a positive association between education and vaccination. When social interactions were incorporated, educational attainment and vaccine awareness exhibited significant associations with vaccination choices. Notably, the interaction strength among urban educated women yielded a negative estimate (−4.06%), suggesting limited imitative effects, whereas rural uneducated women appeared to exert greater social influence on their educated rural counterparts. These findings provide insights for public health authorities seeking to design strategies to improve malaria vaccine uptake and reduce the disease burden among vulnerable populations in Ghana.

Keywords Malaria vaccine, Social interaction, Partial least squares, Ordinary least squares, External field

*Correspondence:
Richard Kwame Ansah
richard.ansah@uenr.edu.gh
Full list of author information is available at the end of the article

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Background

Children under five years old are highly susceptible to various diseases, making vaccination a crucial public health strategy. The World Health Organization (WHO) highlights vaccines as the safest and most cost-effective way to prevent over a million childhood deaths annually [1]. Significant advancements in childhood immunization programs over the past three decades have substantially reduced sickness, disability, and death from infectious diseases, particularly for young children in developing countries, as noted by Touray et al. [2] and the WHO [3].

According to Chan [4], the Expanded Programme on Immunization (EPI), launched globally by WHO in 1974 and implemented in Ghana in 1978, has played a vital role in increasing childhood immunization coverage worldwide from 5% in 1974 to at least 80% by 2014. Despite this progress, challenges in achieving full immunization coverage persist in developing nations, especially in Sub-Saharan Africa (SSA), which accounts for over half (52%) of global under-five mortality, as stated by Ehreth [5] and the IGME [6]. Bridging this gap requires equitable access to vaccines, irrespective of socio-economic, demographic, or geographic disparities, according to the WHO [7].

According to the Ghana Statistical Service [8], vaccination coverage in Ghana increased from 47% in 1988 to 79% in 2008, though it slightly declined to 77% by 2014 [9]. Disparities remain, particularly between rural and urban areas, leading to some children missing critical immunizations, a problem highlighted by Harris et al. [10]. Achieving full immunization coverage is vital for reducing childhood mortality and aligns with Sustainable Development Goal 3 (SDG 3) for universal quality healthcare. This necessitates the involvement of all stakeholders, including mothers and caregivers, while considering household-level conditions.

Malaria remains a leading cause of childhood mortality, despite a nearly 40% global decline in deaths between 2000 and 2019. In 2020, 627,000 malaria-related deaths were reported, with 80% occurring in children under five. According to Willyard [11], the WHO recommends the RTS,S/AS01 vaccine for children in regions with moderate to high malaria transmission. The Centers for Disease Control and Prevention (CDC) reported that this vaccine reduced clinical and severe malaria cases by one-third among children aged 5–17 months over four years, demonstrating a strong safety profile and feasibility for implementation without interfering with other health behaviours [12]. The World Health Organization (WHO) has recommended a second malaria vaccine, R21/Matrix-M, for use in children in malaria-endemic regions. According to Datoo et al. [13], R21/Matrix-M demonstrated approximately 75% efficacy against symptomatic malaria in phase 2 trials, exceeding the WHO's target for malaria vaccines. It has been licensed in Ghana, Nigeria, and Burkina Faso, and is expected to be more affordable and easier to produce at scale compared to RTS,S, potentially enabling broader coverage [14, 15]. The introduction of two WHO-recommended malaria vaccines presents both opportunities and challenges for national immunization programmes, particularly in determining optimal allocation, delivery strategies, and community engagement to ensure high uptake.

According to a report by the Ministry of Health [16], malaria significantly impacts children in Africa, resulting in approximately 500,000 deaths each year among children under the age of five. In 2019, Ghana integrated the malaria vaccine into its routine immunization programme for children under two years of age, following pilot implementation in 42 districts across seven regions based on the WHO's recommendation. In 2021, Ghana reported 5.7 million confirmed cases of malaria and 275 related deaths, with children under five accounting for 1.6 million cases and 125 deaths. In response to this ongoing burden, the National Immunization Technical Advisory Group (NITAG) recommended expanding the program to additional districts.

Despite the introduction of the RTS,S and R21/Matrix-M malaria vaccines in Ghana in 2019 and 2023, respectively, vaccine hesitancy persists. Studies such as that by Saaka et al. [17] indicate that, although awareness is increasing, up to 29% of parents particularly younger mothers and those with limited antenatal care remain hesitant to vaccinate their children. Factors such as misinformation, low trust, and regional differences also influence acceptance, according to Grant et al. [18], suggesting that awareness alone is insufficient to ensure vaccine uptake among Ghanaian women, a point also made by Bam et al. [19].

Tabiri et al. [20] investigated malaria vaccine uptake in Sunyani Municipality, Ghana, finding that while 90.6% of children received the first two doses, only 78.1% completed the full three-dose series. Factors contributing to drop-out included lack of information, vaccine shortages, and discomfort. Maternal education, especially at the university level, was positively correlated with vaccine uptake, and sub-municipality of residence was a significant determinant.

Existing research on malaria vaccine acceptance among children under five years of age in Ghana has not fully explored how women's awareness and socioeconomic status jointly influence vaccination decisions.

The present study addresses this gap by examining the interrelationship between these factors and the acceptance of malaria vaccines for young children. The analysis employs the Multi-population Curie-Weiss Model, a statistical mechanics framework that captures the interplay between social context and individual incentives in binary decision-making, such as the choice to vaccinate or not. This modelling approach offers novel insights into the roles of social influence and awareness in shaping mothers' decisions regarding malaria vaccination.

Methods

Multi-population Curie-Weiss model

Within statistical mechanics, models such as the Multi-population Curie-Weiss Model have been widely used to explain how collective behaviour emerges from social interactions and individual satisfaction, as demonstrated by Brock and Durlauf [21–23]. Similar dynamics have been identified in biological, ecological, and socio-economic systems [21, 24, 25]. Kuran [26] noted that even minor structural changes, such as the introduction of new technologies, can lead to widespread behavioural shifts. For instance, Gallo and Barra [27] applied the model to investigate suicide methods in Italy, whereas Opoku et al. [28] examined variations in educational attainment by gender and residence across five African countries. Further applications, including those by Ansah et al. [29], Burioni et al. [30], and Osabutey et al. [31], illustrate the model's capacity to explore health outcomes, energy consumption, and broader social phenomena.

To examine how socio-economic attributes and awareness influence mothers' decisions regarding malaria vaccination, a modelling framework grounded in statistical mechanics is employed. Specifically, the multi-population Curie-Weiss model, a binary choice framework extensively used in social and behavioural sciences, is applied to represent collective decision-making under the combined influence of individual preferences and social interactions [21, 27]. This formulation enables the analysis of how personal incentives and social imitation jointly shape vaccination behaviour.

Binary decision representation

Let the population size be N, and represent each woman's decision using a binary action:

$$\phi_a = \begin{cases} +1, & \text{if individual } a \text{ accepts child vaccination,} \\ -1, & \text{if individual } a \text{ denies child vaccination,} \end{cases}$$

for $a \in \{1, \cdots, N\}$. The vector $\phi = (\phi_1, \phi_2, \ldots, \phi_N) \in \Omega_N = \{-1, +1\}^N$ represents the decisions of all women [32].

The global utility (or satisfaction) of the population is described by the Hamiltonian

$$H_N(\phi) = N\left[\sum_{g=1}^{2^k}\sum_{g'=1}^{2^k} \hat{Y_{gg'}} m_g m_{g'} + \sum_{g=1}^{2^k} h_g m_g\right], \quad (0.1)$$

where m_g denotes the weighted average decision in group g. The interaction parameter $\hat{Y}_{gg'}$ measures how the behaviour of group g influences group g'. A positive $\hat{Y}_{gg'}$ indicates that the two groups tend to imitate each other (both favour or both oppose vaccination), while a negative value implies the absence of reinforcing social imitation. The term h_g captures the private incentive within group g, such as education level or vaccine awareness [28, 33].

The multi-population Curie-Weiss model captures how binary vaccination choices emerge from both private incentives and peer influence. Each woman's decision depends on her own socio-economic characteristics (education, vaccine awareness, and residence), but social imitation occurs within and across similar groups. For example, if most educated rural women vaccinate their children, another woman in the same group may feel socially encouraged to do the same. Positive interaction terms capture such alignment, whereas negative terms reflect resistance or independent decision-making [27]. This framework enables us to study not only who is likely to vaccinate but also how collective behaviour arises within socio-economic segments.

Group magnetisation and partitions

We define the average decision (magnetisation) in group g as

$$\bar{m}_g = \frac{1}{N_g}\sum_{a \in I_{N_g}} \phi_a, \quad (0.2)$$

where I_{N_g} is the set of individuals in group g. The weighted average is $m_g = \frac{N_g}{N}\bar{m}_g$. Substituting $\bar{m}_g$ yields

$$\bar{m}_g = \frac{1}{N_g}\sum_{a \in I_{N_g}} \phi_a = \frac{1}{N}\left(N_Y^g - N_N^g\right), \quad (0.3)$$

where N_Y^g and N_N^g represent the number of women in group g who accept and reject vaccination, respectively, for $g = 1, 2, \cdots, 8$.

For example:

$$\bar{m}_1 = \frac{1}{3004}(1121 - 85) = 0.34487, \quad \text{(educated rural)}$$
$$\bar{m}_2 = \frac{1}{3004}(590 - 38) = 0.18375, \quad \text{(uneducated rural)}$$
$$\bar{m}_3 = \frac{1}{3004}(905 - 67) = 0.27896, \quad \text{(educated urban)}$$
$$\bar{m}_4 = \frac{1}{3004}(194 - 4) = 0.06325, \quad \text{(uneducated urban)}$$
$$\bar{m}_5 = \frac{1}{3004}(769 - 38) = 0.24334, \quad \text{(aware rural)}$$
$$\bar{m}_6 = \frac{1}{3004}(942 - 85) = 0.28529, \quad \text{(unaware rural)}$$
$$\bar{m}_7 = \frac{1}{3004}(442 - 18) = 0.14115, \quad \text{(aware urban)}$$
$$\bar{m}_8 = \frac{1}{3004}(657 - 53) = 0.20107. \quad \text{(unaware urban)}$$

Socio-economic attribute vectors

Each individual is assigned a vector of socio-economic attributes

$$\lambda_a = \left(\lambda_a^{(1)}, \lambda_a^{(2)}, \ldots, \lambda_a^{(k)}\right), \tag{0.4}$$

where each component is binary:

$$\lambda_a^{(j)} \in \{0, 1\}, \quad j = 1, 2, \ldots, k.$$

For this study:

$\lambda_a^{(1)} = 1$ if educated, 0 if uneducated,
$\lambda_a^{(2)} = 1$ if aware of vaccine, 0 otherwise,
$\lambda_a^{(3)} = 1$ if urban, 0 if rural.

Since three attributes ($k = 3$) are considered, the population is divided into $2^3 = 8$ partitions, representing all possible combinations of the socio-economic characteristics. This formulation enables the model to capture how individual traits and group interactions jointly influence vaccination decisions.

In simple terms, the model captures collective behaviour by considering both individual characteristics (private incentives) and the influence of peers (social incentives) [29]. The private incentive reflects how a woman's education, place of residence, and awareness of the malaria vaccine directly affect her decision to vaccinate her child. The social incentive captures how the decisions of other women with similar characteristics can influence her choice, either encouraging imitation or divergence. For example, if many women in a urban community with some formal education are in favour of vaccination, this shared attitude can increase the likelihood that other women in the same group will also vaccinate their children. Conversely, if awareness is low in an urban neighbourhood, social interactions might reinforce reluctance to vaccinate. In this way, the model links socio-economic attributes and awareness to vaccination behaviour, while also accounting for how group dynamics can amplify or dampen individual decisions.

Data

This study utilized data from the 2019 Ghana Malaria Indicator Survey (GMIS), a comprehensive nationwide study conducted as part of the Ghana Demographic and Health Survey (GDHS) series. Table 1 summarizes the distribution of respondents based on vaccination choices, place of residence, and educational attainment. Out of the total, 2,810 mothers indicated willingness to vaccinate their children against malaria, while 194 declined. With respect to residence, 1,170 respondents lived in urban areas and 1,834 in rural areas. Regarding education, 2,178 mothers had some form of education, whereas 826 had no formal education.

Study design

An analytical cross-sectional study was conducted involving females across all ten regions of Ghana, utilizing data from the 2019 Ghana Malaria Indicator Survey (GMIS). The GMIS was designed based on the 2010 Population and Housing Census (PHC) framework developed by the Ghana Statistical Service (GSS). In 2019, Ghana underwent an administrative reorganization that expanded the number of regions from ten to sixteen, comprising 260 districts, municipalities, and metropolitan areas. However, these newly created regions were not incorporated into the survey design due to their recent establishment. Consequently, the 2019 GMIS sampling frame was based on the ten regional boundaries defined in the 2010 PHC. The GMIS served as a nationally representative survey aimed at collecting data on malaria-related indicators across both urban and rural areas within the ten administrative regions (Western, Central, Greater Accra, Volta, Eastern, Ashanti, Brong Ahafo, Northern, Upper East, and Upper West) as delineated in the 2010 PHC. The sampling frame for the 2019 GMIS

Table 1 Summary of vaccination choices, residence, and education

Category	Response	Count
Vaccination choice		
	Yes	2810
	No	194
Residence		
	Urban	1170
	Rural	1834
Education		
	Some education	2178
	No education	826

consisted of all census enumeration areas (EAs) from the 2010 PHC, as provided by the GSS [16, 34].

In the 2019 GMIS study, the sampling process was executed in two stages and categorized into 20 strata based on urban and rural divisions within each region. During the first stage, 200 Enumeration Areas (EAs) were chosen, comprising 97 urban and 103 rural areas, with selection based on size and conducted independently within each stratum. The second stage involved selecting 30 households from each stratum, culminating in a total of 6,000 households. The sampling frame was organized within each stratum for implicit stratification and proportional allocation at lower administrative levels. For a comprehensive overview of the 2019 GMIS sampling, including data collection methods, tools, and quality control, refer to the full report. The analysis in this study specifically included data from 3,004 women aged 15–49 years [34].

Study variables

The study examined the acceptance of malaria vaccinations as the dependent variable. Acceptance of malaria vaccinations was classified into two categories: acceptance of child vaccination (coded as +1) and denial of child vaccination (coded as −1). Three independent variables were considered: type of residence (rural or urban), educational attainment (with or without formal education), and vaccination awareness (yes or no) within the surveyed households. Educational attainment, place of residence, and vaccine awareness were selected as key socio-economic and awareness variables based on evidence from malaria immunization studies conducted in sub-Saharan Africa. Existing research has consistently demonstrated that these factors are major determinants of vaccine uptake. For instance, a systematic review of vaccination barriers in the region identified awareness and geographical distance as principal obstacles to immunization [35]. Moreover, studies conducted in Ghana have revealed a strong association between maternal awareness and willingness to vaccinate children, with significant disparities observed between urban and rural populations [17]. Additional evidence indicates that maternal education and household wealth contribute substantially to the rural–urban gap in vaccination coverage [36]. Collectively, these findings justify the inclusion of the selected variables in examining malaria vaccine acceptance.

Ethics statement

This research was based on data extracted from the 2019 Ghana Malaria Indicator Survey (GMIS). The authors received authorization to use the data from MEASURE DHS/ICF International. The procedures of the Malaria Indicator Survey (MIS) Programme align with established guidelines for protecting the confidentiality of respondents. ICF International is responsible for ensuring that the survey complies with the Human Subjects Protection Act as set by the U.S. Department of Health and Human Services. The MIS project had previously obtained all necessary ethical clearances before the execution of the survey, thus obviating the need for additional approvals for this study. More information on data and ethical considerations can be found at http://goo.gl/ny8T6X [29, 37].

Estimation

The model parameters are estimated using the least squares method. Accordingly, the estimation involves identifying the parameter values that minimize

$$\sum_{g} \left[\bar{m}_g - \tanh(U_g)\right]^2 \tag{0.5}$$

where $\bar{m_g}$ is the average choice of group g. Note that,

$$U_g = \sum_{g'=1}^{8} J_{gg'} m_{g'} + h_g, \tag{0.6}$$

with $g = 1, \ldots, 8$ and

$$h_g = \sum_{j=1}^{3} \alpha_j \lambda_g^{(j)} + \alpha_0. \tag{0.7}$$

Here, β_0 represents the fundamental private incentive inherent to all individuals, irrespective of their specific socio-economic characteristics. As $\tanh(U_g)$ is non-linear, its computation is highly time-consuming [28]. In the interactive scenario, the independent variables are correlated, which makes the ordinary least squares method unsuitable. Consequently, the partial least squares estimation method is employed. In the following section, this method is applied to estimate parameters associated with women's decisions to accept or reject malaria vaccinations for their children under five years old. These parameters are determined based on socio-economic factors, including educational attainment, awareness of malaria vaccinations, and place of residence [28].

Results

Data from the 2019 Ghana Malaria Indicator Survey (GMIS) were analysed for this study. The survey sampled 3,004 women from both rural and urban settings and collected information on their awareness of the malaria vaccine and educational backgrounds. Participants were categorized into three groups based on the variables λ_a^1, λ_a^2, and λ_a^3, which represent educational attainment,

Table 2 Allow child to be vaccinated against malaria (Yes)

Attributes	Educational attainment		Awareness of malaria vaccine	
Residence	Some form of education	No education	Yes	No
Rural	1121	590	769	942
Urban	905	194	442	657

Table 3 Allow child to be vaccinated against malaria (No)

Attributes	Educational attainment		Awareness of malaria vaccine	
Residence	Some form of education	No education	Yes	No
Rural	85	38	38	85
Urban	67	4	18	53

awareness of malaria vaccinations, and place of residence, respectively. The study investigates the relationships between a woman's education level, awareness of the malaria vaccine, and place of residence, and assesses how these factors influence willingness to have her child vaccinated.

The partitioning of the population based on responses to the yes-or-no question 'Would you allow your child to be vaccinated against malaria?' is depicted in Tables 2 and 3, along with their socio-economic characteristics and awareness of malaria vaccine. Attributes λ_g^1, λ_g^2, and λ_g^3, representing educational attainment, awareness of malaria vaccine, and place of residence, respectively, will be calculated for each subgroup within the eight scenarios presented in Table 4. The assigned values for these attributes across the eight scenarios demonstrate their relative importance to the private incentive component of the utility function. For instance, in case 1, being a female from a rural area does not contribute to the private incentive of a group, whereas being a female from an urban area does contribute to a group's private incentive.

Tables 2 and 3 summarize the vaccination choices and residential status of the 3,004 women surveyed in the 2019 Ghana Malaria Indicator Survey (GMIS). Among these participants, 93.54% preferred to vaccinate their children against malaria, while 6.45% did not. A breakdown of vaccination decisions by education and residence revealed notable patterns. Among those who chose to vaccinate, 72.10% were educated and 27.90% were uneducated. Additionally, 43.10% were aware of the malaria vaccine, while 56.90% lacked prior awareness. Within this group, 39.89% were educated rural women, 32.21% were educated urban women, 21.00% were uneducated rural women, and 6.90% were uneducated urban women.

Conversely, among those who declined vaccination, 78.35% were educated and 21.65% were uneducated. Interestingly, only 28.87% of these women were aware of the malaria vaccine, while 71.13% were unaware. In terms of subgroup composition, 43.81% were educated rural women, 34.54% were educated urban women, 19.59% were uneducated rural women, and 2.06% were uneducated urban women.

Non interacting case

Whether the group decides to permit their children to receive a malaria vaccination depends on the sum of the individual private incentives, α_j. If the total is positive, the decision will be YES; if it is negative, the decision will be NO. Table 5 presents the estimated coefficients for the non-interacting model, representing the sum of private incentives ($\sum \alpha_j$) across different subgroups defined by education, residence, and awareness of the malaria vaccine. The results indicate that females with no education in urban areas exhibit the highest combined private incentives

Table 4 Attributes of the population

Case	Educational attainment (λ_g^1)		Vaccination awareness (λ_g^2)		Residence (λ_g^3)	
	No education	Some education	Yes	No	Urban	Rural
1	0	1	1	0	1	0
2	1	0	0	1	1	0
3	0	1	0	1	0	1
4	1	0	1	0	0	1
5	0	1	1	0	1	0
6	1	0	0	1	1	0
7	0	1	0	1	0	1
8	1	0	1	0	0	1

Table 5 Estimates for the non-interacting model (with sum of private.incentives)

Case	α_1	α_2	α_3	α_0	$\sum \alpha_j$
1. Females with some education in rural	0.0162	– 0.0858	0.0295	0.2399	0.1998
2. Females with no education in rural	0.1145	– 0.0065	0.0099	0.1635	0.2814
3. Females with some education in urban	0.0383	– 0.1022	0.0613	0.2082	0.2056
4. Females with no education in urban	0.1170	0.0351	0.0939	0.1350	0.3810
5. Awareness of vaccine in rural	– 0.1247	0.1254	– 0.0036	0.2074	0.2045
6. Not aware of vaccine in rural	– 0.0431	0.0461	– 0.1771	0.2828	0.1087
7. Awareness of vaccine in urban	– 0.1244	0.0561	– 0.0492	0.2608	0.1433
8. Not aware of vaccine in urban	– 0.0060	– 0.0940	– 0.1504	0.3231	0.0727

Table 6 Interaction matrix $\hat{Y}_{gg'}$ for the multi-population Curie–Weiss model

Group $g \backslash g'$	1	2	3	4	5	6	7	8
1. Rural, Some Education	– 0.0414	– 0.0221	– 0.0335	– 0.0076	– 0.0292	– 0.0343	– 0.0170	– 0.0242
2. Rural, No Education	0.1325	0.0706	0.1072	0.0243	0.0935	0.1096	0.0542	0.0772
3. Urban, Some Education	– 0.0893	– 0.0476	– 0.0723	– 0.0164	– 0.0630	– 0.0739	– 0.0366	– 0.0521
4. Urban, No Education	– 0.1450	– 0.0772	– 0.1173	– 0.0266	– 0.1023	– 0.1199	– 0.0593	– 0.0845
5. Rural, Aware of Vaccine	0.0469	0.0250	0.0379	0.0086	0.0331	0.0388	0.0192	0.0273
6. Rural, Not aware of Vaccine	0.1556	0.0829	0.1259	0.0285	0.1098	0.1287	0.0637	0.0907
7. Urban, Aware of Vaccine	– 0.1253	– 0.0668	– 0.1014	– 0.0230	– 0.0884	– 0.1037	– 0.0513	– 0.0731
8. Urban, Not aware of Vaccine	– 0.1100	– 0.0586	– 0.0889	– 0.0202	– 0.0776	– 0.0910	– 0.0450	– 0.0641

Positive values indicate imitation (groups tend to make the same decision), while negative values indicate divergence

(0.3810), followed by females with no education in rural areas (0.2814). In contrast, the lowest private incentives are observed among urban females who are not aware of the vaccine (0.0727), suggesting that lack of awareness substantially reduces the propensity to vaccinate regardless of residence. Interestingly, while education appears to enhance incentives in rural areas (0.1998 vs. 0.2814 for some vs. no education), the opposite is observed in urban settings, where the educated group records a lower sum of incentives (0.2056) compared to their non-educated counterparts (0.3810). Similarly, awareness plays a stronger role in rural settings (0.2045 vs. 0.1087) than in urban settings (0.1433 vs. 0.0727). Overall, these findings highlight the complex interaction between education, residence, and awareness in shaping private incentives for malaria vaccination. In each of the eight cases, the base private incentive α_0 is positive, which suggests that women would be inclined to agree to their children receiving a malaria vaccination.

Interacting case

In the interactive model, the utility function considers both private and social incentives. When the social incentive, denoted as $\hat{Y_{gg'}}$ for groups g and g', is positive, individuals within these groups are more likely to emulate each other's choices. Conversely, if $\hat{Y_{gg'}}$ is negative, women in these groups tend to make different choices rather than conform. The decision to vaccinate one's child against malaria depends on the total private incentives, represented by α_j. A positive sum of α_j leads the group to favour vaccination for their children, whereas a negative sum results in the group opting not to vaccinate their children against malaria.

Note that $\hat{Y_{11}}$ indicates the interaction strength among females in rural areas with some level of education when they interact with each other. As illustrated in Table 6, the estimated value of $\hat{Y_{11}}$ is negative, which suggests that imitation is perceived as not beneficial in this group. In contrast, $\hat{Y_{55}}$ signifies the interaction strength among females who have aware of the malaria vaccine residing in rural areas. A positive value for $\hat{Y_{55}}$ implies that in this group, imitation is regarded as favourable. The study further suggests that rural females with no education exert a greater influence on their rural counterparts with some form of education when social interaction is incorporated, as indicated by the positive value of $\hat{Y_{21}}$.

Table 6 shows that residence has no relationship with the decision-making of Ghanaian females regarding the vaccination of their children against malaria, as indicated by the negative value of α_3. However, the positive values

Table 7 Variance of $\bar{m}_g$ and U_g explained by the latent vectors and RMSEP for Ghana

Latent vectors	Percentage of explained variances for $\bar{m}_g$	Cumulative percentage of explained variances for $\bar{m}_g$	Percentage of explained variances for U_g	Cumulative percentage of explained variances for U_g	RMSEP for $\bar{m}_g$	RMSEP for U_g
1	34.98	34.98	77.53	77.53	0.9794	0.0883
2	15.33	50.31	16.99	94.52	0.7897	0.0412
3	20.31	70.62	5.46	99.98	0.6904	0.0200
4	12.36	82.98	12.36	99.90	0.5308	0
5	5.68	88.66	0.00	99.90	0.4041	0

of α_1 and α_2 imply that their awareness of the malaria vaccine and their educational attainment are related to their decision to vaccinate their children against malaria. Furthermore, the coefficient α_0 is zero, suggesting that in interactive scenarios, females do not consider their educational level, awareness of the malaria vaccine, or residence as influencing factors in the vaccination decision.

Model diagnostics and validation

In this section, the fit of the interaction model to the data is evaluated. To determine the parameters of the interaction model described in [38], the partial least squares (PLS) method was employed. In the model, U_g represents the dependent variable, while $\bar{m}_g$ represents the independent variable. PLS predicts a set of dependent variables by analysing a set of independent variables (predictors) and constructing orthogonal factors, referred to as latent vectors, from these predictors. These latent vectors are ranked according to their eigenvalues in descending order. The selection of latent vectors is based on their ability to optimally explain the covariance between the independent and dependent variables [39].

Analyses were performed using MATLAB software version R2016a to generate the results. As shown in Table 7, the first five latent vectors explain 99.90% of the variance in U_g and 88.66% of the variance in $\bar{m}_g$, indicating that the model adequately accounts for the variance in both the dependent and independent variables for modelling or prediction purposes. Additionally, the root mean square error of prediction (RMSEP) decreases with an increasing number of latent vectors for both $\bar{m}_g$ and U_g.

Discussion

This study provides essential insights into factors associated with malaria vaccination decisions among women in Ghana, focusing on socio-economic status and awareness about the malaria vaccine. An analysis of data from the 2019 Ghana Malaria Indicator Survey (GMIS) reveals a relationship among educational attainment, awareness of the malaria vaccine, and place of residence in vaccination decision-making. Women with higher education and those residing in urban areas showed greater vaccine acceptance rates, aligning with previous studies linking education to health-enhancing behaviours, including immunization uptake [40–42].

Social influence plays a role in vaccination decisions, particularly among uneducated women in rural areas, who in turn affect the decisions of their educated counterparts living in the same communities. This suggests that community-driven health campaigns could be especially effective in rural Ghana by using community leaders and local networks to raise awareness [20, 43, 44]. Interestingly, urban women with some level of education did not exhibit a significant imitative effect, implying that vaccination decisions in these populations may be shaped more by individual factors, such as media exposure and access to health services, than by social influence. This contrast between urban and rural settings is consistent with findings from similar studies in Sub-Saharan Africa, where community influence tends to be stronger in rural areas due to closer social ties and established leadership structures [45, 46].

The model indicates that awareness may function as an intermediate variable transmitting the effects of structural factors, such as education and residence, to vaccination decisions. For instance, educated urban women are more likely to be aware of vaccination campaigns, and this awareness subsequently drives the positive private incentive toward vaccine acceptance. These findings suggest that awareness not only directly influences vaccination decisions but also mediates the relationship between socio-economic status and collective behaviour, consistent with observations in behavioural epidemiology.

Policy implications and comparative perspectives

The findings highlight several policy implications. Education-centred initiatives may significantly improve vaccine uptake, as evidenced by programs in other regions of Africa with similar social structures [44]. Policies that provide educational access and community-based

information dissemination could amplify vaccine acceptance rates. These policies should consider unique factors that influence rural and urban populations differently, potentially tailoring approaches for each context. Furthermore, it is essential to involve local leaders and prominent members of the community in health initiatives, particularly in rural settings where social influence plays a significant role. Comparable strategies employed in malaria-endemic regions such as Kenya and Malawi have proven effective in utilizing community influence to enhance awareness and acceptance of vaccines [47, 48]. Future research should build upon these findings by exploring social interactions and information dissemination methods that are most effective in urban versus rural settings. Additionally, longitudinal studies could help to better establish the causality between socio-economic factors and vaccination decisions; this would provide a stronger basis for targeted health interventions.

Conclusion

This study explored how education, residence, and awareness of the malaria vaccine relate to Ghanaian women's decisions to vaccinate their children, applying the multi-population Curie-Weiss statistical mechanics model to data from the 2019 Ghana Malaria Indicator Survey. In the non-interactive setting, educational attainment, vaccine awareness, and residence were each associated with vaccination choices. When social influence was considered, awareness and education continued to show associations, although the direction and strength of these associations varied. For instance, rural women without formal education appeared to influence the decisions of their educated rural peers, whereas urban women with some education showed little evidence of such influence. These patterns suggest that community-based approaches in rural areas may have potential to encourage vaccine uptake, although further evidence is required before making policy recommendations.

While the results highlight meaningful patterns, this study is limited by its use of cross-sectional, self-reported data, which restricts causal inference and may introduce recall or social desirability bias. The multi-population Curie-Weiss model simplifies complex decision-making processes into binary choices and assumes uniform social interactions within groups, which may not fully capture real-world behavioural variability. Additionally, some potentially influential factors, such as cultural beliefs and household income, were not included in the analysis.

For future research, developing a more comprehensive understanding of the role of community dynamics in health decisions will be crucial for creating effective malaria vaccination policies. This work adds to the growing body of research on malaria vaccination acceptance and provides practical insights that may inform public health initiatives aimed at reducing malaria through increased vaccination coverage among children under five.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12936-025-05613-1.

Supplementary Material 1.

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Author contributions
R.K.A.: Conceptualization, methodology, formal analysis, writing-original draft preparation, and project administration. S.T.: Investigation, data curation, and writing-review and editing. K.A.A.: Methodology, visualization, and validation. K.T.: Software development, data curation, and validation. B.A.D.: Investigation and data analysis. S.T.A.: Writing-review and editing, and supervision. R.A.T.: Writing-review and editing and resources. M.O.A.: Supervision, review, and final manuscript revision.

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Data availability
The dataset used in this study is included in the supplementary file.

Declarations

Ethics approval and consent to participate
This study is based on publicly available, de-identified secondary data obtained from the Demographic and Health Surveys (DHS) program. Ethical approval for the original data collection was obtained by the institutions responsible for the surveys. As this study involved analysis of secondary data without any identifiable human subjects, no further ethical approval was required.

Consent for publication
Not applicable. The study used secondary data, and no direct involvement of human participants occurred during the analysis.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Mathematics and Statistics, University of Energy and Natural Resources, Sunyani, Ghana. [2]Department of Mathematics, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. [3]Department of Statistics and Actuarial Science, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. [4]Department of Nursing, University of Energy and Natural Resources, Sunyani, Ghana.

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References

1. World Health Organization. State of inequality: childhood immunization. Geneva: World Health Organization; 2016.
2. Touray E, Barrow A, Kinteh B, Badjie M, Nget M, Touray J, et al. Childhood vaccination uptake and associated factors among children 12–23 months in rural settings of the Gambia: a community-based cross-sectional study. BMC Public Health. 2021;21:1740.
3. World Health Organization. WHO guide for standardization of economic evaluations of immunization programmes. Geneva: World Health Organization; 2019.
4. Chan M. The contribution of immunization: saving millions of lives, and more. Public Health Rep. 2014;129:7–8.
5. Ehreth J. The value of vaccination: a global perspective. Vaccine. 2003;21:4105–17.
6. United Nations Inter-agency Group for Child Mortality Estimation. Levels & trends in child mortality: report 2019, estimates developed by the United Nations Inter-agency Group for Child Mortality Estimation. 2019. https://www.unicef.org/media/79371/file/UN-IGME-child-mortality-report-2020.pdf.
7. WHO. Regional strategic plan for immunization 2014–2020. Brazzaville: World Health Organization Regional Office for Africa; 2015.
8. Ghana Statistical Service, ORC Macro. Ghana Demographic and Health Survey 2008. Accra: Ghana Statistical Service. 2009.
9. Ghana Statistical Service (GSS), Ghana Health Service (GHS), ICF International. Ghana Demographic and Health Survey 2014. Rockville: GSS, GHS, and ICF International. 2015.
10. Harris VC, Armah G, Fuentes S, Korpela KE, Parashar U, Victor JC, et al. Significant correlation between the infant gut microbiome and rotavirus vaccine response in rural Ghana. J Infect Dis. 2017;215:34–41.
11. Willyard C. The slow roll-out of the world's first malaria vaccine. Nature. 2022;612:48–9.
12. Centers for Disease Control and Prevention. CDC-Malaria-Malaria Worldwide-how can malaria cases and deaths be reduced. Insecticide-Treated Bed Nets. 2021.
13. Datoo MS, Natama MH, Somé A, Traoré O, Rouamba T, Bellamy D, et al. Efficacy of a low-dose candidate malaria vaccine, R21 in adjuvant Matrix-M, with seasonal administration to children in Burkina Faso: a randomised controlled trial. Lancet. 2021;397:1809–18.
14. Datoo MS, Dicko A, Tinto H, Ouédraogo JB, Hamaluba M, Olotu A, et al. Safety and efficacy of malaria vaccine candidate R21/Matrix-M in African children: a multicentre, double-blind, randomised, phase 3 trial. Lancet. 2024;403:533–44.
15. World Health Organization. WHO recommends R21/Matrix-M vaccine for malaria prevention in updated advice on immunization. Geneva: World Health Organization; 2023.
16. Ministry of Health. Ghana has expanded the malaria vaccine exercise. Accra: Ministry of Health; c2024. 2024. https://www.moh.gov.gh/ghana-has-expanded-the-malaria-vaccine-exercise/.
17. Saaka SA, Mohammed K, Pienaah CA, Luginaah I. Child malaria vaccine uptake in Ghana: factors influencing parents' willingness to allow vaccination of their children under five years. PLoS One. 2024;19:e0296934.
18. Grant J, Gyan T, Agbokey F, Webster J, Greenwood B, Asante KP. Challenges and lessons learned during the planning and early implementation of the RTS, S/AS01E malaria vaccine in three regions of Ghana: a qualitative study. Malar J. 2022;21:147.
19. Bam V, Mohammed A, Kusi-Amponsah A, Armah J, Lomotey AY, Budu HI, et al. Caregivers' perception and acceptance of malaria vaccine for children. PLoS One. 2023;18:e0288686.
20. Tabiri D, Ouédraogo JC, Nortey PA. Factors associated with malaria vaccine uptake in Sunyani Municipality. Ghana Malar J. 2021;20:1–8.
21. Brock WA, Durlauf SN. Discrete choice with social interactions. Rev Econ Stud. 2001;68:235–60.
22. Durlauf SN. How can statistical mechanics contribute to social science? Proc Natl Acad Sci U S A. 1999;96:10582–4.
23. Brock W, Durlauf SN. Discrete choice with social interactions I: theory. J Econ Behav Organ. 2001;46:1–25.
24. Ermentrout B, Terman DH. Mathematical foundations of neuroscience. New York: Springer; 2010.
25. Turchin P, Taylor AD. Complex dynamics in ecological time series. Ecology. 1992;73:289–305.
26. Kuran T. Now out of never: the element of surprise in the East European revolution of 1989. World Polit. 1991;44:7–48.
27. Gallo I. An equilibrium approach to modelling social interaction. arXiv 2009;arXiv:0907.2561.
28. Opoku AA, Osabutey G, Kwofie C. Parameter evaluation for a statistical mechanical model for binary choice with social interaction. J Probab Stat. 2019. https://doi.org/10.1142/S0218202509003863.
29. Ansah RK, Tackie S, Twum RA, Tawiah K, Boadi RK, Addo DA, et al. The relationship between Anaemia and the use of treated bed nets among pregnant and non-pregnant women in Ghana. PLoS One. 2024;19:e0300431.
30. Burioni R, Contucci P, Fedele M, Vernia C, Vezzani A. Enhancing participation to health screening campaigns by group interactions. Sci Rep. 2015;5:9904.
31. Osabutey G, Opoku AA, Gyamfi S. A statistical mechanics approach to the study of energy use behaviour. J Appl Math. 2020;2020:1–4.
32. Thompson CJ. Mathematical statistical mechanics. New Jersey: Princeton University Press; 2015.
33. Selinger JV. Introduction to the theory of soft matter: from ideal gases to liquid crystals. Berlin: Springer International Publishing; 2016.
34. Measure DH. The DHS program: demographic and health surveys. Rockville: ICF Macro; 2016.
35. Bangura JB, Xiao S, Qiu D, Ouyang F, Chen L. Barriers to childhood immunization in sub-Saharan Africa: a systematic review. BMC Public Health. 2020;20:1108.
36. Ameyaw EK, Kareem YO, Ahinkorah BO, Seidu AA, Yaya S. Decomposing the rural-urban gap in factors associated with childhood immunisation in sub-Saharan Africa: evidence from surveys in 23 countries. BMJ Glob Health. 2021. https://doi.org/10.1136/bmjgh-2020-003773.
37. Yeboah D, Boah M, Adokiya MN. Caregivers' use of insecticide-treated nets is associated with the use of ITNs by children under the age of five in Ghana. PLoS One. 2023;18:e0280065.
38. Contucci P, Gallo IA. Bipartite mean field spin systems. Exist Solut MPEJ. 2008;14:1–22.
39. Abdi H. Partial least squares regression and projection on latent structure regression (PLS Regression). Wiley Interdiscip Rev Comput Stat. 2010;2:97–106.
40. Nyalundja AD, Bugeme PM, Guillaume AS, Ntaboba AB, Hatu'm VU, Tamuzi JL, et al. Socio-demographic factors influencing malaria vaccine acceptance for under-five children in a malaria-endemic region: a community-based study in the Democratic Republic of Congo. Vaccines. 2024;12:380.
41. Harris VC, Armah G, Fuentes S, Korpela KE, Parashar U, Victor JC, et al. Significant correlation between the infant gut microbiome and rotavirus vaccine response in rural Ghana. J Infect Dis. 2017;215:34–41.
42. Ehreth J. The value of vaccination: a global perspective. Vaccine. 2003;21:4105–17.
43. Saaka SA, Mohammed K, Pienaah KA, Luginaah I. Child malaria vaccine uptake in Ghana: factors influencing parents' willingness to allow vaccination of their children under five years. PLoS One. 2024;19:e0296934.
44. Nyalundja AD, Bugeme PM, Guillaume AS, Ntaboba AB, Hatu'm VU, Tamuzi JL, et al. Socio-demographic factors influencing malaria vaccine acceptance for under-five children in a malaria-endemic region: a community-based study in the Democratic Republic of Congo. Vaccines. 2024;12:380.
45. Adoma PO, Acquah F, Yakubu A, Cudjoe L, Achiam WK, Agorinya IA. Community engagement in promoting malaria vaccine uptake for children under five. Sci Rep. 2025;15(1):26711.
46. Saaka SA, Mohammed K, Pienaah KA, Luginaah I. Child malaria vaccine uptake in Ghana: factors influencing parents' willingness to allow vaccination of their children under five years. PLoS One. 2024;19:e0296934.
47. CDC. Malaria-Malaria worldwide-how can malaria cases and deaths be reduced? Insecticide-treated bed nets. 2021. https://www.cdc.gov/malaria/malaria_worldwide/itn.html.
48. Willyard C. The slow roll-out of the world's first malaria vaccine. Nature. 2022;612:48–9.

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