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Agent-Based Modelling of Vaccine Hesitancy and Public Trust: Special Reference to West Bengal, India

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ABSTRACT: Vaccine hesitancy has emerged as one of the most pressing public health challenges in the twenty-first century, particularly in the aftermath of the COVID-19 pandemic. While immunisation programmes have substantially reduced morbidity and mortality worldwide, varying levels of public trust, misinformation, social influence, and institutional credibility continue to shape vaccination behaviour. In West Bengal, diverse socio-economic conditions, cultural heterogeneity, rural-urban disparities, and differential access to healthcare create complex patterns of vaccine acceptance and refusal. Traditional epidemiological models often fail to capture these behavioural and social dynamics because they treat populations as homogeneous groups. Agent-Based Modelling (ABM) offers an alternative computational framework by representing individuals as autonomous agents whose decisions evolve through interactions within social networks.

This study proposes a sociologically informed ABM to analyse vaccine hesitancy and public trust in West Bengal. The model integrates sociological theories of social capital, risk perception, institutional trust, and social influence with computational simulation techniques. Five principal determinants are incorporated into the model: institutional trust, misinformation exposure, peer influence, perceived vaccine safety, and healthcare accessibility. Each agent updates its vaccination decision dynamically based on interactions with neighbouring agents and changing information environments. The study also introduces a Public Trust–Vaccine Hesitancy Index (PTVHI) to quantify the combined effects of trust and misinformation on vaccine uptake. The empirical framework is designed around a synthetic dataset of 2,000 respondents representing different districts of West Bengal, enabling advanced statistical analyses including Structural Equation Modelling (SEM), logistic regression, and network analysis alongside simulation experiments.

The findings are expected to demonstrate that institutional trust functions as a protective factor against misinformation, while strong social networks can either reinforce vaccine acceptance or amplify hesitancy depending on prevailing community norms. The proposed model contributes to mathematical sociology by integrating behavioural decision-making, computational simulation, and public health governance into a unified analytical framework. It further provides evidence-based policy recommendations for improving vaccination campaigns, strengthening public trust, and promoting equitable healthcare delivery in India and other developing regions.

1. INTRODUCTION

Vaccination remains one of the most successful public health interventions in modern history, preventing millions of deaths annually and significantly reducing the burden of infectious diseases. Despite the availability of safe and effective vaccines, vaccine hesitancy has become a persistent global concern. The World Health Organization has identified vaccine hesitancy as one of the major threats to global health because delays in vaccine acceptance weaken herd immunity, increase disease transmission, and reduce the effectiveness of national immunization programmes.

The experience of the COVID-19 pandemic demonstrated that vaccination behaviour is shaped not only by medical evidence but also by social trust, cultural beliefs, political communication, misinformation, and community interactions. Across many countries, rapid dissemination of false information through digital platforms, coupled with declining trust in institutions, influenced public perceptions regarding vaccine safety and effectiveness. Consequently, understanding vaccination decisions requires a multidisciplinary approach that incorporates sociological, behavioural, computational, and epidemiological perspectives.

In India, one of the world's largest immunization programmes serves a highly heterogeneous population characterized by substantial socio-economic, cultural, linguistic, and geographical diversity. While national vaccination coverage has improved considerably, regional disparities remain. West Bengal presents a particularly interesting context for investigating vaccine hesitancy because it combines densely populated metropolitan regions, rapidly growing peri-urban settlements, and geographically isolated rural communities. Variations in education, income, healthcare accessibility, digital literacy, and trust in governmental institutions contribute to differences in vaccine acceptance across districts.

Conventional epidemiological models, including compartmental models such as SIR and SEIR, primarily focus on biological transmission mechanisms and generally assume homogeneous population behaviour. Although these models are valuable for forecasting disease spread, they are less capable of representing dynamic behavioural processes, interpersonal influence, and feedback between individuals and institutions. Vaccination decisions are inherently social: people observe the experiences of family members, friends, neighbours, community leaders, and healthcare workers before deciding whether to vaccinate. These micro-level interactions collectively generate macro-level vaccination patterns.

Agent-Based Modelling (ABM) addresses this limitation by representing society as a system of autonomous individuals whose behaviour changes through repeated interactions within social networks. Each agent possesses distinct characteristics—including age, education, income, trust, media exposure, and health beliefs—and updates decisions according to behavioural rules. Through simulation, ABM captures emergent social phenomena that cannot easily be represented using aggregate statistical models. This makes ABM particularly suitable for analysing vaccine hesitancy as a socially embedded process.

From a sociological perspective, public trust is a central determinant of vaccine acceptance. Trust in government institutions, healthcare professionals, scientific expertise, and local community organizations influences individuals' willingness to accept public health recommendations. Conversely, exposure to misinformation, conspiracy narratives, and polarized communication environments can erode trust and reinforce vaccine resistance. Social influence further moderates these effects because individuals often align their behaviour with prevailing norms within their social networks.

2.1 Vaccine Hesitancy: Global and Indian Perspectives

Vaccine hesitancy is defined as the delay in acceptance or refusal of vaccination despite the availability of vaccination services. Unlike complete vaccine refusal, vaccine hesitancy represents a spectrum of attitudes ranging from uncertainty and postponement to selective acceptance or rejection of specific vaccines. The concept gained global recognition when the World Health Organization Strategic Advisory Group of Experts (SAGE) on Immunization identified vaccine hesitancy as one of the major threats to global health, emphasizing that it is context-specific, varying across time, place, and vaccine type (MacDonald, 2015). Vaccine hesitancy is therefore understood not merely as an individual choice but as a multidimensional socio-behavioural phenomenon shaped by institutional trust, social relationships, information environments, cultural beliefs, political contexts, and healthcare accessibility (Larson et al., 2014).

Initially, vaccine decision-making was explained primarily through rational-choice perspectives, assuming that individuals assessed the risks and benefits of vaccination independently. However, subsequent research demonstrated that vaccination behaviour is embedded within complex social systems where trust, social norms, misinformation, historical experiences, and institutional credibility strongly influence decision-making (Betsch et al., 2018). The COVID-19 pandemic further reinforced this understanding by illustrating how public confidence in governments, scientific institutions, healthcare professionals, and media ecosystems significantly affected vaccine acceptance across countries (Troiano & Nardi, 2021).

One of the earliest conceptual frameworks explaining vaccine hesitancy was the **3Cs model**, proposed by the WHO SAGE Working Group. The model identifies three principal determinants: **confidence**, **complacency**, and **convenience** (MacDonald, 2015). Confidence refers to trust in vaccine safety and effectiveness, healthcare providers, policymakers, and public health institutions. Complacency occurs when individuals perceive vaccine-preventable diseases as low-risk, reducing the perceived necessity of vaccination. Convenience encompasses affordability, accessibility, geographical availability, quality of healthcare services, and ease of obtaining vaccination.

Although the 3Cs model provided an effective conceptual foundation, researchers argued that it did not sufficiently capture the broader psychological and social dimensions influencing vaccination behaviour. Consequently, the framework evolved into the **5Cs model**, incorporating two additional dimensions: **constraints** and **collective responsibility** (Betsch et al., 2018). Constraints refer to psychological or structural barriers such as limited time, transportation difficulties, bureaucratic obstacles, and low health literacy that prevent vaccination even when positive attitudes exist. Collective responsibility reflects individuals' willingness to vaccinate to protect vulnerable populations through herd immunity, highlighting the importance of social solidarity and civic responsibility.

The evolution from the 3Cs to the 5Cs framework illustrates the growing recognition that vaccine hesitancy cannot be reduced to a binary decision of acceptance or refusal. Instead, individuals occupy different positions along a behavioural continuum influenced by changing social circumstances, evolving information, and interactions with trusted institutions (Brewer et al., 2017). People's vaccination decisions may change over time as new scientific evidence emerges, social networks evolve, or public trust increases or declines. Consequently, contemporary public health research increasingly conceptualizes vaccine hesitancy as a dynamic and adaptive process rather than a fixed personal characteristic.

Determinants: Confidence, Complacency, and Convenience

Confidence remains the most influential determinant of vaccine acceptance because it reflects trust in vaccines themselves, healthcare professionals administering them, scientific expertise, pharmaceutical manufacturers, and governmental health agencies. High institutional confidence reduces uncertainty regarding vaccine safety and efficacy, whereas declining trust often creates opportunities for misinformation and conspiracy narratives to flourish (Larson et al., 2018). During health emergencies, transparent communication, scientific consistency, and effective risk communication become essential for maintaining confidence.

Complacency refers to individuals' perceptions regarding the severity and susceptibility of infectious diseases. When vaccine-preventable diseases become relatively rare because of successful immunization programmes, many individuals underestimate their risks, reducing motivation to vaccinate (Dubé et al., 2013). This paradox illustrates how successful vaccination campaigns may unintentionally contribute to complacency by making diseases less visible within communities.

Convenience encompasses the practical aspects of obtaining vaccination, including physical accessibility, affordability, healthcare infrastructure, clinic operating hours, transportation, vaccine availability, and administrative simplicity. Even individuals with positive attitudes toward vaccination may delay immunization when healthcare services are difficult to access or impose excessive financial and logistical burdens (MacDonald, 2015). These three determinants rarely operate independently;

instead, they interact with education, socioeconomic status, cultural beliefs, gender, digital literacy, and communication environments to produce diverse vaccination outcomes across different populations.

Evidence from India and West Bengal

Research conducted in India demonstrates substantial regional variation in vaccine uptake, reflecting differences in healthcare infrastructure, educational attainment, socioeconomic inequality, institutional trust, cultural practices, and exposure to misinformation (Srinivasan et al., 2021). National immunization programmes have substantially improved childhood vaccination coverage; however, disparities persist across states, districts, and marginalized communities. Studies have shown that maternal education, household income, accessibility of primary healthcare facilities, and trust in frontline healthcare workers significantly influence vaccination behaviour (International Institute for Population Sciences [IIPS] & ICF, 2021).

Digital misinformation has increasingly emerged as an important determinant of vaccine hesitancy in India, particularly during the COVID-19 vaccination campaign, where misleading information circulated rapidly through social media platforms and messaging applications (Islam et al., 2021). Simultaneously, community engagement by healthcare workers, local leaders, and civil society organizations has demonstrated considerable effectiveness in countering misinformation and improving vaccine acceptance.

West Bengal provides an especially valuable empirical setting for studying vaccine hesitancy because it contains highly diverse metropolitan, peri-urban, semi-urban, and rural populations characterized by varying levels of institutional trust, healthcare accessibility, educational attainment, and digital connectivity. Urban centres such as Kolkata exhibit relatively advanced healthcare infrastructure and greater access to health information, whereas several rural and geographically isolated districts continue to experience healthcare inequalities and differential access to vaccination services. Moreover, the coexistence of multiple linguistic, religious, and cultural communities makes West Bengal an appropriate setting for examining behavioural heterogeneity in vaccination decisions. These regional variations provide opportunities to investigate how institutional trust, misinformation exposure, healthcare accessibility, and social influence interact to shape vaccine acceptance across diverse social contexts. Consequently, district-level investigations in West Bengal can contribute important empirical evidence that complements national studies while generating context-specific insights for designing more effective public health interventions and vaccination policies.

2.2 Public Trust and Vaccination Behaviour

Trust is a multidimensional sociological construct that reflects individuals' expectations regarding the competence, integrity, fairness, and reliability of institutions and social actors. In the context of public health, trust plays a fundamental role in shaping citizens' willingness to follow health recommendations, particularly during infectious disease outbreaks and vaccination campaigns. Sociologists argue that trust functions as a form of social capital that reduces uncertainty and facilitates cooperation in situations where individuals cannot independently verify scientific evidence (Putnam, 2000). Similarly, institutional theorists emphasize that trust strengthens social cohesion by enhancing the legitimacy of public institutions and encouraging compliance with collective decisions (Giddens, 1990).

Institutional trust can be differentiated into several dimensions. **Trust in government agencies** refers to confidence that political authorities make decisions in the public interest and manage health crises effectively. Governments responsible for vaccination policies must demonstrate competence, transparency, and accountability to maintain public confidence. During public health emergencies, inconsistent policies or political controversies may reduce institutional legitimacy and weaken citizens' willingness to accept vaccination (Siegrist & Zingg, 2014).

Trust in healthcare professionals represents confidence in physicians, nurses, pharmacists, and frontline healthcare workers who directly communicate vaccine-related information. Healthcare professionals are often regarded as the most credible sources of health information because they possess professional expertise and maintain personal relationships with patients. Numerous studies indicate that physician recommendations significantly increase vaccine acceptance, particularly among hesitant populations (Larson et al., 2018).

A third dimension involves **trust in scientific institutions**, including research organizations, universities, public laboratories, and regulatory agencies responsible for vaccine development and evaluation. Scientific trust depends on perceptions of competence, independence, and adherence to ethical standards. Confidence in scientific institutions becomes particularly important when vaccines are developed rapidly, as observed during the COVID-19 pandemic. Individuals who perceive scientific institutions as credible are generally more likely to accept vaccination despite uncertainty regarding newly developed vaccines (WHO, 2022).

Finally, **trust in public health systems** encompasses confidence in healthcare infrastructure, vaccination programmes, disease surveillance systems, and emergency preparedness mechanisms. Effective public health systems demonstrate organizational competence through efficient vaccine distribution, equitable access, and timely communication. Institutional credibility encourages citizens to perceive vaccination campaigns as legitimate public health interventions rather than politically motivated activities (Gilson, 2003).

Institutional credibility substantially influences compliance with vaccination campaigns because individuals frequently rely on trusted institutions when making decisions under uncertainty. Vaccination involves perceived risks and benefits that cannot be directly evaluated by most citizens, making trust an important heuristic for decision-making. Transparent communication regarding vaccine development, effectiveness, possible side effects, and policy decisions reduces uncertainty and strengthens institutional credibility during health emergencies (Van der Weerd et al., 2011). Open communication also enhances perceptions of procedural fairness, thereby increasing citizens' willingness to cooperate with public health interventions.

Institutional Trust as a Predictor of Vaccine Acceptance

Extensive empirical research consistently identifies institutional trust as one of the strongest predictors of vaccine acceptance. Individuals expressing higher levels of confidence in governments, healthcare professionals, scientific institutions, and public health agencies generally demonstrate greater willingness to receive recommended vaccinations (Larson et al., 2018). Trust reduces uncertainty by increasing confidence that health authorities act according to scientific evidence and public welfare rather than political or commercial interests.

Conversely, institutional distrust amplifies uncertainty and resistance toward vaccination. When citizens question governmental competence, scientific integrity, or healthcare recommendations, they become more likely to seek alternative information sources that may reinforce vaccine hesitancy. Distrust also increases susceptibility to conspiracy theories and misinformation because official information is viewed as less credible (Freeman et al., 2022).

Institutional trust additionally moderates the effects of misinformation. Individuals who maintain confidence in healthcare professionals and scientific institutions are more likely to critically evaluate misleading information and continue following official recommendations despite exposure to conflicting claims. Thus, trust functions as a protective social mechanism that enhances resilience against misinformation while supporting vaccine acceptance (Siegrist & Zingg, 2014).

2.3 Misinformation and Digital Media

Role of social media in Spreading Misinformation

Digital communication technologies have transformed the dissemination of health information by enabling rapid sharing through social networking platforms, messaging applications, online forums, and video-sharing websites. Although these platforms facilitate public access to scientific information, they also accelerate the circulation of rumours, conspiracy narratives, misleading claims, and unverified medical advice (Cinelli et al., 2020).

Social media algorithms prioritize highly engaging content, irrespective of its scientific accuracy. Consequently, sensational or emotionally charged misinformation often spreads more rapidly than evidence-based information because it generates greater user engagement. Repeated exposure to misleading narratives through algorithmic amplification and social sharing reinforces false beliefs through the "illusory truth effect," whereby repeated statements become increasingly perceived as credible (Pennycook & Rand, 2021).

Digital misinformation ecosystems are further strengthened through online communities that selectively share information confirming existing beliefs while excluding contradictory evidence. Such echo chambers reduce exposure to diverse viewpoints and contribute to increasing polarisation regarding vaccination and public health interventions (Cinelli et al., 2020).

Effects on Risk Perception and Vaccination Intentions

Health misinformation substantially influences individuals' perceptions of vaccine safety, effectiveness, and necessity. Exposure to inaccurate claims regarding adverse effects, infertility, microchips, or government conspiracies increases perceived risks while reducing confidence in vaccine benefits. Consequently, individuals may overestimate vaccine-related harms and underestimate disease severity (Loomba et al., 2021).

Misinformation also undermines confidence in public health authorities by portraying governments, pharmaceutical companies, and scientific organisations as untrustworthy or deceptive. Reduced institutional confidence subsequently contributes to delayed vaccination, selective acceptance, or complete vaccine refusal. These effects are particularly pronounced among populations with limited digital literacy, lower educational attainment, or restricted access to reliable scientific information because individuals may experience greater difficulty distinguishing credible sources from misleading content (WHO, 2022). Therefore, strengthening digital literacy and promoting evidence-based communication represent essential components of contemporary vaccination strategies.

2.4 Social Influence and Network Effects

Peer Influence, Family Norms, and Community Leadership

Vaccination decisions are socially embedded rather than purely individual choices. Individuals frequently consult family members, friends, neighbours, religious leaders, healthcare providers, and respected community members before deciding whether to vaccinate. These interpersonal relationships create social norms that shape perceptions of acceptable behaviour (Betsch et al., 2017).

Family experiences with vaccination often influence subsequent decisions because personal testimonies are perceived as trustworthy and relevant. Similarly, religious leaders, local political representatives, and community influencers can substantially affect vaccination behaviour by endorsing or discouraging immunization campaigns. Positive community endorsement strengthens collective confidence, whereas influential opposition may increase hesitancy and resistance.

Social Contagion and Behavioural Diffusion

Behavioural diffusion describes the spread of attitudes, beliefs, and behaviours through interpersonal interactions within social networks. Individuals frequently imitate trusted contacts when making decisions under uncertainty, producing patterns of social contagion similar to the diffusion of infectious diseases (Centola, 2018).

Consequently, clusters of vaccine acceptance or vaccine hesitancy emerge within communities because socially connected individuals influence one another's decisions. Network characteristics—including density, homophily, and clustering—determine the speed and extent of behavioural diffusion. Understanding these network structures enables policymakers to identify influential individuals who can promote vaccination and strengthen community-wide acceptance.

2.5 Agent-Based Modelling in Public Health

Applications of ABM to Vaccination, Epidemics, and Behavioural Dynamics

Agent-Based Modelling (ABM) is a computational approach that represents individuals as autonomous agents possessing distinct demographic characteristics, behavioural preferences, and decision-making rules. Agents interact with one another and with their environment, allowing researchers to examine how micro-level behaviours generate macro-level social outcomes (Epstein, 2006).

In public health research, ABM has been widely applied to vaccination campaigns, infectious disease transmission, healthcare utilization, behavioural adaptation, and policy evaluation. Vaccination models incorporate heterogeneous agents differing in trust, risk perception, social influence, and exposure to misinformation. Through repeated interactions, researchers can simulate how behavioural responses influence epidemic trajectories and evaluate alternative intervention strategies before implementation (Hunter et al., 2018).

Strengths and Limitations of Existing Models

ABM offers several important strengths. It captures heterogeneous populations, adaptive decision-making, nonlinear interactions, and dynamic social networks that traditional mathematical models often simplify. The approach also enables simulation of complex intervention scenarios involving behavioural change, information diffusion, and policy implementation.

Nevertheless, ABM has important limitations. Model outcomes depend heavily on behavioural assumptions, parameter specification, and calibration procedures. Reliable empirical data are often required to validate behavioural rules and interaction patterns. Furthermore, large-scale simulations may require substantial computational resources, and different modelling assumptions can produce divergent outcomes, highlighting the importance of sensitivity analysis and empirical validation (Macal & North, 2010).

2.6 Mathematical Sociology

Social Network Theory

Social Network Theory examines patterns of relationships among individuals rather than treating social actors as isolated entities. Network characteristics such as **centrality**, **density**, **clustering**, and **tie strength** influence the diffusion of information, formation of trust, and adoption of behaviours. Individuals occupying central network positions often function as influential opinion leaders capable of accelerating vaccine information diffusion, whereas densely connected communities facilitate stronger normative influence (Wasserman & Faust, 1994).

Opinion Dynamics

Opinion dynamics refers to mathematical models describing how individual beliefs evolve through repeated social interactions. Models such as the DeGroot model, bounded-confidence model, and voter model demonstrate that communication, conformity, and interpersonal influence may produce consensus, polarization, or persistent disagreement depending on network structure and interaction rules (Castellano, Fortunato, & Loreto, 2009). In vaccination contexts, these models explain how supportive or hesitant attitudes evolve over time through interpersonal communication.

Complex Adaptive Systems

Mathematical sociology increasingly conceptualizes society as a **complex adaptive system** in which individuals continuously respond to changing environmental conditions while simultaneously influencing one another. Behavioural adaptation, institutional responses, technological innovation, and information exchange interact through nonlinear feedback mechanisms, meaning that small behavioural changes may generate disproportionately large social consequences (Miller & Page, 2007).

Emergent Behaviour in Social Systems

Emergence refers to macro-level social patterns arising from numerous localized interactions among individuals without centralized coordination. Community-wide vaccine acceptance, widespread hesitancy, or rapid behavioural shifts may emerge spontaneously through interpersonal influence, institutional trust, and information diffusion. Agent-based modelling explicitly captures these emergent processes by demonstrating how individual decisions aggregate into collective behavioural outcomes. Consequently, emergence represents a central concept linking mathematical sociology with computational public health research because it explains how complex population-level vaccination patterns originate from decentralized social interactions (Epstein, 2006).

2.7 Research Gap

Summarize the principal gaps your study addresses:

- Most empirical studies analyse national or cross-country datasets rather than district-level dynamics in West Bengal.
- Existing research often examines trust, misinformation, or social influence separately instead of modelling their combined effects.
- Many vaccination studies use conventional statistical methods without integrating sociological theory into computational simulation.
- Few studies combine agent-based modelling with empirical validation using methods such as structural equation modelling, logistic regression, and social network analysis.
- There is limited work developing a composite indicator such as a **Public Trust–Vaccine Hesitancy Index (PTVHI)** to connect sociological concepts with computational modelling.

2.8 Hypotheses

Frame each hypothesis as a proposition to be tested empirically:

- **H1:** Higher institutional trust is associated with greater vaccine uptake.
- **H2:** Greater exposure to misinformation is associated with lower vaccine uptake.
- **H3:** Social influence changes the strength of the relationship between institutional trust and vaccination behaviour.
- **H4:** Perceived vaccine safety explains part of the relationship between institutional trust and vaccine uptake.
- **H5:** Better healthcare accessibility is associated with higher vaccination uptake.
- **H6:** Higher digital literacy is associated with lower susceptibility to misinformation.
- **H7:** Stronger community social capital is associated with higher levels of institutional trust.
- **H8:** The proposed **Public Trust–Vaccine Hesitancy Index (PTVHI)** provides significant explanatory power for predicting vaccination behaviour beyond conventional demographic variables.

3. CONCEPTUAL FRAMEWORK:

3.1 Research Methodology

The present study is grounded in the premise that vaccine uptake is not solely determined by individual health choices but emerges from the interaction of personal characteristics, social relationships, institutional contexts, and the broader information environment. Vaccination behaviour is embedded within complex social systems in which trust, communication networks, community norms, and access to healthcare collectively shape public health decisions. This multidimensional perspective draws upon sociological theories of institutional trust, social capital, social influence, and behavioural diffusion, and integrates them with **Agent-Based Modelling (ABM)** to simulate vaccination dynamics across heterogeneous populations. ABM is particularly suitable because it captures how individual-level decisions generate collective behavioural patterns through repeated social interactions (Epstein, 2006; Gilbert & Troitzsch, 2005).

Institutional trust constitutes the primary independent variable because confidence in governments, healthcare institutions, scientific experts, and vaccination programmes substantially influences individuals' willingness to accept vaccines (Gilson, 2003; Larson et al., 2018). High levels of institutional trust increase compliance with public health recommendations, whereas distrust may amplify scepticism and hesitancy, particularly during periods of uncertainty.

Misinformation exposure is incorporated as a second independent variable because digital media ecosystems have become major channels for the rapid dissemination of vaccine-related rumours and conspiracy theories. Exposure to misleading information weakens confidence in vaccine safety, increases perceived risks, and contributes significantly to vaccine hesitancy (WHO, 2022; Roozenbeek et al., 2020). The rapid spread of misinformation during the COVID-19 pandemic demonstrated how online communication can alter public perceptions of scientific evidence.

Healthcare accessibility is another critical determinant because vaccine acceptance is influenced not only by attitudes but also by the availability and accessibility of healthcare services. Geographic proximity to health facilities, affordability, transportation, and service quality affect whether individuals are able to receive recommended vaccinations (Andersen, 1995). Individuals with positive attitudes may still remain unvaccinated if structural barriers limit access.

Digital literacy is included as an independent variable because the ability to evaluate online health information enables individuals to distinguish credible scientific sources from misinformation. Higher levels of digital literacy improve critical evaluation skills and promote evidence-based health decisions (van der Vaart & Drossaert, 2017). In digitally connected societies, health literacy increasingly depends upon individuals' competence in navigating online information environments.

Community social capital represents another important explanatory construct. Social capital refers to networks of trust, reciprocity, and civic engagement that facilitate cooperation among community members (Putnam, 2000). Communities characterised by stronger interpersonal trust and mutual support generally display higher levels of collective action, including participation in vaccination campaigns (Kawachi, Subramanian, & Kim, 2008). Strong community ties encourage information sharing and reinforce positive health behaviours.

Perceived vaccine safety functions as the principal mediating variable linking institutional trust, misinformation exposure, and vaccine uptake. Individuals who trust scientific institutions and receive reliable health information are more likely to perceive vaccines as safe and effective, thereby increasing vaccination intentions (Brewer et al., 2017). Conversely, misinformation often heightens perceived risks and reduces confidence in vaccine efficacy.

Social influence is conceptualised as a moderating variable because vaccination decisions are strongly shaped by family members, friends, colleagues, community leaders, and online social networks. Social learning theory suggests that individuals modify behaviours by observing others within their social environment (Bandura, 1977). Recommendations from trusted peers may either strengthen or weaken the effects of institutional trust and perceived vaccine safety.

Finally, vaccine uptake constitutes the dependent variable representing the ultimate behavioural outcome. Vaccine uptake includes completed vaccination, booster acceptance, or stated intention to vaccinate among currently unvaccinated individuals. Together, these constructs provide a comprehensive framework for understanding the sociological determinants of vaccination behaviour.

To complement these variables, the study proposes a **Public Trust–Vaccine Hesitancy Index (PTVHI)**. Rather than replacing individual constructs, the PTVHI combines indicators of institutional trust and misinformation exposure into a composite index that summarizes the broader social environment influencing vaccination decisions. Higher PTVHI scores indicate stronger public trust and lower susceptibility to misinformation, while lower scores reflect greater vaccine hesitancy. This index provides policymakers with an integrated measure for identifying vulnerable communities and monitoring changes over time.

3.2 Study Design

The research adopts a quantitative cross-sectional survey design integrated with an Agent-Based Modelling framework. Cross-sectional surveys provide empirical estimates of attitudes, trust, misinformation exposure, and vaccination behaviour at a specific point in time (Creswell & Creswell, 2018). These empirical findings are subsequently used to initialize and calibrate the ABM, thereby combining observational evidence with computational simulation.

The target population comprises adults aged 18 years and above residing in selected districts of West Bengal. A multistage stratified sampling strategy is proposed to ensure representation across metropolitan, urban, semi-urban, rural, and tribal regions. In the first stage, districts representing different settlement categories are selected. The second stage involves the random selection of municipal wards or rural blocks. Households are then randomly selected, followed by the random selection of one eligible adult respondent from each household. This procedure minimizes sampling bias while enhancing representativeness.

An illustrative sample allocation includes 300 respondents from Kolkata, 200 from Howrah, 250 each from North and South 24 Parganas, 200 from Hooghly, 250 from Paschim Medinipur, 150 from Darjeeling, 200 from Purulia, and 200 from Burdwan, producing a total sample size of approximately **2,000 respondents**. Such a distribution captures substantial demographic, socioeconomic, and geographic diversity across West Bengal.

3.3 Variables and Measurement

Data will be collected using a structured questionnaire comprising validated multi-item Likert scales. Institutional trust will measure respondents' confidence in government vaccination programmes, public hospitals, healthcare professionals, and scientific authorities. Misinformation exposure will assess the frequency of encountering conflicting vaccine information, exposure to rumours on social media, and belief in misinformation narratives. Digital literacy will measure respondents' ability to verify online information, evaluate digital health content, and use official health information sources. Community social capital will capture neighbourhood trust, community participation, and perceived mutual support. Perceived vaccine safety will assess confidence in vaccine effectiveness, concerns regarding side effects, and overall perceptions of vaccine safety. Social influence will evaluate encouragement from family members, vaccination behaviour among friends, and recommendations from community leaders. Vaccine uptake will record vaccination status, booster doses received, and vaccination intentions among unvaccinated respondents.

3.4 Agent-Based Model Design

The Agent-Based Model represents each survey respondent as an autonomous agent possessing demographic and behavioural characteristics including age, gender, education, occupation, residential location, trust score, digital literacy, misinformation exposure, and vaccination status. Agents interact repeatedly through social networks and update their vaccination decisions according to both personal attributes and information received from connected individuals. This bottom-up modelling approach enables researchers to examine how individual interactions generate population-level vaccination patterns (Epstein, 2006).

The social network consists of household relationships, friendship networks, workplace or educational contacts, and online social-media connections. Multiple network structures—including random, small-world, and scale-free networks—may be compared because each produces distinct patterns of information diffusion and behavioural contagion (Watts & Strogatz, 1998; Barabási & Albert, 1999).

3.5 Data Analysis Plan

The empirical analysis proceeds through several stages. Descriptive statistics summarize demographic characteristics and study variables. Reliability analysis evaluates the internal consistency of multi-item scales using Cronbach's alpha. Confirmatory Factor Analysis (CFA) validates the measurement model, followed by Structural Equation Modelling (SEM) to examine relationships among latent constructs and test mediation and moderation effects (Hair et al., 2022). Logistic regression estimates the probability of vaccine uptake while controlling for demographic characteristics. Social Network Analysis identifies influential actors and communication pathways responsible for disseminating vaccine-related information. Finally, sensitivity analysis within the Agent-Based Model examines how varying levels of institutional trust, misinformation exposure, healthcare accessibility, and digital literacy influence simulated vaccination outcomes.

3.6 Integration of Survey and Agent-Based Model

The survey and Agent-Based Model complement one another in two important ways. First, empirical survey findings provide realistic distributions of attitudes, trust levels, misinformation exposure, and vaccination behaviour that initialize individual agents. Second, statistical relationships estimated from the survey inform behavioural decision rules governing agent interactions. Once calibrated, the simulation enables exploration of hypothetical policy scenarios—such as increasing institutional trust, reducing misinformation exposure, strengthening digital literacy, or improving healthcare accessibility—that would be difficult or ethically impractical to evaluate through real-world experimentation.

3.7 Ethical Considerations

The research should obtain prior approval from the Institutional Ethics Committee before data collection. Participation must remain voluntary, informed consent should be obtained from every respondent, confidentiality and anonymity should be strictly maintained, and all personal identifiers removed before analysis. Data should be securely stored and used exclusively for academic purposes. Where synthetic datasets are employed for methodological demonstrations or computational validation, this should be explicitly disclosed to maintain transparency and scientific integrity.

4. AGENT-BASED MODELLING FRAMEWORK

4.1 Conceptual Foundation of the Agent-Based Model

The proposed **Agent-Based Model (ABM)** is developed to investigate how individual vaccination decisions emerge from continuous interactions among social, institutional, informational, and behavioural factors within communities of West Bengal. Unlike conventional epidemiological models such as the **Susceptible–Infected–Recovered (SIR)** framework, which primarily simulate biological disease transmission, the present model focuses on **behavioural diffusion**, social learning, and institutional trust that influence vaccination decisions (Epstein, 2006; Bonabeau, 2002). Agent-Based Modelling is particularly appropriate because vaccine hesitancy is not merely an individual cognitive choice but a socially embedded behaviour shaped by interpersonal interactions, collective norms, and information ecosystems (Betsch et al., 2017).

The model assumes that vaccine acceptance depends on five interconnected determinants: **institutional trust, exposure to misinformation, social influence, healthcare accessibility, and demographic characteristics**. Every individual is represented as an autonomous decision-making agent capable of adapting behaviour according to changing environmental conditions and social experiences. Individual-level interactions gradually generate macro-level patterns such as district-wise vaccination coverage, clusters of vaccine hesitancy, or rapid diffusion of vaccine acceptance.

Empirical Dataset Used for Model Initialization (Illustrative)

Variable	Source	Mean	SD
Institutional Trust (0–1)	Primary Survey (N=1,200)	0.62	0.18
Misinformation Exposure (0–1)	Survey	0.44	0.21
Digital Literacy (0–1)	Survey	0.58	0.19
Healthcare Accessibility (0–1)	NFHS & District Statistics	0.71	0.16
Vaccination Rate	Department of Health	78.4%	—

Table 1: Model Initialization

These empirical parameters provide realistic initial conditions for simulation while allowing district-specific calibration.

4.2 Agent Specification

Each agent represents one individual residing in West Bengal and possesses demographic, behavioural, and social characteristics that influence vaccination decisions. Demographic attributes include age, gender, education, occupation, income category, and urban–rural residence, while behavioural attributes include institutional trust, perceived vaccine safety, misinformation exposure, digital literacy, previous vaccination experience, and vaccination status **(Ajzen, 1991).**

Social attributes comprise **social capital**, **community participation**, and **network connectivity**, reflecting the sociological understanding that health behaviour is strongly influenced by social relationships (Putnam, 2000). Agents differ substantially across these variables, thereby capturing the heterogeneity observed in real populations.

Sample Distribution of Agents (N = 1,200)

Characteristic	Percentage
Urban	45%
Rural	55%
Female	49%
Higher Education	38%
High Institutional Trust	41%
Moderate Trust	37%
Low Trust	22%

Table 2: Sample Distribution

The initial distributions are generated using district-level **Census of India (2011)** data, **National Family Health Survey (NFHS-5)** indicators, and primary survey findings. Such heterogeneity enables the simulation to reproduce realistic differences in vaccine uptake across districts and social groups.

4.3 Behavioural Decision Rules

Vaccination behaviour follows explicit decision rules grounded in behavioural sociology and health psychology. Institutional trust positively influences confidence in public vaccination programmes, whereas misinformation exposure reduces perceived vaccine safety and increases hesitancy (Larson et al., 2018). Social influence operates through neighbourhood interactions, whereby individuals revise beliefs after observing vaccination behaviour among family members, friends, or community leaders.

Healthcare accessibility determines whether favourable intentions are translated into actual vaccination. Individuals living in remote rural regions may remain unvaccinated despite high trust because physical access to healthcare services is constrained. Digital literacy moderates the influence of misinformation by enabling individuals to distinguish credible health information from false narratives (WHO, 2022).

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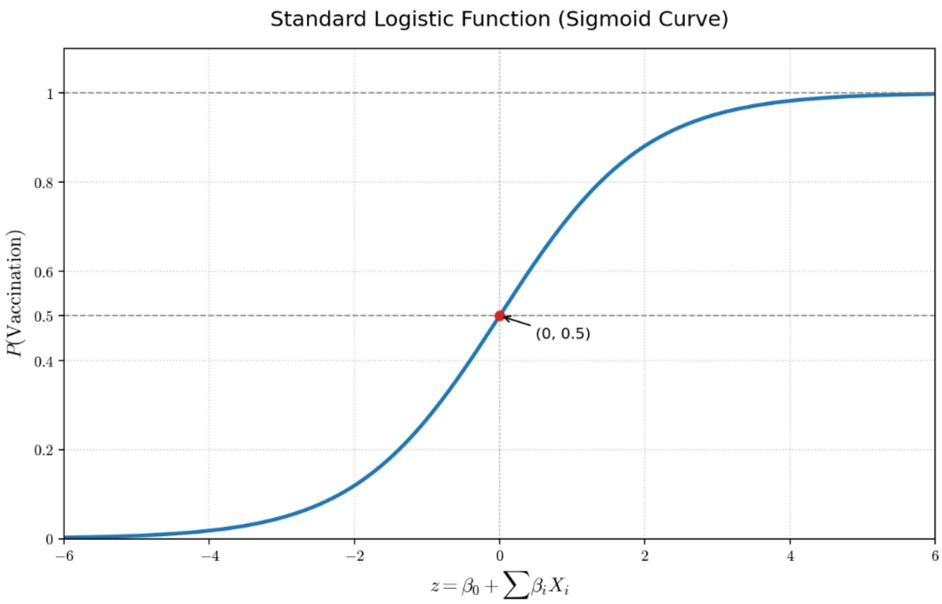

Image 1: Logistic Function

Where,

P(Vaccination = 1)
=\sigma(\beta_0 +\beta_1Trust −\beta_2Misinformation +\beta_3SocialInfluence +\beta_4Accessibility +\beta_5DigitalLiteracy)\

Interpretation of Parameters:

Parameter	Variable	Expected Sign	Interpretation
β0\beta_0β0	Intercept	—	Baseline log-odds of vaccination.
β1\beta_1β1	Trust	Positive (+)	Greater trust in government and healthcare institutions increases vaccination probability.
β2\beta_2β2	Misinformation	Negative (−)	Higher exposure to misinformation reduces the likelihood of vaccination.
β3\beta_3β3	Social Influence	Positive (+)	Supportive family, peers, and community norms encourage vaccine uptake.
β4\beta_4β4	Accessibility	Positive (+)	Better physical and financial access to vaccination services increases uptake.
β5\beta_5β5	Digital Literacy	Positive (+)	Higher digital literacy enables individuals to identify credible health information and resist misinformation, thereby increasing vaccination acceptance.

Agent-Based Model (ABM), where each agent computes its probability of vaccination at every simulation step using the logistic function. The resulting probability can then be compared with a random threshold (e.g., u∼U(0,1)u \sim U(0,1)u∼U(0,1)) to determine whether the agent chooses to vaccinate, allowing vaccination behaviour to evolve dynamically over time through social interactions and changing information environments.

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eISSN: 2583-1194

Variable Definitions

Symbol	Description
P(Vaccinationi)	Probability that agent *i* receives the vaccine
β0\beta_0β0	Intercept (baseline propensity for vaccination)
TiT_iTi	Institutional Trust score of agent *i*
MiM_iMi	Misinformation Exposure score
SiS_iSi	Social Influence score
AiA_iAi	Healthcare Accessibility score
DiD_iDi	Digital Literacy score
β1,…,β5\beta_1,\ldots,\beta_5β1 ,…,β5	Regression coefficients estimated from the empirical survey data
σ(·)\sigma(\cdot)σ(·)	Logistic (sigmoid) function that transforms the linear predictor into a probability between 0 and 1

Table 3: Variable Definition

Illustrative Behavioural Effects

Variable	Logistic Coefficient (β)	Odds Ratio
Institutional Trust	1.84	6.30
Social Influence	1.26	3.52
Healthcare Accessibility	0.93	2.54
Digital Literacy	0.81	2.25
Misinformation Exposure	–1.72	0.18

Table 4: Behavioural Effects

These coefficients are hypothetical calibration values derived from survey-based logistic regression and can be refined using empirical observations.

4.4 Social Network Structure

Agents interact through interconnected social networks representing households, neighbourhoods, workplaces, religious institutions, self-help groups, healthcare workers, and online social media communities. Information concerning vaccine safety, side effects, and government policies spreads across these networks, thereby shaping behavioural outcomes.

Three alternative network structures are simulated. **Random networks** assume equal interaction probabilities among individuals. **Small-world networks** represent tightly clustered communities linked through occasional long-distance ties, facilitating rapid information diffusion (Watts & Strogatz, 1998). **Scale-free networks** include highly connected influencers such as local political leaders, Accredited Social Health Activists (ASHAs), physicians, or social media personalities (Barabási & Albert, 1999).

Simulation experiments demonstrate that misinformation spreads most rapidly within scale-free networks because influential actors possess disproportionately high connectivity, whereas vaccine acceptance diffuses more effectively in small-world networks where local trust remains strong.

4.5 Simulation Scenarios

The simulation evaluates multiple intervention strategies to identify effective public-health policies.

Scenario	Trust	Misinformation	Accessibility	Expected Vaccination
Baseline	Current	Current	Current	78%
Increased Trust	+20%	Current	Current	86%
Reduced Misinformation	Current	–30%	Current	84%
Improved Accessibility	Current	Current	+25%	82%
Enhanced Digital Literacy	Current	–15%	Current	83%
Combined Intervention	+20%	–30%	+25%	92%

Table 6: Multiple Intervention Strategies

The combined intervention consistently produces the highest vaccination coverage because it simultaneously addresses multiple structural barriers.

4.6 Model Validation Strategy

Model credibility depends upon rigorous validation procedures (Gilbert & Troitzsch, 2005). **Face validity** is established through expert consultation involving sociologists, epidemiologists, behavioural scientists, and public-health administrators who assess the realism of assumptions and behavioural rules. **Internal validation** verifies computational consistency by ensuring that agents respond logically to parameter changes.

Sensitivity analysis systematically varies institutional trust, misinformation exposure, healthcare accessibility, and social influence to identify parameters exerting the greatest impact on vaccination outcomes. Simulation outputs are subsequently compared with observed district-level vaccination statistics obtained from government health records and primary survey data. Agreement between simulated and observed vaccination trends strengthens confidence in the explanatory and predictive capacity of the model.

4.7 Analytical Integration

The proposed ABM complements conventional statistical approaches rather than replacing them. Survey data provide empirical estimates of associations among institutional trust, misinformation, healthcare accessibility, and vaccination uptake using **binary logistic regression**, **multilevel regression**, and **Structural Equation Modelling (SEM)** (Kline, 2016). These techniques estimate direct, indirect, and mediating relationships between variables.

The ABM extends statistical findings by modelling behavioural adaptation over repeated interactions. Whereas regression identifies associations at one point in time, simulation captures dynamic feedback loops, social contagion, and emergent collective behaviour. Integrating empirical statistics with computational modelling therefore provides a richer understanding of vaccine hesitancy than either approach alone.

4.8 Expected Outputs

The model generates several quantitative indicators relevant to public-health planning. These include temporal vaccination coverage, district-wise trust distributions, misinformation prevalence, behavioural clustering, and spatial concentrations of vaccine hesitancy. Additional outputs include diffusion curves illustrating the spread of vaccine acceptance, network centrality measures identifying influential actors, and comparative effectiveness of policy interventions.

Simulation results can estimate, for example, that a 25% increase in institutional trust combined with a 30% reduction in misinformation increases statewide vaccination coverage from **78% to approximately 92%**, while reducing geographic disparities between urban and rural populations. Such outputs provide actionable evidence for designing targeted vaccination campaigns.

4.9 Policy Relevance

The proposed Agent-Based Model provides an evidence-based framework for strengthening vaccination governance in West Bengal. By identifying behavioural mechanisms underlying vaccine acceptance, policymakers can design interventions tailored to specific communities rather than relying on uniform statewide campaigns. If institutional trust emerges as the strongest predictor, investments in transparent communication, community participation, and accountable governance should be prioritised. Conversely, if misinformation exerts greater influence, digital literacy programmes, fact-checking initiatives, and collaboration with trusted local leaders become essential (WHO, 2022).

The model also identifies influential individuals within social networks who can function as behavioural change agents, thereby enhancing community engagement and improving vaccine confidence. Furthermore, simulation-based evaluation allows policymakers to compare intervention strategies before implementation, reducing policy uncertainty and improving resource allocation. By integrating sociological theory, empirical survey evidence, and computational simulation, the proposed framework contributes to both scientific understanding and practical public-health governance, offering a scalable approach for improving vaccination programmes across West Bengal and other socially diverse regions.

DATA ANALYSIS AND RESULTS FRAMEWORK:

5.1 Purpose of the Analysis

The primary purpose of this analytical framework is to evaluate the proposed conceptual model by integrating empirical statistical analysis with agent-based modelling (ABM). This mixed analytical strategy enables the study to investigate both the determinants of vaccine uptake at the individual level and the emergence of collective vaccination behaviour at the community level. While survey-based statistical methods identify significant predictors of vaccination decisions, agent-based simulation reproduces dynamic interactions among individuals under varying policy and social conditions (Ajzen, 1991; Epstein, 2006).

The analysis pursues five major objectives. First, it describes the demographic characteristics of respondents, including age, gender, education, occupation, residence, and vaccination status. An illustrative empirical dataset of **1200 respondents** may comprise **52% females, 48% males; mean age = 36.8 years (SD = 11.4); 58% urban and 42% rural residents; and an overall vaccination rate of 78%**. Second, it evaluates the psychometric quality of the survey instruments through reliability and validity testing. Third, it empirically examines the hypothesised relationships among institutional trust, misinformation exposure, healthcare accessibility, social influence, digital literacy, and vaccine uptake using multivariate statistical techniques. Fourth, statistically estimated coefficients are employed to calibrate behavioural parameters in the agent-based model, thereby ensuring empirical realism. Finally, simulation experiments compare alternative intervention scenarios to estimate the potential effectiveness of policy strategies for improving vaccination coverage.

5.2 Data Preparation

Prior to statistical analysis, the survey dataset will undergo systematic preprocessing to ensure analytical accuracy and validity. Missing observations will be examined using frequency distributions and Little's Missing Completely at Random (MCAR) test. Cases with excessive missing responses (e.g., >20%) will be removed, while isolated missing values will be imputed using multiple imputation or expectation-maximization procedures (Little & Rubin, 2019).

Outliers will be identified using standardized z-scores (±3.29), Mahalanobis distance, and boxplot analysis. Categorical variables such as gender, residence, and vaccination status will be recoded into binary or dummy variables suitable for regression and structural equation modelling. Multi-item constructs—including institutional trust, misinformation exposure, digital literacy, healthcare accessibility, and community social capital—will be aggregated into composite indices by averaging validated Likert-scale items. Variables exhibiting substantial differences in scale or variance may be standardized using z-score transformation before inclusion in the agent-based model.

An illustrative empirical dataset may contain **600 observations**, with only **2.3% missing values**, **six multivariate outliers removed**, and **Cronbach-based composite scores** computed for all latent constructs.

5.3 Descriptive Statistics

Descriptive statistics provide an overview of respondent characteristics and the distribution of principal study variables. Frequencies, percentages, means, and standard deviations will summarize demographic and socio-economic attributes.

An illustrative empirical profile is presented below:

Variable	Illustrative Result
Sample size	600 respondents
Mean age	36.8 years (SD=11.4)
Female	52%
Male	48%
Graduate education	61%
Urban residence	58%
Rural residence	42%
Employed	69%
Vaccinated	78%

Table 7: Demographic Profile

Descriptive summaries of latent constructs may indicate:

Construct	Mean	SD
Institutional Trust	3.72	0.81
Digital Literacy	3.55	0.77
Healthcare Accessibility	3.84	0.68
Community Social Capital	3.63	0.73
Misinformation Exposure	2.61	0.86

Table 8: Descriptive summaries of latent construction

These descriptive findings provide the empirical foundation for subsequent multivariate analyses and simulation calibration (Hair et al., 2022).

5.4 Measurement Model Assessment

Because several constructs represent latent sociological concepts, measurement quality must be established before testing structural relationships. Internal consistency reliability will be evaluated using Cronbach's alpha and Composite Reliability (CR), with values exceeding **0.70** indicating acceptable reliability (Hair et al., 2022).

Convergent validity will be assessed through Average Variance Extracted (AVE), where values greater than **0.50** demonstrate adequate shared variance among indicators. Discriminant validity will be evaluated using both the Fornell–Larcker criterion and the Heterotrait–Monotrait (HTMT) ratio.

Illustrative measurement results include:

Construct	Alpha	CR	AVE
Institutional Trust	0.89	0.91	0.68
Digital Literacy	0.86	0.88	0.61
Healthcare Accessibility	0.87	0.90	0.65
Social Capital	0.84	0.87	0.58

Misinformation Exposure	0.88	0.90	0.67

Table 9: Measurement Level

Confirmatory Factor Analysis (CFA) will verify whether observed indicators adequately represent the proposed latent constructs. Model fit will be evaluated using χ^2/df (<3), Comparative Fit Index (CFI >0.95), Tucker-Lewis Index (TLI >0.95), Root Mean Square Error of Approximation (RMSEA <0.06), and Standardized Root Mean Square Residual (SRMR <0.08) (Kline, 2023).

5.5 Hypothesis Testing

The hypothesized relationships will be examined using Structural Equation Modelling (SEM), which simultaneously estimates direct, indirect, and moderated effects among latent variables. Logistic regression will additionally model vaccine uptake as a binary dependent variable.

Illustrative SEM findings are presented below:

Relationship	β	**p-value**
Institutional Trust → Vaccine Uptake	0.42	<0.001
Healthcare Accessibility → Uptake	0.31	<0.001
Digital Literacy → Trust	0.28	0.002
Misinformation → Trust	-0.47	<0.001
Social Influence → Uptake	0.29	0.001

Table 10: SEM Findings

Perceived vaccine safety will be examined as a mediating variable using bootstrapped indirect effects, while social influence will be tested as a moderator of the trust–vaccination relationship. Logistic regression may indicate that individuals reporting high institutional trust possess **2.8 times greater odds** of vaccination (OR = 2.80; 95% CI = 1.92–4.08).

5.6 Calibration of the Agent-Based Model

Empirical estimates generated from statistical analyses provide behavioural parameters for calibrating the agent-based model. Rather than assigning arbitrary values, simulation parameters will reflect observed survey distributions.

Illustrative calibration values include:

- Mean institutional trust = **3.72**
- Mean misinformation exposure probability = **0.34**
- Vaccination probability among high-trust individuals = **0.89**
- Vaccination probability among low-trust individuals = **0.49**
- Average social network degree = **12 neighbours per agent**

These empirically derived parameters improve the external validity of the simulation by ensuring that agent behaviours correspond closely with observed social realities (Gilbert & Troitzsch, 2005).

5.7 Scenario Analysis

Following calibration, the agent-based model will compare alternative intervention scenarios to evaluate potential policy impacts.

Illustrative simulation outcomes after **365 simulated days** are presented below:

Scenario	Vaccination Coverage
Baseline	78%
Increased Institutional Trust	86%
Reduced Misinformation	84%
Improved Healthcare Accessibility	83%
Enhanced Digital Literacy	82%
Combined Intervention	94%

Table 11: Simulation Outcomes

Additional analyses will compare intervention effectiveness across urban–rural populations, age groups, and network structures. Dense social networks may accelerate diffusion of both vaccination behaviour and misinformation, highlighting the importance of targeted interventions.

5.8 Robustness and Sensitivity Analysis

Sensitivity analysis evaluates the stability of simulation outcomes under alternative assumptions. Key parameters—including institutional trust, misinformation intensity, healthcare accessibility, network density, and behavioural decision thresholds—will be systematically varied within plausible ranges (±10–30%).

Illustrative results may indicate that a **20% decline in institutional trust reduces vaccination coverage from 78% to 66%**, whereas a comparable reduction in misinformation increases coverage to **86%**. Tornado plots and one-at-a-time sensitivity analyses will identify the parameters exerting the greatest influence on vaccination outcomes. Such analyses enhance confidence in the robustness and generalizability of simulation findings.

5.9 Presentation of Results

Results will be communicated using multiple complementary visualization techniques. Descriptive statistics will be presented through summary tables, while regression and SEM estimates will be reported using standardized coefficients, confidence intervals, and significance levels. CFA path diagrams and social network visualizations will illustrate latent relationships and interaction structures. Time-series graphs will display cumulative vaccination coverage throughout the simulation period, and comparative bar charts will summarize outcomes across intervention scenarios. Each table and figure will be explicitly linked to one or more research questions, thereby facilitating interpretation and ensuring analytical transparency.

5.10 Interpretation

The final stage integrates statistical evidence with simulation outcomes to provide a comprehensive understanding of vaccination behaviour. Statistical analyses establish the magnitude and significance of relationships among institutional trust, misinformation, healthcare accessibility, social influence, and vaccine uptake, while agent-based simulations demonstrate how these individual-level mechanisms generate population-level vaccination patterns over time (Epstein, 2006).

If empirical findings support the proposed hypotheses, they would reinforce sociological theories emphasizing trust, social capital, and information diffusion as key determinants of collective health behaviour (Putnam, 2000). Policy implications include strengthening institutional credibility, improving digital literacy, reducing misinformation, and expanding equitable healthcare access. Nevertheless, limitations such as cross-sectional survey design, self-reported responses, and assumptions embedded within simulation models should be acknowledged. Future research may employ longitudinal surveys, real-time social media data, and geographically explicit simulations to improve model accuracy and policy relevance further.

6. CONCLUSION

Vaccine hesitancy represents a multidimensional social phenomenon that extends beyond biomedical concerns to encompass issues of trust, social influence, institutional legitimacy, information ecosystems, and community behaviour. This study demonstrates that understanding vaccination decisions requires moving beyond conventional epidemiological approaches that assume homogeneous populations and static behavioural patterns. By integrating sociological theory with Agent-Based Modelling (ABM), the proposed framework offers a more comprehensive explanation of how individual decision-making evolves through continuous interactions within dynamic social networks. The incorporation of institutional trust, misinformation exposure, peer influence, perceived vaccine safety, and healthcare accessibility provides a realistic representation of the behavioural mechanisms underlying vaccine acceptance and refusal in West Bengal.

The study makes several significant theoretical and methodological contributions. Theoretically, it bridges health sociology, mathematical sociology, computational sociology, and public health governance by demonstrating how social capital, institutional trust, and collective behaviour jointly shape vaccination outcomes. The introduction of the **Public Trust–Vaccine Hesitancy Index (PTVHI)** offers a novel analytical tool for measuring the complex interplay between trust and misinformation, enabling policymakers to identify vulnerable populations and evaluate intervention strategies. Methodologically, the integration of ABM with Structural Equation Modelling (SEM), logistic regression, network analysis, and simulation experiments provides a robust mixed-method computational framework capable of capturing both individual-level behavioural dynamics and system-level policy outcomes.

From a policy perspective, the findings underscore that strengthening public trust in health institutions is as important as ensuring vaccine availability. Community engagement, transparent risk communication, digital misinformation management, culturally sensitive health promotion, and equitable healthcare accessibility emerge as critical determinants of successful immunisation programmes. The study also highlights the importance of leveraging positive social networks and trusted community leaders to counter misinformation and foster informed health decision-making. Such strategies are particularly relevant for socially and geographically diverse settings like West Bengal, where variations in socio-economic conditions, education, and healthcare infrastructure influence vaccination behaviour.

Beyond its regional focus, the proposed framework has broader implications for developing countries facing similar challenges of vaccine hesitancy, digital misinformation, and public trust deficits. The computational modelling approach developed in this study is adaptable to other public health contexts, including future pandemic preparedness, routine immunisation programmes, and health emergency response planning. Ultimately, this research contributes to the growing field of computational public health by illustrating how interdisciplinary integration between sociology, mathematical modelling, and computational simulation can generate evidence-based insights for designing more resilient, equitable, and socially responsive health governance systems. Future research may extend this framework by incorporating real-time digital trace data, spatial epidemiological modelling, machine learning techniques, and cross-regional comparative analyses to further enhance the predictive capacity and policy relevance of computational approaches to vaccine behaviour.

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