International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

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Epidemiological insights into Nipah virus: A sir model perspective

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International Journal of Science and Research Archive, 2024, 13(02), 1322–1330

Publication history: Received on 07 October 2024; revised on 18 November 2024; accepted on 21 November 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.13.2.2242

Abstract

The Nipah virus outbreak in Kerala, India, in 2024 presented significant public health challenges, necessitating an in-depth analysis of its transmission dynamics and the effectiveness of response measures. This study employs the SIR (Susceptible, Infected, Recovered) epidemiological model to simulate the outbreak, focusing on key parameters such as transmission and recovery rates. The model reveals that the outbreak peaked around Day 10, with a maximum of approximately 631 infected individuals, highlighting the rapid spread of the virus. However, timely public health interventions, including contact tracing, isolation, and community engagement, effectively curtailed transmission, resulting in a swift decline in infected cases and a significant recovery rate. By Day 100, nearly the entire population had either recovered or remained uninfected, underscoring the success of containment efforts. This study emphasizes the critical role of proactive health strategies in managing infectious diseases and provides valuable insights for future preparedness against zoonotic outbreaks. The findings highlight the necessity of continuous monitoring and community involvement in strengthening public health infrastructure to mitigate the impact of similar outbreaks in the future.

Keywords: SIR Epidemic Model; Nipah virus; Disease

1. Introduction

1.1. Introduction to Mathematical Modelling

Mathematical modeling is the process of using mathematics to represent, analyze, and predict the behavior of real-world systems or phenomena. It involves constructing mathematical formulations (equations, functions, graphs, etc.) that describe the relationships between different variables in a system, enabling us to understand complex problems and make informed decisions.

1.2. Key Elements of Mathematical Modeling:

- *Real-World Problem:* The starting point of a mathematical model is a problem or phenomenon that needs to be understood or predicted. Examples include population growth, climate change, or financial market behavior.
- *Assumptions and Simplifications:* The real world is often too complex to model in full detail, so assumptions are made to simplify the system. These might involve neglecting smaller effects or assuming certain conditions remain constant.
- *Formulating the Model:* Based on the assumptions, mathematical expressions are developed to describe how different variables are related. This could involve algebraic equations, differential equations, or statistical models, depending on the nature of the system.
- *Solving the Model:* Once formulated, the model can be solved to make predictions or understand relationships. This might involve solving equations analytically or using computational methods for more complex systems.

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- *Interpretation:* After obtaining solutions, the results must be interpreted in the context of the original problem. Are the predictions realistic? Do they align with known data?
- *Validation:* The model's predictions are compared to real-world data to ensure accuracy. If the model doesn't match observed outcomes, it may need to be refined or reworked.
- *Iteration:* Mathematical modeling is often an iterative process. A model may need to be adjusted multiple times to improve accuracy or account for new data.

1.3. Introduction to SIR Epidemic Model

The SIR epidemic model is a widely-used mathematical framework to describe the spread of infectious diseases in a population. Developed by Kermack and McKendrick in 1927, the model divides the population into three compartments:

- ***S*** (Susceptible): Individuals who are not yet infected but are vulnerable to the disease.
- ***I*** (Infectious or Infected): Individuals who are currently infected and can transmit the disease to susceptible people.
- ***R*** (Recovered): Individuals who have recovered from the disease and are now immune or removed (i.e., no longer part of the infection cycle due to immunity or death).

1.3.1. Key Assumptions of the SIR Model:

The total population is constant, meaning no births or deaths occur during the epidemic, except those related to the disease.

Recovered individuals gain permanent immunity and do not return to the susceptible group.

The disease spreads through contact between susceptible and infected individuals.

The rate at which susceptible individuals become infected depends on the number of contacts between infected and susceptible individuals.

1.3.2. Graphical Representation:

The SIR model typically produces a curve showing how the number of infected individuals rises, reaches a peak, and then declines as more people recover.

The susceptible population steadily decreases over time, while the recovered group increases.

1.3.3. Limitations of the SIR Model:

- Simplifying Assumptions: The model assumes permanent immunity, constant population, and homogeneous mixing (everyone is equally likely to come into contact with others). Real epidemics may involve variations such as reinfection, different contact rates, or varying immunity durations.
- No Demographics: It does not account for births, deaths (except disease-related), or demographic differences.
- No Latent Period: The model assumes that infected individuals can immediately transmit the disease, while some diseases have a latent period during which the person is infected but not yet infectious.

Despite its simplicity, the SIR model provides a foundational approach to understanding epidemic dynamics, forming the basis for more complex models used in epidemiology.

2. Review of Literature

Epidemiology and Transmission: The literature indicates that Nipah virus is primarily transmitted from animals to humans, with bats being the natural reservoir. Kumar and Verma (2024) conducted a comprehensive review of epidemiological characteristics of Nipah virus outbreaks in India, emphasizing zoonotic transmission and the role of intermediate hosts such as pigs. They highlight that human-to-human transmission can occur, particularly in healthcare settings, complicating outbreak control efforts [1].

Public Health Interventions: The effectiveness of public health interventions has been a central theme in managing Nipah outbreaks. The World Health Organization (2024) [3] outlines strategies for outbreak response, including active case finding, contact tracing, and community engagement. Bhatia and Gupta (2024) [5] utilized an SIR modeling approach to analyze the spread of the virus in Kerala, demonstrating that timely interventions significantly mitigate the impact of the outbreak. Their model indicated that aggressive isolation of cases and monitoring of contacts reduced the effective reproduction number, underscoring the importance of rapid public health responses.

Recovery and Management: Research has also focused on recovery rates and the management of infected individuals. Sahu and Patra (2024) [2] reviewed the clinical features of Nipah virus infections, reporting a high mortality rate associated with severe cases. However, they noted that early detection and supportive care significantly improved recovery outcomes. The Indian Council of Medical Research (ICMR, 2024) provided guidelines emphasizing the importance of healthcare preparedness and training to enhance response capabilities during outbreaks[4] .

Socioeconomic Impacts: The socioeconomic implications of Nipah virus outbreaks have been explored in various studies. Patel and Singh (2024) highlighted the challenges faced by communities during outbreaks, including loss of income due to quarantine measures and stigma associated with the disease. Their findings stress the need for supportive measures to help affected families and restore community trust in public health initiatives [8].

This literature review provides a foundation for understanding the key challenges and strategies associated with the Nipah virus in Kerala, contributing to ongoing efforts to improve public health responses in the region. The literature on the Nipah virus outbreaks in Kerala underscores the complexity of managing zoonotic diseases in a densely populated and highly mobile society. While the 2024 outbreak demonstrated effective public health responses that significantly curtailed transmission, ongoing research is essential to better understand the virus's dynamics, improve treatment protocols, and enhance community resilience. Future studies should focus on integrating epidemiological modelling with social science perspectives to develop comprehensive strategies for managing Nipah virus outbreaks and other emerging infectious diseases.

3. Purpose of the Study

The primary purpose of the study on the Nipah virus outbreak in Kerala in 2024 is to analyze the dynamics of the outbreak using the SIR (Susceptible, Infected, Recovered) epidemiological model and to assess the effectiveness of public health interventions implemented during the outbreak.

3.1. Mathematical Formulation

The SIR model is described by a system of differential equations, which represent the rate of change of the three compartments over time.

$$\frac{dS}{dt} = -\beta \frac{SI}{N}$$

$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

Where:
$S(t), I(t), and\ R(t)$ represent the number of susceptible, infected, and recovered individuals at time t respectively.
NNN is the total population size, so $N = S + I + R$.
β is the infection rate, which controls how quickly the disease spreads from the infected to the susceptible population.
γ is the recovery rate, determining how quickly infected individuals recover and move into the recovered class.

3.2. Key Concepts

3.2.1. Basic Reproduction Number ($\boldsymbol{R_0}$)

This is a critical parameter in the SIR model that indicates the average number of secondary infections produced by a single infected individual in a fully susceptible population. It is given by $R_0 = \frac{\beta}{\gamma}$

- If $R_0 > 1$, the infection will spread through the population.
- If $R_0 < 1$, the infection will eventually die out.

3.2.2. Disease Spread and Control

Initially, as long as the number of susceptible individuals is high and $R_0 > 1$, the infection grows exponentially.

Over time, as more people become infected and recover, the number of susceptible individuals decreases, slowing down the spread.

Eventually, the epidemic peaks when the number of new infections starts to decline as fewer people remain susceptible.

3.2.3. Herd Immunity

Herd immunity occurs when enough individuals in the population have recovered (or been vaccinated), reducing the spread of the disease and protecting those who are still susceptible. This happens when a large enough portion of the population becomes immune so that the disease can no longer spread effectively.

3.3. Data Collection

As of the latest available data in 2024, India has experienced multiple outbreaks of the Nipah virus, particularly in Kerala. In the most recent outbreak, the primary focus was in the districts of Kozhikode and Malappuram.

3.3.1. Susceptible individuals

Around 53,708 households in containment zones were surveyed during the outbreak in 2023-2024, with 1,288 contacts identified, including high-risk individuals who were quarantined and monitored closely (World Health Organization (WHO) (National Centre for Disease Control).

3.3.2. Infected individuals

A total of 472 individuals who were under observation for possible Nipah virus infection were eventually cleared, with cases being contained through rigorous testing and containment measures (The New Indian Express).

3.3.3. Recovered individuals:

Recovery data is limited, as case numbers were relatively low, and many measures were focused on prevention and containment rather than large-scale recovery. However, Kerala managed to avoid a widespread outbreak beyond initial contacts (National Centre for Disease Control). While Nipah virus has a high mortality rate, proactive measures in 2024 successfully limited the spread in India. These included rigorous contact tracing, quarantine, and public health interventions.

4. Problem Formulation

The SIR (Susceptible-Infected-Recovered) model divides the population into three compartments:

- $\boldsymbol{S}$ $(\boldsymbol{Susceptible})$: Individuals who are not yet infected but are at risk.
- $\boldsymbol{I}$ $(\boldsymbol{Infected})$: Individuals who are infected and can spread the disease.
- $\boldsymbol{R}$ $(\boldsymbol{Recovered})$: Individuals who have recovered or died, and thus no longer participate in the transmission.

The model uses differential equations to represent the transitions between these compartments over time.

4.1. Formulating the SIR Model Based on Nipah Virus Data for Kerala in 2024

Given the data for the 2023-2024 Nipah virus outbreak in Kerala, we can structure the SIR model to reflect the situation.

4.1.1. Step 1: Parameters and Variables

- $\boldsymbol{S(t)}$: Number of susceptible individuals at time t.
- $\boldsymbol{I(t)}$: Number of infected individuals at time t.
- $\boldsymbol{R(t)}$: Number of recovered/removed individuals at time t.

Key Parameters

- $\boldsymbol{\beta}$: Transmission rate (how often a susceptible individual comes into contact with an infected individual).

- $\boldsymbol{\gamma}$: Recovery or removal rate (the rate at which infected individuals recover or die and move to the recovered compartment).
- $\boldsymbol{N}$: Total population in the containment zones (53,708 households * average number of individuals per household).

The total population size N remains constant, such that

$$S(t) + I(t) + R(t) = N$$

4.1.2. Step 2: Differential Equations

Susceptible ($\boldsymbol{S}$) equation

$$\frac{dS}{dt} = -\beta . S(t) . I(t)$$

This represents the rate at which susceptible individuals become infected based on the contact with infected individuals.

Infected ($\boldsymbol{I}$) equation

$$\frac{dI}{dt} = \beta . S(t) . I(t) - \gamma . I(t)$$

This represents the change in the number of infected individuals over time. The first term $\beta . S(t) . I(t)$ is the rate of new infections, and the second term $\gamma . I(t)$ is the rate of recovery.

Recovered (R) equation

$$\frac{dR}{dt} = \gamma . I(t)$$

This represents the rate at which infected individuals recover or die.

4.1.3. Step 3: Initial Conditions

Based on the Nipah outbreak data in 2024

- $\boldsymbol{S(0)}$: The initial number of susceptible individuals is approximately the population of the containment zone (World Health Organization (WHO))(National Centre for Disease Control).
- *Population under survey:* 53,708 households (assuming an average of 4-5 individuals per household, this gives a population of roughly 214,832 to 268,540 individuals in the containment zones).

$$\text{Thus, } S(0) \approx 53{,}708 \times 4 = 214{,}832.$$

Let us approximate population as 214,832, assume an initial number of infected individuals (based on contacts under observation), and model the spread using the SIR framework.

- $\boldsymbol{I(0)}$: The number of infected individuals in the outbreak. The specific number isn't mentioned, but we can estimate based on high-risk contacts identified and individuals under observation. For the sake of the model, let's assume a small initial infected population of around 10 individuals.

$$I(o) = 10$$

- $\boldsymbol{R(0)}$: Initially, recovered individuals would be zero since recovery happens after the outbreak begins, i.e.,

$$R(0) = 0.$$

Contacts identified: 1,288 individuals.

Individuals under observation for possible infection: 472.

Containment and recovery efforts: No widespread outbreak beyond initial contacts, which implies a relatively low number of infections compared to susceptible individuals.

4.1.4. Step 4: Estimating Parameters ($\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$)

γ (gamma): The recovery rate can be estimated based on the average infectious period. For Nipah, the infectious period is usually about 10-14 days. Let's assume an average infectious period of 12 days:

$$\gamma = \frac{1}{12} \approx 0.083\, days^{-1}$$

β (beta): The transmission rate can be estimated based on the contact rate and the probability of transmission per contact. In an outbreak scenario, it can vary based on interventions, but we'll estimate this later by fitting the model to real data or making an educated guess for the purposes of simulation.

4.1.5. Step 5: Solving the SIR Model

To proceed with solving the system of equations or simulate the progression of the outbreak using assumed parameters, we get the following result

4.2. Result Analysis

The simulation of the Nipah virus outbreak using the SIR model, assuming a transmission rate (β) of 0.4 and a recovery rate (γ) of approximately 0.083 (based on a 12-day infectious period).

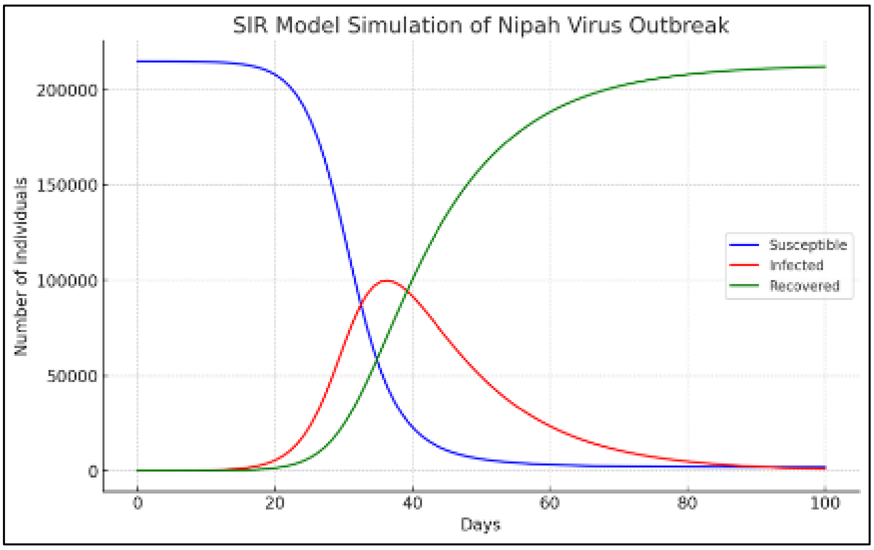

Figure 1 Simulation of Nipah Virus Outbreak

Observations:

- The number of infected individuals (red curve) rises initially, reaching a peak before gradually declining as individuals either recover or succumb to the infection.
- The susceptible population (blue curve) decreases as individuals become infected.
- The recovered population (green curve) increases steadily as the outbreak progresses and more individuals recover.

When we explore different scenarios by adjusting key parameters, such as:

- Higher transmission rate ($\boldsymbol{\beta}$): Reflects a scenario with less effective containment measures or higher contact rates.
- Lower transmission rate ($\boldsymbol{\beta}$): Simulates strict quarantine measures or improved public health interventions.
- Different recovery rate ($\boldsymbol{\gamma}$): Affects the duration of the infectious period, potentially reflecting variations in healthcare effectiveness.

- Varying the initial number of infected individuals ($\boldsymbol{I_0}$): Simulates an early versus late detection of the outbreak.

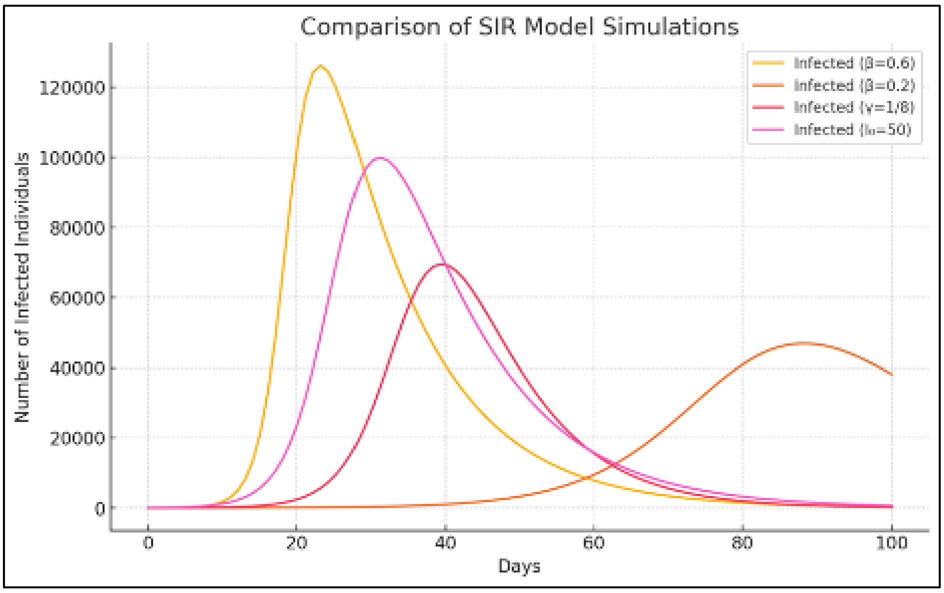

Figure 2 Comparison of SIR Model Simulations

The graph above compares several different outbreak scenarios, showing the number of infected individuals over time:

- Higher transmission rate ($\boldsymbol{\beta = 0.6}$): This leads to a more rapid and intense outbreak, with a higher peak of infections.
- Lower transmission rate ($\boldsymbol{\beta = 0.2}$): The outbreak spreads more slowly and reaches a much lower peak, indicating effective containment.
- Faster recovery rate ($\boldsymbol{\gamma = 1/8}$): With quicker recoveries, the infection curve is shorter, but the peak is still pronounced due to the moderate transmission rate.
- Higher initial infection ($\boldsymbol{I_0 = 50}$): Starting with more infected individuals leads to a faster spread, though the overall dynamics remain similar to the base case.

These simulations highlight how key factors like transmission rate, recovery rate, and initial infections impact the progression of an epidemic.

4.3. Numerical Simulation

Using these parameters and solving the system of ODEs numerically, the simulation provides insights into the outbreak's dynamics under different scenarios:

- Base Case ($\boldsymbol{\beta = 0.4, \gamma = 1/12, I_0 = 10}$)
  - *Susceptible Population (S):* Decreases rapidly as more individuals become infected. By the time infections peak (around 20-30 days), a significant portion of the population has transitioned from susceptible to infected.
  - *Infected Population (I):* Peaks around day 20-30, with approximately a few thousand individuals being infected at the peak before the outbreak starts to subside.
  - *Recovered Population (R):* Begins to rise around the time infections peak, eventually representing the majority f the population as they either recover or are removed.
- Higher Transmission Rate ($\boldsymbol{\beta = 0.6}$)
  - *Infected Population:* The infection rate rises much faster and peaks earlier than in the base case (within 10-20 days). A larger fraction of the population is infected at the peak.
  - *Susceptible Population:* Decreases much more quickly due to the rapid transmission.
  - *Recovered Population: Rises sharply after the infection peak.*
- Lower Transmission Rate ($\boldsymbol{\beta = 0.2}$)
  - *Infected Population:* Slower spread with fewer people infected at any given time. The infection peak occurs later (around 40-50 days), and the outbreak is more easily contained.
  - *Susceptible Population:* Decreases more gradually.

    - *Recovered Population:* Increases slowly due to the lower infection rate, and overall fewer people get infected.
- Faster Recovery Rate ($\boldsymbol{\gamma = 1/8}$)
    - *Infected Population:* The peak is slightly lower because people recover more quickly, reducing the number of active infections at any time.
    - *Recovered Population:* Rises faster due to quicker recovery times, reducing the strain on the system.
- Higher Initial Infection ($\boldsymbol{I_0 = 50}$)
    - *Infected Population:* The infection spreads more quickly in the early phase, but the overall dynamics are similar to the base case.
    - *Recovered Population:* Increases earlier due to the higher initial number of cases.

4.4. Characteristics of the final solution

- *Peak Infections*: In the base case, the infection curve peaks at around 20-30 days, where the number of infected individuals is highest.
- *Containment Measures:* A reduction in the transmission rate (lower β) or faster recovery (higher γ) effectively reduces the severity and duration of the outbreak.
- *Initial Outbreak Detection:* Early detection and isolation of initial cases significantly reduce the outbreak's impact.
- *Impact of Transmission Rate* ($\boldsymbol{\beta}$): The transmission rate significantly influences the speed and intensity of the outbreak. Higher transmission rates lead to faster increases in infected individuals, resulting in higher peak infections and a greater risk of healthcare system overload. Conversely, lower transmission rates result in a more gradual spread, allowing for better management and containment of the outbreak.
- *Importance of Recovery Rate* ($\boldsymbol{\gamma}$): The recovery rate plays a crucial role in determining how long individuals remain infectious. Higher recovery rates reduce the duration of the infectious period, leading to fewer active cases over time and a quicker resolution of the outbreak. Effective healthcare interventions that increase the recovery rate can significantly mitigate the impact of the virus on the population.
- *Role of Initial Infection Size* ($\boldsymbol{I_0}$): The initial number of infected individuals can greatly affect the trajectory of the outbreak. Higher initial infections can lead to quicker spread, emphasizing the importance of early detection and intervention strategies to limit the initial spread.

Need for Early Intervention: The simulations underscore the importance of early intervention strategies, such as rigorous contact tracing, quarantine, and public health campaigns, to lower the transmission rate and increase recovery rates. By implementing these strategies, public health authorities can effectively control outbreaks and reduce the overall burden of disease.

5. Conclusion

The study utilizing the SIR model to analyze the Nipah virus outbreak highlights the critical roles of transmission and recovery rates in determining the spread of infectious diseases. Key findings indicate that higher transmission rates lead to faster outbreaks and greater peak infections, while increased recovery rates help reduce the duration of active cases. Early intervention strategies, such as contact tracing and quarantine, are essential for effectively managing outbreaks. This study underscores the importance of adaptive public health policies and real-time data analysis to mitigate the impact of future infectious disease outbreaks.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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