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Solution of the Sir Epidemic Model for the Spread of Tuberculosis using the Fourth Order Runge-Kutta and Milne Method

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Abstract: Tuberculosis (TB) is an infectious disease of the human respiratory tract caused by the bacterium Mycobacterium tuberculosis (Mtb). The bacteria that cause TB are a type of bacillus bacteria that are very strong, so it takes a long time to treat this TB disease. This research is a literature study examining the mathematical model of SIR in TB disease. This research involves several stages, including the numerical integration of the SIR model, converting the resulting model into a computer programming language, performing numerical simulations, and observing solution graphs. This study aims to solve the SIR model of tuberculosis transmission using the fourth-order Runge-Kutta method and the Milne method. The resulting SIR model is a nonlinear differential equation model. The object of research in this study is the SIR Mathematical Model. The procedure for creating the SIR mathematical model consists of seven steps: case identification, establishing assumptions, creating the mathematical model, model analysis, model interpretation, model validation, and using the model. The research method employed is a literature study approach with a numerical component. Simulations were carried out twice for each method. The results of the numerical simulation in the MATLAB program show that both methods produce solutions with similar behaviour. However, in theory, the Milne method has a higher level of accuracy than the fourth-order Runge-Kutta method. The graph also shows that a population/individual suffering from tuberculosis will recover over time, assuming they undergo treatment or adopt a healthy lifestyle. The infection population will experience a decline towards an equilibrium point as time passes.

Keywords: Fourth-order Runge-Kutta Method; Milne method; SIR Model; Tuberculosis Transmission.

Introduction

Tuberculosis (TB) is a contagious disease that affects the human respiratory system and is caused by the bacterium Mycobacterium tuberculosis (M. tb). The bacteria that cause TB are a very strong type of bacillus, so it takes a long time to treat this disease. TB is spread through the air contaminated with M.tb, which is then inhaled and enters the lungs. This Mycobacterium is transmitted through airborne droplets, so a person with tuberculosis is a source of tuberculosis transmission to the surrounding population. The infectiousness of a sufferer is determined by the number of germs expelled from their lungs. The higher the degree of positivity in the sputum test result, the higher the risk of the sufferer contracting TB [1]. Patients infected with tuberculosis generally experience several symptoms, including: 1) Coughing for more than 3 weeks or coughing up blood, 2) Shortness of breath, 3) Chest pain, 4) Fever, 5) Night sweats, 6) Weight loss, 7) Fatigue, 8) Decreased appetite, and 9) Fever and chills.

Tuberculosis remains a major global health problem, especially in Indonesia. Most tuberculosis cases occur in low- and middle-income developing countries. Half of the TB population comes from eight countries: Bangladesh, China, India, Indonesia, Nigeria, Pakistan, the Philippines, and South Africa [2]. According to WHO (World Health Organization) data, the number of tuberculosis sufferers in Indonesia reaches 8.5% of the global number of sufferers, which is 10 million people [2]. The Global TB Report [3] reports that there are an estimated 824,000 TB cases in Indonesia. However, only 393,323 (48%) of these patients have been successfully identified, treated, and reported to the national information system. Approximately 52% of TB cases remain undetected or unreported. By 2023, the total number of tuberculosis cases in Indonesia will reach 969,000, with a death rate of 93,000 per year, equivalent to 11 deaths per hour [4]. Data on tuberculosis cases in East Flores Regency, as recorded by the East Nusa Tenggara Central Statistics Agency (BPS NTT), shows that the total number of tuberculosis cases in East Flores Regency reached 249 in 2022 [4]. This figure undoubtedly contributes to Indonesia's position as the country with the second-highest number of tuberculosis cases in the world after India.

The increasing number of tuberculosis cases indicates that tuberculosis is not a minor issue but a major problem that must be addressed urgently [5]. Discussing problems means we will also talk about finding solutions to those problems. One alternative to solving problems is to model the problem in mathematical language. This modelling is referred to as a mathematical model [6]. Mathematical modelling is one technique for representing a complex system as a mathematical model. In other words, mathematical modelling is a system of equations that can represent a complex problem being studied. Mathematical models consist of variables, parameters and functions that state the relationship between variables and parameters [7]. One method used to formulate real-world problems into mathematical models is the use of differential equations [8].

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Differential Equations (DD) is a branch of mathematics used to solve mathematical models of problems in everyday life. Furthermore, [9] stated that every physical situation related to the rate of change of another variable will lead to a differential equation [8]. This study aims to solve the SIR model using the 4th Order Runge-Kutta method and the Milne method. The Runge-Kutta method is one of the methods used to solve differential equations with given initial conditions [10]. The Milne method is a predictor-corrector method that involves using a single formula to make an initial prediction of the next yk value, followed by the use of a more precise correction formula that then produces sequential improvements [11]. The simulation results of both methods will analyze the behavior of the graphical solution.

In this study, two numerical simulations will be conducted for each method. These simulations are conducted to observe the behavior of the solution graphs for the fourth-order Runge-Kutta method and the Milne method. These graphs will provide information on the accuracy of each method.

Research Methods

The research method employed is a literature study, examining the SIR Model [12]. The procedure for creating a mathematical SIR model involves seven steps: case identification, establishing assumptions, creating a mathematical model, model analysis, model interpretation, model validation, and using the model to study the case. Furthermore, after the model is generated, it will be solved using the fourth-order Runge-Kutta method and the Milne method. The focus of this research is the numerical solution of the SIR Model.

The steps for solving the SIR model in this research focused on MATLAB programming and simulation. The SIR model is derived from seven modelling procedures, namely: case identification, assumption determination, model creation, model analysis, model interpretation, model validation, and using the model to study the problem [13]. The research flow for the spread of tuberculosis is detailed in five stages as follows [14]:

1. Applying the SIR model to the spread of tuberculosis.
2. Numerical Criticism of the SIR Model Using the Fourth-Order Runge-Kutta Method and the Milne Method.
3. Converting the critized model into a computer programming language/modifying the SIR model in MATLAB software.
4. Numerical simulation of the spread of tuberculosis using MATLAB.
5. Observing the resulting solution graph in MATLAB.
6. Analyzing the resulting solution graph.

A diagram illustrating the spread of tuberculosis in a population is presented below:

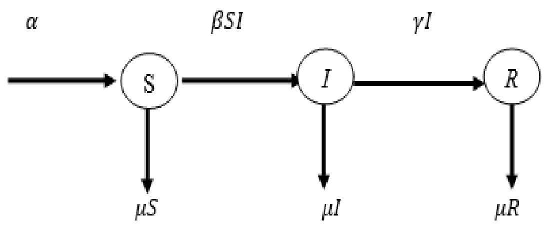


Figure 1. SIR model schematic

The SIR model schematic in Figure 1 above shows that transmission in each state represents a form of population dynamics. The SIR model is used to model a population consisting of susceptible (S), infected (I), and recovered (R) individuals, each representing the size of the corresponding group. Initially, all populations enter a susceptible subpopulation, where susceptible individuals transition to infected individuals, resulting in a reduction in the susceptible population and an increase in the infected population. Subsequently, individuals in the infected population who have recovered will move to the recovered population, resulting in an increase in the recovered population, while the infected population decreases [15]. This is due to the fact that all populations experience natural mortality.

The SIR model schematic illustrates that the number of susceptible populations (S) increases due to a birth rate of α. The schematic also emphasizes that each population will decrease or increase if transmission occurs between the susceptible, infected, and recovered populations. Each population in the SIR model will experience natural mortality, resulting in a reduction in the number of individuals within each population [16].

Based on the schematic above, the SIR model formulation is as follows:

$$\frac{dS}{dt} = \alpha - \mu S - \beta SI \quad (1)$$

$$\frac{dI}{dt} = \beta SI - \mu I - \gamma I \quad (2)$$

$$\frac{dR}{dt} = \gamma I - \mu R \quad (3)$$

With $N = S + I + R$

Table 1. Parameters and descriptions Parameters

Simbol	Defenition	Type	Condition	Unit
N	Total human population	variables	$N \geq 0$	Soul
S	Number of vulnerable individuals	variables	$S \geq 0$	Soul
I	Number of infected individuals	variables	$I \geq 0$	Soul
R	Number of individuals recovered	variables	$R \geq 0$	Soul
α	Birth rate	Parameter	$0 < \alpha < 1$	Per time
μ	natural death	Parameter	$0 < \mu < 1$	Per time
β	Rate of disease transmission	Parameter	$0 < \beta < 1$	Per time
γ	Recovery rate of infected individuals	Parameter	$0 < \gamma < 1$	Per time

Results and Discussion

In this section, we will discuss the TBC Mathematical Model using the Mathematical Modelling Procedure and the Solution of the SIR Model Using the Euler and Runge Kutta Fourth Order Methods.

SIR Model of Tuberculosis Disease Spread

Mathematical modelling is a method used to describe a real-world phenomenon in a mathematical form, making it easier to study and perform calculations. The representation of a mathematical model takes the form of a system of equations or a mathematical function. Mathematical modelling is a stage in mathematical problem solving. The goal is to analyze and understand real phenomena or problems more systematically and to be able to find solutions to these problems [17]. Based on Figure 1, the general procedure for implementing a mathematical model is outlined in several stages as follows:

Case Identification

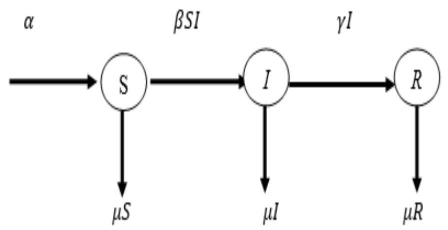
In the case of TB, the main problem identified is tuberculosis transmission in a population susceptible to TB, which then, through the stage of transmission by the Mycobacterium tuberculosis bacteria, becomes a population actively transmitting TB, thus reducing the number of susceptible populations by considering deaths and births assumed to directly enter the susceptible subpopulation.

Establishing Assumptions on TB Disease Transmission

The assumption-setting stage involves two stages: Identifying the factors causing disease transmission in general and specifically (or those potentially infected). The factors causing TB disease are as follows: Every individual in the population at time t is always in one of the sub-populations, namely susceptible (S), infected (I), or recovered (R), Individuals who have recovered from TB are in a closed environment, meaning there is no immigration or emigration, so the total population is constant, Every newborn and living individual enters the population susceptible to TB disease, TB disease is transmitted through direct contact, There is no incubation period, individuals who have recovered are not attacked by the disease, The population has a weak immune system, The environment is not supportive, natural death, It is assumed that there is no population that is susceptible again after recovery., It is assumed that individuals who have recovered from TB disease will be included in the recovered sub-population. Next, significant factors causing TB disease will be selected: Each individual in the population at any given time is always in one of the subpopulations: susceptible (S), infected (I), or recovered (R); Every newborn and surviving individual is included in the susceptible population; There is no incubation period; Every individual who has recovered from TB; There is natural mortality in a population; It is assumed that individuals who have recovered from TB will be included in the recovered subpopulation; It is assumed that no susceptible population re-emerges after recovery.

Model Construction

This section will involve two stages: schema formation and model construction. The diagram of the spread of tuberculosis in a population is presented in the following schema:



Based on the scheme above, the SIR model formulation can be obtained as follows:

$$\frac{dS}{dt} = \alpha - \mu S - \beta SI \quad (3)$$

$$\frac{dI}{dt} = \beta SI - \mu I - \gamma I \quad (4)$$

$$\frac{dR}{dt} = \gamma I - \mu R \quad (5)$$

With $N = S + I + R$

SIR Model Solution

The solution to the SiR Epidemic Model for the Spread of this disease was obtained through numerical simulation using MATLAB software. For all simulations, the initial values and parameter values are presented in Table 2. The initial values and parameter values in Table 2 are assumptions. The values in Table 2 were specifically chosen with the consideration that the simulation results will be quite accurate and the simulation process is relatively short (simulation only takes a few seconds on a laptop computer). The initial values and parameters selected are the result of assumptions about factors that influence TB transmission. The more accurate the parameter values, the more realistic the solution will be [18].

This section contains two subsections. The first subsection contains the solution for the SIR model using the 4th-order Runge-Kutta method. The second subsection reports the solution for the SIR model using the Milne method.

Table 2. Initial Values and Parameter/Variable Values for the Spread of Tuberculosis Disease (Researcher's Assumptions)

Parameter and Variable	Initial Condition Value	
	Simulation I	Simulation II
N	0.9877761287	0.9877761287
S	0.9806770567	0.9806770567
I	0.00709902	0.00709902
R	0.1256700	0.000000052
α	0.003002	0.003002
μ	0.0045000	0.0045000
β	0.62300000	0.62300000
γ	0.0088330	0.0088330

Solving the SIR model using the Fourth Order Runge Kutta method

The formulation of the Fourth Order Runge-Kutta method to solve the SIR model of the spread of Tuberculosis can be written as follows:

$$S_{n+1} = S_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \quad (6)$$

$$I_{n+1} = I_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \quad (7)$$

$$R_{n+1} = R_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \quad (8)$$

By substituting the initial values in Table 2, the simulation of solving the SIR model using the Fourth Order Runge Kutta method will be obtained as follows:

a) Simulation I

The initial data values in Table 2 for Simulation I with $h = 0.1$ in the SIR model equation above produce a solution graph, namely:

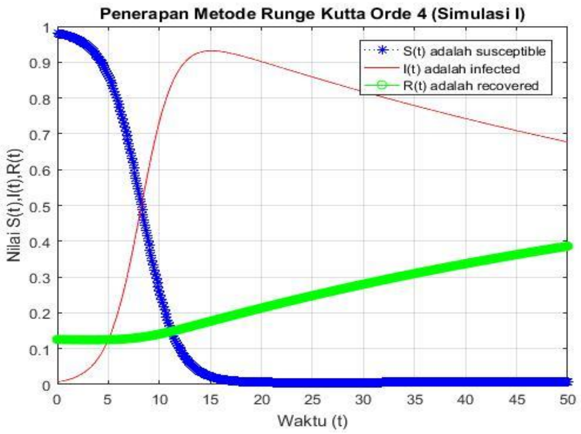


Figure 2. Graph of the solution for the tuberculosis transmission system of the SIR epidemic model using the Fourth Order Runge Kutta method (Simulation I)

Figure 2 illustrates that at the onset of the disease outbreak, the number of susceptible individuals (S), initially 0.9806770567, will decrease over time due to interactions with the infected population (I). This is indicated by the decreasing blue line on the graph. The number of infected individuals (I) will increase over time until it reaches a peak at a certain point (between days 10 and 15), and then decrease as they recover and develop immunity. Recovered individuals (R) will continue to increase over time and eventually reach a stable number. This is illustrated by the increasing green line on the graph.

b) Simulation II

By using the MATLAB program for Simulation II, a solution graph is obtained, as shown in Figure 3 below.

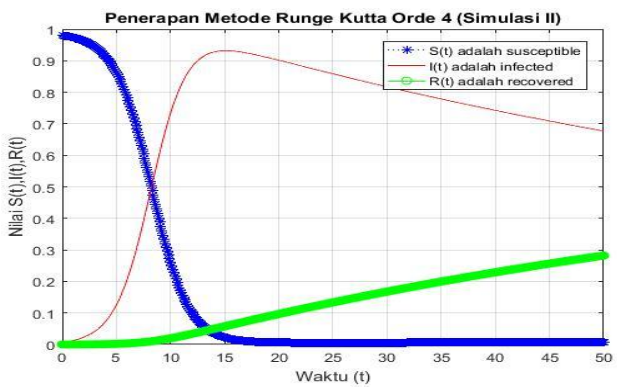


Figure 3. Graph of the solution for the tuberculosis transmission system of the SIR epidemic model using the Fourth Order Runge Kutta method (Simulation II)

Figure 3 above shows a graph behavior that is relatively similar to the graph in Figure 2. Initially, no individuals have recovered. However, due to the rate of recovery of infected individuals, the recovered population will gradually increase over time. This is illustrated by the upward-moving green line on the graph. This figure also clearly shows that the susceptible population will initially decline but will eventually stabilize because it does not interact with the infected and recovered populations.

Solving the SIR model using the Milne method

The Milne method for solving the SIR model, which is considered to have a predictor-corrector numerical scheme, is as follows [19-21]:

Predictor:

$$S^*_{n+1} = S_{n-3} + \frac{4h}{3}[2(\alpha - \mu S_{n-2} - \beta S_{n-2}I_{n-2}) - (\alpha - \mu S_{n-1} - \beta S_{n-1}I_{n-1}) + 2(\alpha - \mu S_n - \beta S_n I_n)] \quad (9)$$

$$I^*_{n+1} = I_{n-3} + \frac{4h}{3}[2(\beta S_{n-2}I_{n-2} - \mu I_{n-2} - \gamma I_{n-2}) - (\beta S_{n-1}I_{n-1} - \mu I_{n-1} - \gamma I_{n-1}) + 2(\beta S_n I_n - \mu I_n - \gamma I_n)] \quad (10)$$

$$R^*_{n+1} = R_{n-3} + \frac{4h}{3}[2(\gamma I_{n-2} - \mu R_{n-2}) - (\gamma I_{n-1} - \mu R_{n-1}) + 2(\gamma I_n - \mu R_n)] \quad (9)$$

Corrector:

$$S_{n+1} = S_{n-1} + \frac{h}{3}[(\alpha - \mu S_{n-1} - \beta S_{n-1}I_{n-1}) + 4(\alpha - \mu S_n - \beta S_n I_n) + (\alpha - \mu S^*_{n+1} - \beta S^*_{n+1}I^*_{n+1})] \quad (11)$$

$$I_{n+1} = I_{n-1} + \frac{h}{3}[(\beta S_{n-1}I_{n-1} - \mu I_{n-1} - \gamma I_{n-1}) + 4(\beta S_n I_n - \mu I_n - \gamma I_n) + (\beta S^*_{n+1}I^*_{n+1} - \mu I^*_{n+1} - \gamma I^*_{n+1}] \quad (12)$$

$$R_{n+1} = R_{n-1} + \frac{h}{3}[\gamma I_{n-1} - \mu R_{n-1}) + 4(\gamma I_n - \mu R_n) + (\gamma I^*_{n+1} - \mu R^*_{n+1})] \quad (13)$$

Based on the Milne equation, a tuberculosis disease solution model will be simulated using the initial data in Table 2.

a) Simulation I

Using MATLAB for simulation I, the solution graph is obtained as shown in Figure 4 below:

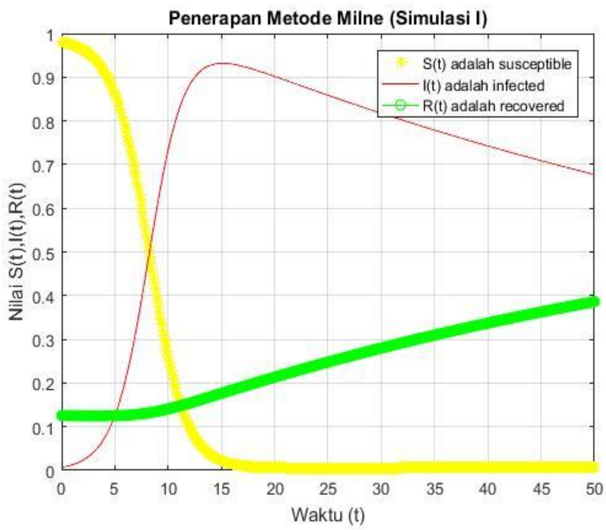


Figure 4. Graph of the solution for the tuberculosis transmission system of the SIR epidemic model using the Milne method (Simulation I)

Figure 4 shows that this approach is quite accurate compared to the Runge-Kutta method. This approach assumes that all individuals in the population are affected by tuberculosis, including those who are susceptible, infected, and recovered. The recovered population will increase and stabilize over time because it does not interact with the susceptible or infected populations.

This graph also shows that the susceptible population will experience a decline as individuals interact with the infected population and reach a state of equilibrium.

b) Simulation II

Based on MATLAB, a graph of the completion of the SIR model will be obtained as follows:

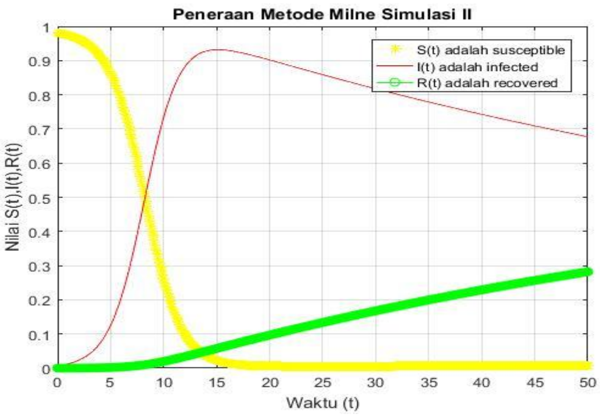


Figure 5. Graph of the solution for the tuberculosis transmission system of the SIR epidemic model using the Milne method (Simulation II)

Figure 5 shows the interaction between the susceptible population, the infected population, and the recovered population. Changing the initial parameter values significantly impacts the resulting solution graph. The higher the initial value assigned to each parameter, the faster the rate of change. The figure above also shows that the recovered population will continue to increase, meaning it will recover after interacting with the susceptible and infected populations. This increase in recovery also assumes that, after individuals are infected with the disease, they will undergo treatment and/or maintain a healthy lifestyle, ultimately leading to recovery.

Based on the simulation results and analysis of the solution graph, it is evident that changes in the number of individuals in each population are influenced by the interactions between the three populations. Furthermore, the parameters assigned initial values also significantly influence the resulting solution graph. The initial values used in each numerical simulation significantly influence the determination of realistic solutions for each simulation. Incorrect or erroneous initial values will result in unrealistic solution graphs.

Conclusion

The solution to this model is presented in the form of a numerical solution graph generated through simulation in the MATLAB program. The results of the analysis of the solution graph show that both methods produce solutions with the same behavior. However, it should be noted that, theoretically, the Milne method has a higher level of accuracy compared to the fourth-order Runge-Kutta method, but both models are very suitable for solving nonlinear equations. The graph also shows that a population/individual suffering from tuberculosis will recover over time, assuming they undergo treatment or adopt a healthy lifestyle. The infection population will experience a decline towards the equilibrium point as time passes. The resulting graph shows that the interaction between each population can influence changes in population size, in this case, increasing or decreasing the number of each population. Furthermore, the initial values used also have a significant impact on the changes in the graph, so careful consideration is required when selecting these initial values.

Author's Contribution

Roberta Uron Hurit: Contribution in this research is to create a mathematical model of SIR and simulate the Model in Matlab Program and analyze the Solution Graph. Veronika Lapeng: contributed to discretizing the mathematical model into the Fourth Order Runge Kutta method and the Milne Method, Irwanius Piter Muaraya: contributed to analyzing the Solution Graph.

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