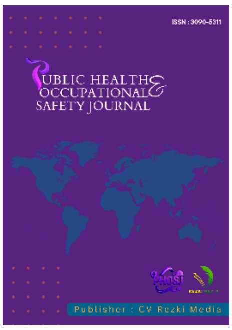

Correlation analysis of vaccination coverage, positivity rate, and community mobility rate on COVID-19 effective reproductive rate: SIR modeling study from Indonesia

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ABSTRACT

Background: Effective Reproduction Rate (Rt) is used to evaluate COVID-19 transmission; although Tegal City has the lowest cumulative cases in Central Java, the spread of the virus remains rapid. Intervention efforts are carried out through vaccination coverage, positivity rate, and level assessment as a shared responsibility to reduce the transmission rate.
Objectives: The purpose of this study was to estimate the spread of COVID-19 with the intervention and to determine whether there is a correlation between the COVID-19 Rt Number and vaccination coverage, positivity rate, and level assessment situation in Tegal City.
Methods: Observational quantitative research design. The type of research used was SIR (Susceptible Infected Removed) mathematical modeling and descriptive analysis through an ecological study approach and Spearman correlation statistical analysis.
Results: The results of the study showed a decrease in the number of cases of vulnerable and infected subpopulations after public health interventions, followed by the results that the positivity rate and level assessment situation were significantly correlated with the strength of the relationship powerful to the Covid-19 Effective Reproductive Rate with values (r=0.856; p=0.00) and (r=-0.712; p=0.00), while vaccination coverage was not statistically significantly correlated with a value of (r=-0.209; p=0.137).
Conclusions: The positivity rate and COVID-19 level assessment situation were statistically significantly correlated to the effective reproductive rate of COVID-19 in Tegal City with a strong correlation. Meanwhile, vaccination coverage did not correlate statistically with effective reproductive rate. Further studies must evaluate the effectiveness of combined interventions (vaccination + testing + mobility restriction) in various epidemiological settings.

Keywords: effective reproductive rate, positivity rate, vaccination coverage.

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INTRODUCTION

Estimating the level of COVID-19 transmission for evaluating public health interventions can be seen from the Reproductive Number. Reproductive numbers consist of the Basic Reproductive Number (hereinafter abbreviated as R0) and the Effective Reproductive Number (hereinafter abbreviated as Rt). The calculation of R0 is done at the beginning of the pandemic, while Rt is done after an intervention in the population. This study focuses on the Effective Reproductive Number, the number of new cases from old cases in a population that is half susceptible or has had an intervention. The calculation of the Rt number is carried out throughout the existence of an outbreak, such as during the COVID-19 pandemic. Transmission will continue as long as the Rt > 1 because positive cases will multiply exponentially. The calculation of Rt is done by estimating mathematical epidemiological models such as SIR (Susceptible Infected Removed) or SEIRD (Susceptible Exposed Infected Removed Death), which depends on the way of reporting and public health intervention strategies to control pandemic outbreaks (Linka, Peirlinck, & Kuhl, 2020; Xiang et al., 2021; Xiong et al., 2024).

The SIR mathematical model is a model that classifies the population into three (3) groups that can be described as S (Susceptible), which is a healthy subpopulation at risk of disease infection; I (Infected), which is a subpopulation that is infected with the disease and has been confirmed using a PCR (Polymerase Chain Reaction) swab test or rapid antigen test, and R (Recovered), which is a subpopulation that is resistant and has immunity to disease or individuals who recover or die. The total population of all these groups is N=S+I+R. Mathematical modeling using the SIR equation is used to explain the optimum point of spread of outbreak infection, predict the end of the outbreak, determine the number of individuals susceptible to infection with the outbreak, and can also be estimated for the basic and effective reproductive values of Covid-19 (Wahyudi & Palupi, 2021).

The COVID-19 Rt number worldwide and in Indonesia has experienced fluctuating developments. The Rt number from July 2021 to June 2022 increased by 0.15 from 1.04-1.19. Meanwhile, in Indonesia, during the same period, it experienced a decrease in the impact of a decrease in daily cases, the BOR (Bed Occupation Rate) decreased, and the recovery rate increased by 0.09 from the Rt Number 1.34-1.26 even though it was still in the high transmission rate category (Mathieu et al., 2020). Several epidemiological regions in Indonesia, provinces, and districts/cities experienced a decrease in Rt. The Rt. rate also improved on all islands, with an average of 0.99 as of April 2022, such as in the provinces of Central Java, West Java, and North Kalimantan, with Rt—rates less than 1 (Kemenkes, 2022). Meanwhile, the Rt rate in Tegal City increased in February - March 2022 but began to decline in May 2022, and on average, the Rt rate in Tegal City was less than 1 (Dinas Kesehatan Kota Tegal, 2022).

The high virus transmission rate caused the Tegal City government to carry out community mitigation strategies and public health interventions such as COVID-19 vaccination, massive tracing and testing, mobility restrictions from level assessment, self-quarantine and isolation, and socialization on appropriately protecting oneself from the virus. In this study, when Tegal City began to relax intervention measures, researchers were interested in correlating several public health interventions with the dynamics of the COVID-19 Rt Rate. This is due to Indonesia's lack of literature examining the COVID-19 Rt Number against public health interventions. In Tegal

City, the calculation of the Rt number was carried out consistently so that every week, the condition of the virus transmission rate in the population could be presented, which was integrated with the evaluation of public health interventions that had been carried out.

The local government intensively carries out public health interventions, namely vaccination coverage, positivity rate, and situation assessment of the COVID-19 level in Tegal City. COVID-19 vaccination coverage in Tegal City for dose one and dose two has exceeded the target of >70%, namely 115.55% and 97.80%, while for dose 3, it is still far below the target of 33.83%, data until June 30, 2022 (Dinas Kesehatan Kota Tegal, 2022). The research of Mu'tamar et al. (2021) found that the intervention of COVID-19 vaccination can reduce the Rt number below one. The Rt number will be influenced by the effectiveness of control measures such as COVID-19 vaccination to achieve herd immunity and as a parameter for intervening to reduce the rate of virus spread in the community (Ganasegeran et al., 2021).

A high COVID-19 positivity rate will reduce the Rt below 1 (Kucharski et al., 2020). In Tegal City, the positivity rate tended to increase in the first few weeks of 2022 but decreased in April-May and increased again in June 2022, until in week 31, the positivity rate in Tegal City reached 14.06%, which exceeded the WHO standard limit of 5% (Dinas Kesehatan Kota Tegal, 2022). This indicates that the number of positive cases in the community is still high, or it can be said that there are 15 positive people out of 100 specimens tested either by PCR (Polymerase Chain Reaction) swab test or rapid antigen test. The low positivity rate indicates that the number of people who are positive from the number of specimens examined is small; this will affect the decrease in the effective reproduction rate of COVID-19. Research conducted in Osaka, Japan, found a relationship between the positivity rate and the effective reproduction rate of COVID-19 (Furuse et al., 2021).

Population mobility policy in Indonesia is carried out by assessing the level of the COVID-19 situation according to the epidemiological region both nationally, provincially and city/district. The policy of tightening community mobility was carried out through PPKM (Enforcement of Restrictions on Community Activities) by the assessment of the Covid-19 situation level every week as stated in the Decree of the Minister of Health Number HK.01.07/Menkes/4805/2022, which was updated with the Decree of the Minister of Health Number HK.01.07/Menkes/762/2022 and the Instruction of the Minister of Home Affairs (INMENDAGRI) Number 18 of 2022. The assessment level situation in Tegal City in February - March 2022 was at level 4, which means that the implementation of social restrictions is rigorous because virus transmission is still high, but after that, it continues to decline. Population mobility policies such as restrictions on activities outside the home can reduce the high COVID-19 Rt Rate, such as the results of the Kajitani & Hatayama study (2021), which examined the results of the effect of mobility on the Rt Rate in Japan.

Based on the background of the problems described, namely COVID-19 vaccination, positivity rate, and level assessment situation during the pandemic on the effective reproduction rate of COVID-19, which has not been widely studied, the researchers are interested in analyzing the correlation of this topic. In addition, the research of Furuse et al. (2021), which has limitations from unexamined variables such as vaccination and community mobility policies, which are assumed to affect the COVID-19 Rt Number, can be used as renewable research, as in Linka et al.'s research, (2020) which focuses on finding that there is a strong correlation between social mobility restrictions and Rt Rates, which also does not include other public health interventions. The combination of several variables in this study, which are assumed to affect the COVID-19 Rt Rate, is expected to be used to evaluate policies in tackling COVID-19 transmission cases, especially in Tegal City, which is a COVID-19 epidemiology area with the lowest cases in Central Java but a high transmission rate. The purpose of this study is to estimate the level of COVID-19 spread using SIR mathematical modeling with intervention and to know and examine how there is or is not a correlation between the effective reproductive rate of COVID-19 with vaccination coverage, positivity rate, and COVID-19 level assessment in Tegal City.

METHODS

Study Design and Participants

This research design is mathematical epidemiological modeling and observational quantitative. Epidemiological modeling uses the SIR (Susceptible Infected Removed) mathematical model to estimate the spread rate of the COVID-19 virus with simulation analysis using Maple 2013 software.

The SIR model was validated using the goodness-of-fit method, comparing the model simulation results with actual data on weekly COVID-19 cases in Tegal City. The coefficient of determination (R^2) was used to assess how the model could explain variations in actual data. In addition, a visual analysis was conducted using a trend graph comparison between the model simulation output and empirical data as a form of qualitative validation. The data used were weekly data from July 2021 to June 2022 verified and completed by the Tegal City Health Office. Weeks with incomplete data, such as no positivity rate or vaccination reports, were excluded from the analysis to avoid calculation bias. Therefore, only data with complete information on all variables were included in the analysis.

This type of quantitative research is descriptive, with an ecological study approach conducted in November 2022 - February 2023 and located in Tegal City. The data used in the study were secondary data taken from the Tegal City Health Office, including COVID-19 and COVID-19 vaccination report documents from all data records in the period of July 2021 to June 2022 as the population and at the same time, the sample, because it used total sampling with a sample in the form of (n) COVID-19 records for all villages in Tegal City as the unit of analysis. The period data taken in this study was adjusted to the implementation of the COVID-19 level assessment regulation, which came into effect from the beginning of July 2021 until the implementation of level 1 generalization in all provinces in July 2022.

Ethical approval statement

This study has received ethical approval from the Ethics Institute of the Faculty of Medicine, Universitas Airlangga, with ethical certificate number 167/HRECC.FODM/II/2023. The study did not involve direct interaction with human subjects because it used secondary data from official agencies, and the principles of research ethics carried out all procedures.

Research Instruments

Data collection techniques were carried out using the documentation method, which examined the contents of document reports or databases of the Tegal City

Health Office with research instruments using non-test instruments in the form of documentation. The dependent variable is the Effective Reproduction Rate of COVID-19, which is defined as the average number of people infected due to exposure from one sick person, which is calculated per week from July 2021 to June 2022, with three (3) categories, namely Rt < 1 case decreases, Rt = 1 case stagnates, and Rt > 1 case multiplies. The independent variables are Vaccination Coverage, Positivity Rate, and Covid-19 Level Assessment. Vaccination coverage is defined as the cumulative coverage of COVID-19 vaccination from July 2021 to June 2022 in people who have been vaccinated with COVID-19 up to dose two at all ages calculated per week, with three (3) categories, namely >70% adequate, 50-70% moderate, and <50% limited. The positivity rate is defined as the proportion of the number of specimen examinations compared to positive specimen results calculated weekly from July 2021 to June 2022, with three (3) categories, namely <5% adequate, 5-15% moderate, and >15% limited. Meanwhile, the Covid-19 level assessment is defined as the Covid-19 situation level calculated from the indicators of the transmission level category, response capacity level category, and vaccination level category per week from July 2021 to June 2022, with four (4) categories, namely level 1, level 2, level 3, level 4.

Data Analysis

Data analysis was performed with descriptive statistical tests to see the distribution of characteristics, components, and data distribution and bivariate analysis with Spearman correlation statistical tests to determine the correlation between the dependent variable (Effective Reproductive Rate) and the independent variable (Vaccination Coverage Positivity Rate, and Situation Assessment Level).

RESULTS

Simulation Overview of the Spread of Covid-19 Cases in Tegal City Using the SIR Model

The SIR (Susceptible Infected Removed) mathematical modeling used in estimating the spread of cases after the intervention is shown in Figure 1.

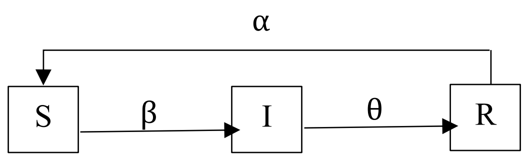

Figure 1. Schematic of SIR Mathematical Model

Constant variables and parameters states:

S(t): Susceptible subpopulation, healthy individuals who are susceptible to the virus.

I(t): Infected subpopulation, individuals who have been confirmed to be infected with the virus using PCR and antigen swab tests.

R(t): Removed subpopulation, individuals who are free of the virus, either recovered or dead.

β: the success rate of infection from the infected population to the susceptible population.

θ: the rate of recovery (death) of the infected population.

α: vaccination control effectiveness index, positivity rate, and assessment level.

Based on the scheme of Figure 1, the SIR mathematical model used to describe the spread of COVID-19 infection can be described through a non-linear differential equation as follows:

$$\frac{dS(t)}{dt} = -\beta S(t)\frac{I(t)}{N}$$
$$\frac{dI(t)}{dt} = \beta S(t)\frac{I(t)}{N} - \alpha(t) - \theta(t) \quad (1)$$
$$\frac{dR(t)}{dt} = \theta I(t)$$

The total population at each time is N = S(t) + I(t) + R(t). Therefore, the population at each time is constant so that the model can be transformed into a dimensionless model. Defined as s(t)=(S(t))/N,i(t)=(I(t))/N,r(t)=(R(t))/NThe dimensionless SIR model of the spread of COVID-19 in Tegal City is obtained as follows:

$$\frac{ds}{dt} = -\beta si$$
$$\frac{di}{dt} = \beta si - \alpha i - \theta i \quad (2)$$
$$\frac{dr}{dt} = \theta i$$

$$\frac{ds}{dt} = \frac{di}{dt} = \frac{di}{dt} = 0$$

The endemic equilibrium point of the SIR model is obtained at the time so that equation (3-5) is obtained.

$$\frac{ds}{dt} = -\beta si = 0 \quad (3)$$
$$\frac{di}{dt} = \beta si - \alpha i - \theta i = 0 \quad (4)$$
$$\frac{dr}{dt} = \theta i = 0 \quad (5)$$

The effective reproductive number is the number of reproductions during an epidemic that can reduce or increase the spread of the virus as a function of the prevention and control measures of public health interventions, so it is set as follows $\frac{di(t)}{dt} > 0$ in equation (2) without the control μ=0. In order for infected individuals to spread the infection, since i(t)≠0, with an initial population s(t)≈1, the basic and effective reproduction numbers of the SIR equation model (2) are expressed by:

$$R0 = \frac{\beta}{\theta} \quad (6)$$

$$Rt = R0 \times \alpha(t)\frac{S}{N} \quad (7)$$

The disease will spread if Rt>1

To simulate the COVID-19 virus spread model in Tegal City, it was determined by estimating the parameter values in the SIR model to explain the condition of the disease spread that will be displayed on the curve based on the data listed in Table 1.

Table 1. Parameter Estimation Value

Variable/parameter	Estimation Value
S	250.139
I	0,0176741732
R	0,0175582376
β	0,14
θ	0,4999999998
α	6,5507727705

Source: Dinas Kesehatan Kota Tegal (2022)

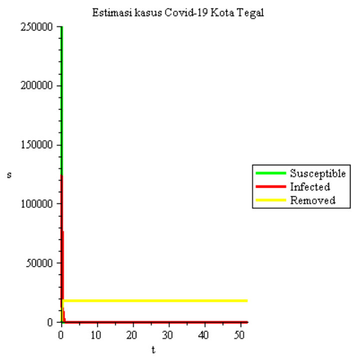

Figure 2. Simulation of the Spread of Covid-19 Cases in Tegal City with the SIR Model

Figure 2 shows that the number of people in the Susceptible and Infected subpopulations decreased constantly, while for the Removed subpopulation, the number of people increased significantly. The results of the research on the SIR model of COVID-19 transmission in Tegal City by looking at the correlation of the application of public health interventions such as vaccination, testing for positivity rates, and social mobility from the results of the COVID-19 level assessment showed that the higher the application of public health interventions in Tegal City, the rate of spread decreased. Side et al.'s research (2022) showed that implementing 3M in Makassar City could reduce the rate of transmission of COVID-19 cases using SEIR (Susceptible Exposed Infected Removed) modeling.

From equation (6), the reproduction number (R0) with the calculated parameters, an R0 value of 0.28 was obtained. This value is the reproductive value of COVID-19 in all observations made in this study. The value of R0 = 0.28 means that the transmission rate of COVID-19 cases in the Tegal City area is decreasing. Meanwhile, the value of the effective reproductive number (Rt) from the calculation of equation (7) COVID-19 Tegal City in all observations was 1.83, which means that it can be explained by the existence of public health interventions such as COVID-19 vaccination, ratio testing, and restrictions on social mobility that the Tegal City government has carried out have not reduced the rate of transmission in the community.

$$\text{R0} = \frac{\beta}{\theta} \qquad \{\beta=0{,}14;\ \theta=0{,}497\}$$

$$R0 = 0{,}28$$

$$Rt = R0 \times \alpha(t)\frac{S}{N} \qquad \{\alpha=0{,}651;\ S/N=1\}$$

$$Rt = 1{,}83$$

Overview of COVID-19 Cases in Tegal City

The trend of weekly positive cases from July 2021 to June 2022 in Tegal City can be seen in Figure 3. which illustrates the peak increase in the seventh week of 2022 or February 2022, reaching 797 cases. This was influenced by the second wave after the new COVID-19 variant, Omicron, entered the Indonesian epidemiological region and the relaxation of public health interventions due to long holidays. Furthermore, weekly positive cases declined after the Tegal City government tightened health interventions such as social restrictions, intensified COVID-19 vaccination, and added specimen tests for tracing COVID-19 patients.

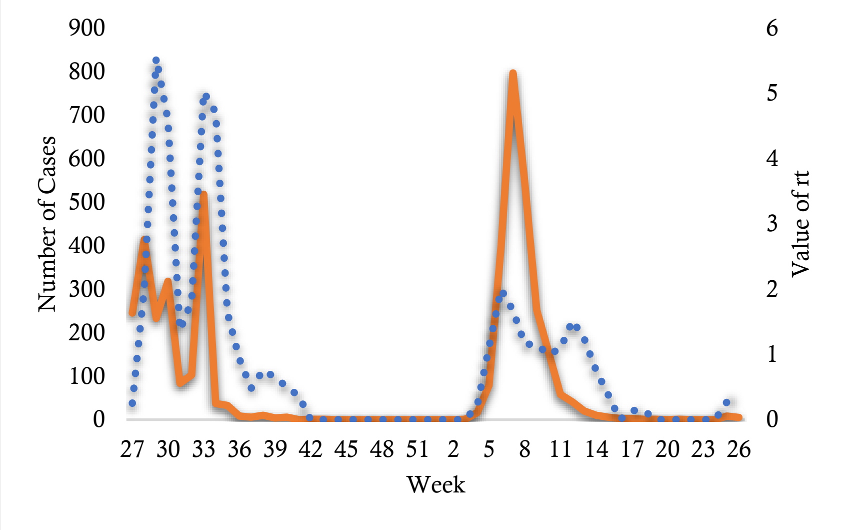

Figure 3. Trend of Number of Positive Cases with Covid-19 Rt Score in Tegal City

The orange line illustrates the dynamics of the COVID-19 outbreak in Tegal City. The blue dots represent the Effective Reproduction Rate (Rt) of COVID-19 every week in Tegal City. The COVID-19 Rt in Tegal City peaked during July - August 2021. This is due to inadequate specimen testing targeting contact groups and low vaccination coverage, so transmission is still spreading in vulnerable communities. This high Rt rate will affect the trend of positive COVID-19 cases after 5 - 14 days since the positive patient is in the latent period of first contracting the virus and can transmit it to others.

The COVID-19 Rt number in Tegal City has a maximum value of 5.55, which results in multiple positive cases and a minimum value of 0.00 or cases experiencing stagnant conditions with a median Rt number of 0.32. The average Rt in the population was between 0.49 and 1.24, with a 95% confidence level. COVID-19 vaccination coverage in Tegal City up to dose 2 had a cumulative maximum value of 98.49%, which exceeded the government target of 70% with a median value of 78.36%.

The average coverage of COVID-19 vaccination in Tegal City was 68.89%, with a 95% confidence interval between 60.69% - and 77.09% (Table 2). The lowest positivity rate of Covid-19 in Tegal City was 0.00%, and the maximum was 55.88% with an average value of 10.13% (CI = 5.68% - 14.58%), which means that out of 100 people tested using both PCR (Polymerase Chain Reaction) and rapid antigen tests, there were 11 people (± 6-15 people) who were positive for Covid-19 infection. This indicates that the examination of specimen samples in Tegal City is still slightly above the WHO (World Health Organization) standard of <5%.

Table 2. Effective Reproductive Rate, Vaccination Coverage, Covid-19 Positivity Rate

Variable	N	Min-Max	*Mean*	Median	SD	95% *CI for Mean*
Effective reproductive rate (Rt)	52	0,00–5,55	0,86	0,32	1,35	0,49–1,24
COVID-19 vaccination coverage	52	12,47–98,49	68,89	78,36	29,46	60,69–77,09
Positivity rate Covid-19	52	0,00–55,88	10,13	1,77	15,99	5,68–14,58

The proportion of the effective reproductive rate (Rt) of COVID-19 in Tegal City in the period July 2021 to June 2022 was mainly in the Rt < 1 category (67.3%), which means that COVID-19 cases tend to decrease. However, it was in the Rt > 1 category several times at 30.8%, indicating that COVID-19 cases experienced an exponential increase during the latent period. This high Rt number during the wave two and wave 3 periods in the Indonesian region, namely around July - August 2021 and February - March 2022, was triggered by new COVID-19 variants, namely Delta and Omicron.

The cumulative coverage of COVID-19 vaccination in Tegal City up to dose two has been adequate, with a proportion exceeding the target of >70% by 61.5%, with a total coverage of 98.49% of people. Meanwhile, the proportion of COVID-19 patient specimen sample examinations in Tegal City or the positivity rate has been in the adequate category of 65.4%, which has met the WHO standard of <5%. Likewise, the COVID-19 pandemic level assessment in Tegal City was mainly at Level 1, with a proportion of 44.2%. Thus, the joint public health interventions carried out by Tegal City have run according to and meet the standards set.

Table 3. Proportion of Effective Reproductive Rate by Public Health Intervention

Public Health Interventions	Effective Reproduction Rate (Rt)		
	Multiple (%)	Stagnant (%)	Decreased (%)
Covid-19 vaccination coverage			
- Adequate	15,4	1,9	44,2
- Medium	-	-	11,5
- Limited	15,4	-	11,5
Positivity rate COVID-19			
- Adequate	1,9	-	63,5
- Medium	9,6	-	1,9
- Limited	19,2	1,9	1,9
Covid-19 level assessment			
- Level 1	1,9	-	42,3
- Level 2	3,9	-	21,1
- Level 3	7,7	1,9	1,9
- Level 4	17,3	-	1,9

Maximum and targeted joint public health interventions have been shown to reduce the Rt rate in Tegal City. Table 3 shows that 44.2% of adequate COVID-19 vaccination coverage had a low Rt rate or decreased cases. The adequate COVID-19 positivity rate also had a high Rt < 1 of 63.5%, indicating that the examination ratio of 1 per 1000 per week was achieved, which could reduce the Rt below 1. In the COVID-19 pandemic, level assessment at Level 1 of 42.3% had a high Rt < 1, indicating that in the situation of community transmission with limited social restrictions, the Rt also decreased.

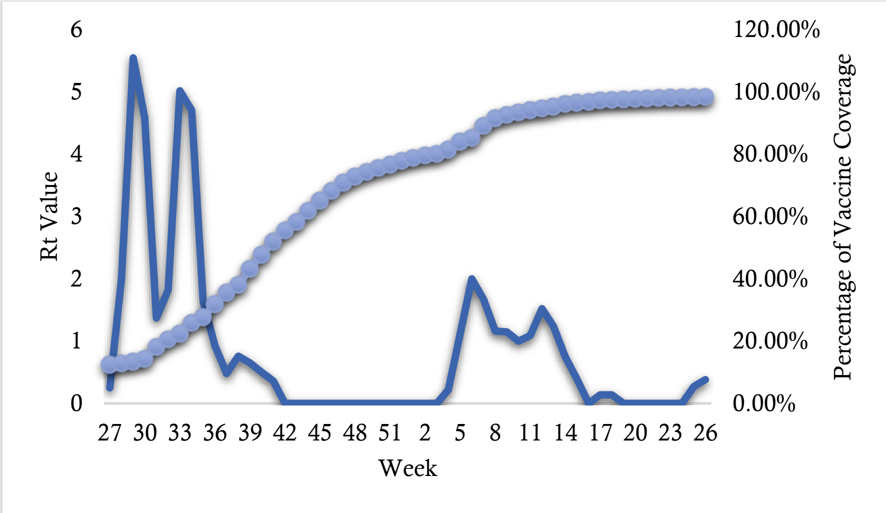

Figure 4. Vaccination Coverage Trend with Covid-19 Rt Rate Tegal City

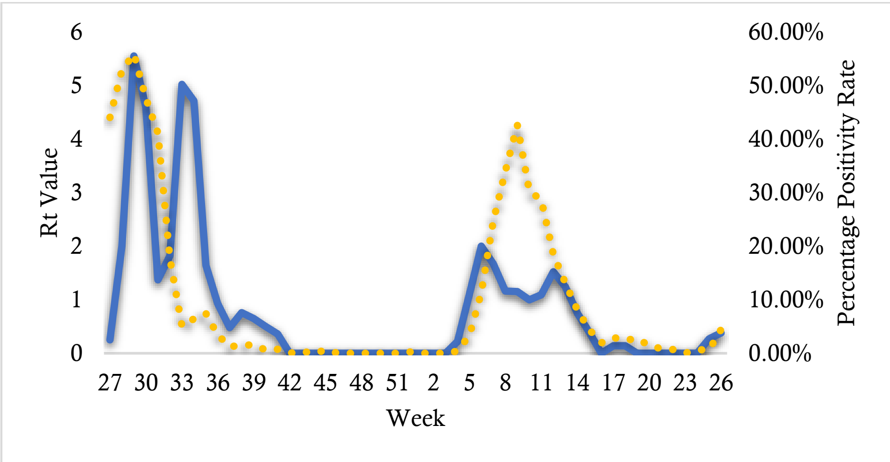

Figure 5. Positivity Rate Trend with Covid-19 Rt Number Tegal City

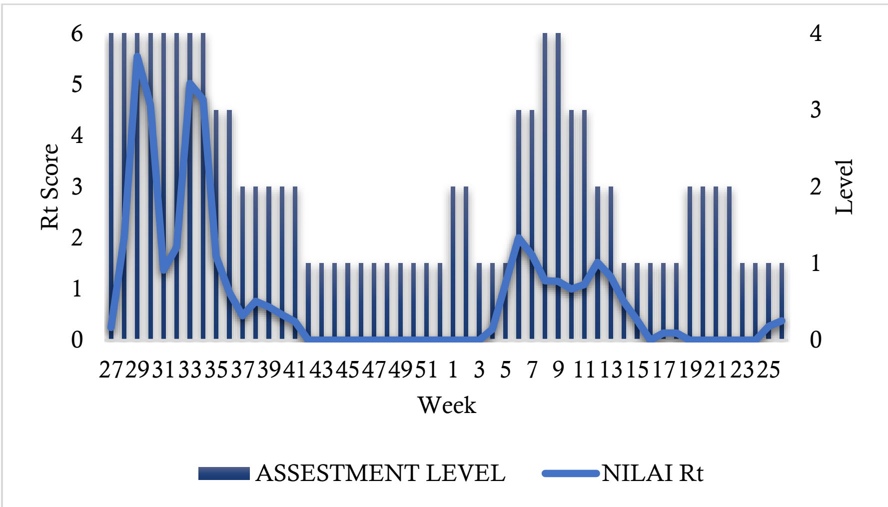

Figure 6. Trends in Level Assessment with Covid-19 Rt Score Tegal City

The weekly trend graph presented above shows that the joint public health interventions of vaccination coverage, positivity rate, and COVID-19 level assessment can explain the fluctuating Rt rate in Tegal City. Figure 4 shows that the trend graph of vaccination coverage with the COVID-19 Rt Rate in Tegal City shows that the more the population is vaccinated, the more the COVID-19 Rt Rate decreases in the graph of Figure 5. An adequate or low positivity rate value decreases the COVID-19 Rt Score in Tegal City. Meanwhile, Figure 6 shows that the higher the Rt value, the tighter the social mobility restrictions at level 4 in Tegal City.

Correlation between Joint Public Health Interventions and COVID-19 Effective Reproductive Rate

Table 4. Correlation Analysis Results Between Rt Rate Variables with Vaccination Coverage, Positivity Rate, and Level Assessment

Variable	N	P	*Ro*	Keterangan
Rt Rate with Vaccination Coverage	52	0,137	−0,209	No Correlation, Low Correlation Strength, Negative Direction
Rt with Positivity Rate	52	0,000	0,856	There is a Correlation, Strength of Correlation is Very Strong, Direction is Positive
Rt Score with Level Assessment	52	0,000	−0,712	There is a Correlation, Strength of Correlation is Strong, Direction is Negative

From the results of the Spearman correlation test analysis (Table 4) after coding the data, it was found that only the Covid-19 vaccination coverage variable was not significantly correlated with the Rt Score with a p-value of 0.137. The other variables, positivity rate and level assessment, correlate significantly with the Rt Score with a p-value of 0.000 and strong relationship strength. Of the three variables analyzed, the positivity rate variable was the highest correlated to the Rt rate in Tegal City.

DISCUSSION

Relationship between Vaccination Coverage and Effective Reproduction Rate of COVID-19 in Tegal City

The correlation between COVID-19 vaccination coverage and Rt Rate in Tegal City was -0.209; this correlation was not statistically significant, with a p-value (of 0.137). There is no relationship or a very weak relationship between COVID-19 vaccination coverage and the RT rate in Tegal City, which shows a negative direction that the higher the vaccination coverage, the lower the COVID-19 RT rate. This result is not in line with research from Mu'tamar et al. (2021) that the presence of vaccination intervention controls can suppress the growth of infected populations from modeling Rt Rates, but this depends on the high effectiveness of vaccination to keep the population group awake. This happens because other factors are not analyzed, such as how effective the vaccines that have been given to vulnerable populations are, as well as small sample data and limited vaccine data up to dose two only. In addition, the development of mutations of the COVID-19 virus and socio-demographic characteristics were not analyzed in this study.

The effectiveness of the COVID-19 vaccine at dose two alone will decrease after 6 months from the last vaccination. Due to reduced immunity and variant-induced changes in vaccine effectiveness, additional doses may be required in the population (Suthar et al., 2022). In this study, the data was limited to dose two only because dose three vaccination in Tegal City was carried out starting in August 2021, while this study took data in July 2022 following the implementation of the COVID-19 level assessment situation, so dose 3 data was not included to avoid missing values and bias. In addition, the low coverage of dose 3 is not for promising public health interventions in Tegal City. Thus, the reduced effectiveness of the vaccine in the body can increase the virus's transmission rate, which contributes to an increase in the Rt Rate in the population.

Adequate vaccination coverage is not associated with Rt rates, possibly due to the mutation of the COVID-19 virus into a new, stronger variant. The emergence of the Delta wave variant in July 2021, which was not matched by booster vaccination, resulted in the vaccine's effectiveness against the virus being lost and immunity by natural infection being low, eventually triggering exponential cases in the population. The Harris study (2022) found that higher full vaccination coverage was associated with significantly lower COVID-19 incidence during the Delta wave and significantly milder disease cases. The mutation of the COVID-19 virus that continues to evolve results in the virus being resistant to antibodies that have been formed in the population, so that virus transmission still occurs even though the community has formed herd immunity.

Virus transmission can still occur in protected populations but will reduce morbidity and mortality due to COVID-19. The administration of the COVID-19 vaccine to community groups is carried out to reduce morbidity and mortality due to exposure to the COVID-19 virus through the concept of stimulating antibody formation in the body (Novitasari et al., 2021). This theory can explain that vaccination's primary purpose is to reduce morbidity and mortality due to the COVID-19 virus, so it is not statistically correlated with the COVID-19 Rt Rate. This is consistent with the study findings from (McLaughlin et al., 2022) that a higher proportion of people aged ≥ 12 years who were fully vaccinated against COVID-19 had significantly lower rates of COVID-19 cases and deaths.

High vaccination rates are not significantly correlated with a decrease in the COVID-19 RT rate in Tegal City but can reduce the mortality rate due to COVID-19. This is in line with research from Suthar et al. (2022), which found that higher levels of vaccination coverage were associated with reduced mortality and incidence rates during the dominance of alpha and delta variants. However, the mortality rate in Tegal City based on vaccination status up to dose two is higher than someone with vaccination status already dose 3. This is because in a population that has been fully vaccinated and booster reaches more than half of the population; it will form a group immunity that can reduce the rate of transmission, according to the findings of Oshakbayev et al. (2022) that an increase in fully vaccinated people, from 3% to 30% of the world's population, reduces new confirmed Covid-19 cases, although the dependence is not significant.

This study finds that vaccination coverage is not significantly correlated with Rt Rates, in contrast to the results of the study by McLaughlin et al. (2022) in the United States, in the United States, which showed that high vaccination coverage significantly reduced cases and deaths from COVID-19. This difference could be due to social context, coverage of the third dose (booster) vaccination, and virus variants circulating in each region. This confirms that the effectiveness of vaccination interventions in reducing transmission rates is highly dependent on local factors and implementation strategies.

Relationship between Positivity Rate and Effective Reproduction Rate of COVID-19 in Tegal City

The results of the Spearman correlation showed that the correlation coefficient between the positivity rate and the COVID-19 Rt Score in Tegal City was 0.856, which means that the strength of the relationship is extreme in a positive direction. This correlation is statistically significant with a p-value (0.00). This shows that the lower the positivity rate value, the lower the Rt number or adequate specimen examination can reduce the Rt number in the population. This result is in line with the research of Furuse et al. (2021), which suggests that there is a relationship between the positivity rate and the COVID-19 Rt number in the Osaka region, Japan.

Adequate or high-test positivity rates are positively correlated with Rt Rates, suggesting that more people tested after an increase in the number of cases in the population makes it possible to control the spread of the virus through aggressive self-testing and isolation. Adequate intensity of specimen testing after an increase in the number of cases triggers an increase in the stringency of isolation and comprehensive treatment, can slow down the rate of virus transmission in the population, and result in the Rt number decreasing below 1 (Furuse et al., 2021). Monitoring the positivity rate about concurrent Rt can help assess and strengthen public health management and testing systems and deepen understanding of the dynamics of the COVID-19 epidemic.

Testing or examination of specimens from massive case tracking negatively correlates with the COVID-19 positivity rate, although the relationship is not strong.

Testing these specimens uses PCR (Polymerase Chain Reaction) and rapid antigen tests. This decreases the positivity rate and will reduce the COVID-19 Rt in the population (Sitompul & Gani, 2022).

Regardless of symptoms, targeted testing of high-risk contacts in an outbreak is much more efficient, especially as asymptomatic infections are common. Therefore, massive testing should be conducted targeting all individuals in contact with sick individuals with and/or without symptoms to reduce cases from spreading as the results of a study from Kucharski et al. (2020) found that a 64% reduction in the Rt rate in addition to a low positivity rate was also combined with self-isolation and household quarantine with the addition of manual contact tracing of all contacts. The correlation between the positivity rate and Rt rate was the highest, indicating that the joint intervention through specimen examination from case tracking significantly reduced the Rt rate in Tegal City. When testing of contact groups was intensively conducted, and the number of tests conducted met the standard of 1000 tests per week, the spread of the virus could be recognized early, and isolation and treatment could be carried out immediately to lock the transmission of the virus so as not to spread. This will reduce positive cases in the community, as indicated by the calculated Rt Rate. If the specimen examination is carried out correctly and according to the indicators, there will be a decrease in the positivity rate, which will also reduce the Rt number in the population.

The finding that the positivity rate is strongly correlated with the Rt number is in line with the study by Furuse et al. (2021) in Osaka, Japan, which concluded that increased specimen testing significantly reduced the rate of COVID-19 spread. This reinforces the importance of early detection through testing as a key outbreak control strategy, which may have a more direct impact on reducing Rt Rates than vaccination interventions in specific contexts.

Relationship between Level Assessment and Effective Reproduction Rate of COVID-19 in Tegal City

Table 4 shows that the correlation between assessment level and COVID-19 Rt Score in Tegal City was -0.712, which means the strength of the relationship is strong with a negative direction. This correlation was statistically significant with a p-value (0.00). This negative correlation can be explained by the higher the level category of the assessment situation, the lower the COVID-19 Rt Score in the population. If the assessment level is at level 4, social mobility restrictions will be tightened; this will affect the virus's transmission rate and reduce the Rt. The results of this study are similar to research from Linka et al. (2020), which found a strong correlation between restrictions on social mobility, such as not being allowed to travel outside the home with the Rt. The public health intervention of this social restriction has succeeded in reducing the Rt. and shows a time delay in the inflection point of reducing the Rt.

In situation level 4, where conditions with uncontrolled local transmission and inadequate response capacity result in high-risk cases, the government's social restriction policy is tightened, which refers to the regulation of the Minister of Home Affairs Instruction (INMENDAGRI) concerning the Enforcement of Restrictions on Community Activities (PPKM) according to the level of the situation in the local epidemiological area. This PPKM includes restrictions in public spaces, social distancing, wearing masks, WFH (Work from Home), tightening health protocols, online school activities, and social mobility restrictions. The existence of these restrictions is done to reduce virus transmission in the population and can reduce the Rt Score < 1. Research from Setti & Tollis (2022) found a non-linear correlation between Rt Score and residential mobility in many countries. Mobility restriction measures must consider local cultural determinants and social behavior to reduce the Rt number below one or reduce the transmission rate.

Level assessment in Tegal City, accompanied by appropriate policies, can reduce the rate of transmission of the COVID-19 virus in the community. The COVID-19 level assessment will contain the pandemic with a 20%-35% reduction in weekly mobility depending on the region to reduce the effective reproduction rate of COVID-19 and predict the Rt number that occurs appropriately (Jung, Endo, Akhmetzhanov, & Nishiura, 2021; Kajitani & Hatayama, 2021). Likewise, the rate of spread of COVID-19 can be suppressed by the PPKM social restriction policy (Pemberlakuan Pembatasan Kegiatan Masyarakat) such as stay-at-home, work-from-home, school-from-home (Nugroho & Rakhman, 2021). The PPKM policy from the study findings of Marwiyah & Salvira (2021) shows that it effectively reduces the rate of transmission of the COVID-19 virus in the population from the assessment of the COVID-19 pandemic situation level.

Restriction of social mobility in the community follows the COVID-19 level assessment. This intervention is carried out to control the community's mobility to stay at home, comply with health protocols, and limit interactions with others if they feel sick. The facts in the field can show a reduction in the transmission rate from the low Rt number, which will eventually reduce the level assessment to level 1, where transmission occurs in the community and other public health interventions are under control as the findings of the Setti & Tollis study (2022) suggest that restrictions on residential mobility in some countries can reduce the Rt number below 1.

Limitations of the study

This study has several limitations. First, the vaccination coverage data used only includes doses 1 and 2, so it cannot capture the impact of booster vaccination (3rd dose), which began to be intensified in the middle of the observation period. This may lead to an underestimation of the full protective effect of vaccination on transmission rates. Second, this study did not control for other confounding factors that may also affect the effective reproductive rate (Rt), such as community compliance with health protocols (wearing masks, washing hands, maintaining distance), individual mobility behavior, and environmental and socio-economic conditions. The absence of primary data on these factors limits the interpretation of causal relationships between the variables analyzed.

CONCLUSIONS

From the analysis, it was found that the positivity rate and Covid-19 level assessment situation were statistically significantly correlated to the effective reproduction rate (Rt) of Covid-19 in Tegal City, with the strength of the relationship being extreme and intense (r=0.856; p=0.00 and r=-0.712; p=0.00). Meanwhile, vaccination coverage was not statistically significantly correlated with Rt (r=-0.209; p=0.137).

The policy implications of these findings indicate the importance of strengthening risk-based testing strategies, especially in urban areas with high mobility, such as Tegal City. Local governments are advised to expand the reach of specimen testing, tighten weekly data-based level assessments, and consider booster vaccination coverage as part of a combined intervention.

For further research, it is necessary to conduct longitudinal studies in various epidemiological regions to evaluate the effectiveness of combined public health interventions on effective reproductive rates, especially in the face of new COVID-19 variants that continue to evolve.

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DATA AVAILABILITY

The data used in this study are secondary data from the Tegal City Health Office in the form of weekly COVID-19 reports and vaccination coverage from July 2021 to June 2022. The data is not publicly available but can be accessed by the correspondence author upon reasonable request and with the consent of the agency that owns the data.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in the conduct of this research or in the process of preparing this scientific article.

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