

Supplementary Table 1. List of key system parameters and baseline values used in the model.

Symbol	Parameter	Base line value	Note
Thai pilgrims			
N_{Thai}	Thai pilgrims	13,000	The annual quota allocation for Thai pilgrims. ¹¹
S_{Thai}	Susceptible individuals, representing the pilgrims who have not been infected with MERS-CoV	$N_{\text{Thai}} - (N_{\text{Thai}} \times c \times v_e)$	Derived c = vaccine coverage v_e = vaccine effectiveness
E_{Thai}	Exposed individuals who are not quarantined	0	Assumed
$I_{S\text{Thai}}$	Symptomatic infected individuals who are not isolated	0	Assumed
$I_{a\text{Thai}}$	Asymptomatic infected individuals who are not isolated	0	Assumed
$I_{i\text{Thai}}$	Symptomatic infected individuals who are isolated	0	Assumed
H_{Thai}	Symptomatic infected individuals with severe symptoms requiring hospitalization	0	Assumed
R_{Thai}	Recovered individuals	0	Assumed
D_{Thai}	Deaths	0	Assumed
Non-Thai pilgrims			
$N_{\text{Non-Thai}}$	Non-Thai pilgrims	1,660,230	According to the report from the General Authority for Statistics (GASTAT) in 2025, a total of 1,506,576 pilgrims came from outside the Kingdom of Saudi Arabia including Thailand, while 166,654 were Saudi citizens. ¹⁷ $N_{\text{Non-Thai}} = 1,673,230 - 13,000$
$S_{\text{Non-Thai}}$	Susceptible individuals, representing the pilgrims who have not been infected with MERS-CoV	1,659,400	Calculated as $S = N - E - E_q - A - A_q - I - I_q - H - R - D$
$E_{\text{Non-Thai}}$	Exposed individuals who are not quarantined	0	Assumed
$I_{S\text{Non-Thai}}$	Symptomatic infected individuals who are not isolated	48	Assumed This study assumed a rare disease prevalence (≤ 1 case per 2,000 persons) among Saudi Arabia pilgrims. ¹⁸ Applying this threshold to a population of 166,654 pilgrims yields approximately 83 infected individuals. Of these infections, 58% were assumed to be symptomatic.
$I_{a\text{Non-Thai}}$	Asymptomatic infected individuals who are not isolated	35	Assumed
$I_{i\text{Non-Thai}}$	Symptomatic infected individuals who are isolated	0	Assumed
$H_{\text{Non-Thai}}$	Symptomatic infected individuals with severe symptoms requiring hospitalization	0	Assumed
$R_{\text{Non-Thai}}$	Recovered individuals	0	Assumed
$D_{\text{Non-Thai}}$	Deaths	0	Assumed

Supplementary Table 2. List of key system variables and value used in the model

Symbol	Description	Value	Source
β	Average number of infections produced per a unit time	R_0/d	Derived
R_0	Basic reproductive number or average number of secondary infections per case	1, 2, 4, 6, 8	The reproductive number of MERS-CoV is reported to range from 0.8 to 1.3. However, it reached up to 8.1 during the South Korea outbreak, compared with an overall estimate of about 0.45 in Saudi Arabia. ^{19–22}
d	Duration of infectiousness	14 days	Assumed The infectious period for MERS-CoV has not been clearly established.
v_e	Vaccine effectiveness against infection	0.3, 0.5, 0.5, 0.9	Assumed It can range from 0 to 1.
c	Vaccine coverage among Thai pilgrims	0, 1	Assumed Full vaccine coverage = 1, no vaccine = 0
a	Probability of an infected individuals remaining asymptomatic	0.42	Among the secondary MERS-CoV infections occurring outside healthcare setting, approximately 42% (74/177) were asymptomatic. ²³
σ	Incubation period	5 days	The median incubation period is about 5 days, with a range of 2–14 days. ²⁴
s	Probability of symptomatic case becoming severe	0.73	Among 67 confirmed MERS-CoV with symptomatic, 49 required ICU care (73%). ²⁵
p_d	Probability of severe case resulting in death	0.86	MERS-CoV cases died in hospital 42 from 49 cases required ICU care (86%). ²⁵
e	Probability of symptomatic being isolated	0.05	Assumed
τ	Time from becoming infectious (symptomatic) to isolation	4 days	Assumed
γ_s	Time from onset to severe	5 days	Median time from onset to ICU admission is approximately 5 days. ²⁴
γ_d	Time from severe to death	8 days	In hospitalized MERS patients, the median time from symptom onset to hospitalization was approximately 4 days, and from onset to death was approximately 12 days. Therefore, this study assumed 12 - 4 = 8 days from hospitalization to death. ²⁴
γ_a	Recovery time (asymptomatic case)	10 days	Assumed
γ_{ns}	Recovery time (non-severe symptomatic case)	14 days	Assumed
γ_{ss}	Recovery time (severe symptomatic case)	12 days	Assumed
τ_{ns}	Remaining recovery time after isolation (non-severe symptomatic case) Isolation delay = $\gamma_{ns} - \tau = 14 - 4$	10 days	Derived
τ_s	Remaining time to severe after isolation delay = $\gamma_s - \tau = 5 - 4$	1 day	Derived
k_{tn}	Proportion of contacts with non-Thai among total contacts of Thai individuals	0.7	Assumed
k_{nt}	Proportion of contacts with Thai among total contacts of non-Thai individuals	0.02	Assumed

Supplementary Table 3. Model equations for MERS-CoV transmission among Thai pilgrims attending the Hajj.

Change of compartment	Equation
dS_{Thai}/dt	$-\beta_{\text{Thai}} \times S_{\text{Thai}} \times [(1 - k_{\text{tn}}) \times (I_{\text{SThai}} + I_{\text{aThai}}) + k_{\text{tn}} \times (I_{\text{SNon-Thai}} + I_{\text{aNon-Thai}})] / (N_{\text{Thai}} + N_{\text{Non-Thai}})$
dE_{Thai}/dt	$\beta_{\text{Thai}} \times S_{\text{Thai}} \times [(1 - k_{\text{tn}}) \times (I_{\text{SThai}} + I_{\text{aThai}}) + k_{\text{tn}} \times (I_{\text{SNon-Thai}} + I_{\text{aNon-Thai}})] / (N_{\text{Thai}} + N_{\text{Non-Thai}}) - [E_{\text{Thai}} \times a / \sigma] - [E_{\text{Thai}} \times (1-a) / \sigma]$
dI_{SThai}/dt	$[E_{\text{Thai}} \times (1-a) / \sigma] - [I_{\text{SThai}} \times (1-e) \times (1-s) / \gamma_{\text{ns}}] - [I_{\text{SThai}} \times e / \tau] - [I_{\text{SThai}} \times (1-e) \times s / \gamma_s]$
dI_{aThai}/dt	$[E_{\text{Thai}} \times a / \sigma] - [I_{\text{aThai}} / \gamma_a]$
dI_{SiThai}/dt	$[I_{\text{SThai}} \times e / \tau] - [I_{\text{SiThai}} \times s / \tau_s] - [I_{\text{SiThai}} \times (1-s) / \tau_{\text{ns}}]$
dH_{Thai}/dt	$[I_{\text{SThai}} \times (1-e) \times s / \gamma_s] + [I_{\text{SiThai}} \times s / \tau_s] - [H_{\text{Thai}} \times p_d / \gamma_d] - [H_{\text{Thai}} \times (1 - p_d) / \gamma_{\text{ss}}]$
dR_{Thai}/dt	$[I_{\text{SThai}} \times (1-e) \times (1-s) / \gamma_{\text{ns}}] + [I_{\text{aThai}} / \gamma_a] + [I_{\text{SiThai}} \times (1-s) / \tau_{\text{ns}}] + [H_{\text{Thai}} \times (1 - p_d) / \gamma_{\text{ss}}]$
dD_{Thai}/dt	$[H_{\text{Thai}} \times p_d / \gamma_d]$