Chapter 17
Bio-waste Management During COVID-19

Nita H. Shah, Ekta N. Jayswal, and Purvi M. Pandya

Abstract Ever since the transmission of novel coronavirus through human-to-human hit the world. As this disease is spreading every day, hospitalisation of individuals increased. Consequence of this, there is a sudden surge of millions of gloves, masks, hand sanitizers and the other essential equipment in each month. Disposal of these commodities is a big challenge for hospitals and COVID-centre, as they may became the reason of creating pollution and infect the surroundings. Increasing hospitalisation cases of COVID-19 results in raising bio-waste which creates pollution. Observing the scenario, a mathematical model with four compartments is constructed in this article. The threshold value indicates the intensity of pollution that emerged from bio-waste. Stability of the equilibrium point gave the necessary condition. Optimal control theory is outlined to achieve the purpose of this chapter by reducing pollution. Outcomes are analytically proven and also numerically simulated.

Keywords COVID-19 outbreak · Bio-waste · Hospitalisation · Optimal control · Pollution

Mathematics Subject Classification 37NXX · 97NXX

Introduction

In February 2020, COVID 19 as pandemic globally, the World Health Organization (WHO) stated that this outbreak is highly infectious [1]. Such a contagious and contaminate disease, plastic plays a vital role in making confident social worker to deal with it. As per the latest (2020c) WHO evaluations, the world has consumed

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89 million masks, 30 million gowns, 1.59 million goggles, and 76 million gloves per month alone due to the COVID-19 [2]. As these things cannot be reused, it can only be dumped or recycled becomes waste. Thus, along with Personal Protective Equipment (PPEs) and sanitization, this biomedical waste is also a big challenge for any hospital having COVID patients. The waste produced by healthcare taken at home during COVID-19 pandemic time is also classified as bio-waste but this research only includes bio-waste produced due to hospitalisation. As time passed, the disposal of bio-waste creates pollution.

In March 2020, the government of India has released guidelines for handling safe disposal of bio-waste generated during the treatment of a patient having novel coronavirus [3]. In a very short time, the COVID-19 outbreak becomes epidemic in some highly populated regions and it becomes more complicated for doctors to handle the large scale of infected population henceforth, rigorous monitoring may not be possible. If medication guidelines could be followed then transmission of COVID-19 and pollution through bio-waste can also be controlled [4].

Observing each situation, a mathematical model with a system of nonlinear differential equations is illustrated in Sect. Mathematical Modelling. The data collection is done precisely. The data which are not available taken as hypothetically. The formulation of the basic reproduction number gives a significant result of the model that resolves the amount of pollution created from bio-waste. Section Stability includes the stability of equilibrium points of the system. To control pollution, optimal control theory is used and three controls are applied to the system in Sect. Optimal Control. Section Numerical Simulation concludes all results graphically with validated data.

Mathematical Modelling

Transmission of COVID infection is spreading frequently all-around the world. A mathematical model consists four compartments. The first compartment is infected individuals by the coronavirus (C_I) who are getting hospitalised (H). Due to hospitalisation, all necessary equipment are used, which increase the density of bio-waste (B_W) and day by day increment contaminates the environment called pollution (P).

Dynamics of the model are shown in Fig. 17.1. Parameters that connect each compartment called rates show the flow of the model.

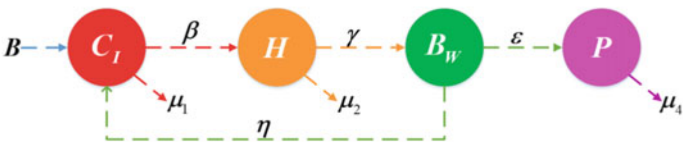


Fig. 17.1 Transmission of model. *Source* Own

Description and parametric values:

Data is taken on July 23, 2020, 07:55 GMT.

$B = 0.22$, growth rate is the ratio of active cases to total cases, i.e. 3,474,060/15,642,265 [5].

$\beta = 0.5760$, the rate at which COVID infected individuals are getting hospitalised. Centers for Disease Control and Prevention (CDC) reported that the overall cumulative COVID-19 hospitalisation rate is 113.6 per 1,00,000 [6]. Hence, from this rate, total hospitalised infected individuals are 88,60,741; hence, the rate at which infected individuals are hospitalised is the ratio of the number of hospitalised cases to total infected cases.

$\mu_1 = 0.6537$, is death rate of coronavirus infected individuals. This is the ratio of death cases to total infected cases, i.e. 6,30,370/15,382,854 [5].

$\mu_2 = 0.0711$, is death rate of hospitalised individuals. This is the ratio of death cases to total hospitalisation cases, i.e. 6,30,370/88,60,741 [6].

$\gamma = 0.75$, is the rate bio-waste created due to hospitalisation. This data is from different channels suggests that world could generate an entire year's worth of medical waste in two or three months because of the impact of COVID-19 [7]. It means we can say that there is approximately 0.75% raise is seen in biomedical waste.

$\varepsilon = 0.6$ is increasing rate of pollution due to produced bio-waste (data is taken from [8]).

$\eta = 0.3$ is the rate at which bio-waste infect the individual.

$\mu_4 = 0.4$ is the escape rate.

Note that μ_4 and η are taken hypothetically considering by current situation of world due to novel corona virus.

By using four compartments which are connected with these parameters mentioned in Sect. Mathematical Modelling, the following system of equations can be generated,

$$\begin{aligned}
\frac{\mathrm{d}C_I}{\mathrm{d}t} &= B - \beta H C_I + \eta B_W - \mu_1 C_I \\
\frac{\mathrm{d}H}{\mathrm{d}t} &= \beta H C_I - \gamma H - \mu_2 H \\
\frac{\mathrm{d}B_W}{\mathrm{d}t} &= \gamma H - \varepsilon B_W - \eta B_W \\
\frac{\mathrm{d}P}{\mathrm{d}t} &= \varepsilon B_W - \mu_4 P
\end{aligned} \tag{17.1}$$

with $C_I > 0$ and $H, B_W, P \geq 0$.

By accumulating and this initial condition gives the feasible region of the model, $\Lambda = \left\{ (C_I, H, B_W, P) \in R^4 : C_I + H + B_W + P \leq \frac{B}{\mu_1} \right\}$.

Solving system (17.1), two equilibrium points are evaluated. First is pollution-free and another is endemic equilibrium point having optimum value.

(i) $E_0\left(\frac{B}{\mu_1}, 0, 0, 0\right)$
(ii) $E^*\left(C_I^*, H^*, B_W^*, P^*\right)$

where $C_I^* = \frac{\gamma_1+\mu_2}{\beta}$, $H^* = \frac{(B\beta-\mu_1(\gamma_1+\mu_2))(\varepsilon+\eta)}{\beta(\varepsilon\gamma_1+\mu_2(\varepsilon+\eta))}$, $B_W^* = \frac{\gamma_1(B\beta-\mu_1(\gamma_1+\mu_2))}{\beta(\varepsilon\gamma_1+\mu_2(\varepsilon+\eta))}$ and $P^* = \frac{\varepsilon\gamma_1(B\beta-\mu_1(\gamma_1+\mu_2))}{\beta\mu_4(\varepsilon\gamma_1+\mu_2(\varepsilon+\eta))}$.

The threshold value is calculated by using next-generation matrix method called basic reproduction number (R_0) [9].

$$F = \begin{bmatrix} \beta H C_I \\ 0 \\ 0 \\ 0 \end{bmatrix} \text{ and } V = \begin{bmatrix} \gamma H + \mu_2 H \\ -\gamma H + \varepsilon B_W + \eta B_W \\ -\varepsilon B_W + \mu_4 P \\ -B + \beta H C_I - \eta B_W + \mu_1 C_I \end{bmatrix}.$$

Calculating Jacobian matrix of F and V, the mathematical expression of R_0 is, $\frac{B\beta}{\mu_1(\gamma_1+\mu_2)}$.

R_0 is very important mathematical term for the dynamical model. After substitution of the parameter threshold value suggest that, 23.64% pollution is observed.

Stability

Local Stability

Theorem 1 The pollution-free equilibrium point E_0 is locally asymptotically stable if $B\beta < \mu_1(\gamma_1 + \mu_2)$.

Proof The Jacobian matrix of the system at E_0 is derived and eigenvalues of this matrix are:

(i) $-\mu_4$, (ii) $-\mu_1$, (iii) $-(\varepsilon + \eta)$, (iv) $\frac{B\beta-\mu_1(\gamma_1+\mu_2)}{\mu_1}$.

Equilibrium point is stable if each eigenvalue of Jacobian matrix at E_0 is negative and here it seems that, fourth eigenvalue is positive. Hence, equilibrium point is locally asymptotically stable if $B\beta < \mu_1(\gamma_1 + \mu_2)$.

Theorem 2 The optimum issue point E^* is locally asymptotically stable if $C_I\beta < \min\{1, \varepsilon + \eta, \varepsilon + \eta + \mu_1 + \mu_4\} + (\gamma_1 + \mu_2)$.

Proof The characteristic equation of the Jacobian matrix at endemic equilibrium point,

$$\lambda^4 + a_1\lambda^3 + a_2\lambda^2 + a_3\lambda + a_4 = 0$$

where

$$a_1 = -C_I\beta + H\beta + \varepsilon + \eta + \gamma + \mu_1 + \mu_2 + \mu_4$$

$$a_2 = (\mu_1 + \mu_4)(-C_I\beta + \varepsilon + \eta + \gamma + \mu_2) + \mu_1\mu_4 + (\varepsilon + \eta)(-C_I\beta + H\beta + \gamma + \mu_2)$$
$$a_3 = (\varepsilon + \eta)(\mu_1 + \mu_4)(-C_I\beta + \gamma + \mu_2) + \mu_1\mu_4(-C_I\beta + \varepsilon + \eta + \gamma + \mu_2) + H\beta((\varepsilon + \eta)(\mu_1 + \mu_4) + \gamma(\varepsilon + \mu_4) + \mu_2\mu_4)$$
$$a_4 = \mu_4((\varepsilon + \eta)(\mu_1(-C_I\beta + \gamma + \mu_2) + H\beta\mu_2) + H\beta\varepsilon\gamma)$$

Using Routh-Hurwitz (1877) [10] criteria, this optimum issue point is globally asymptotically stable if $C_I\beta < \min\{1, \varepsilon+\eta, \varepsilon+\eta+\mu_1+\mu_4\}+(\gamma_1 + \mu_2)$ condition is satisfied.

Stability analysis advices that if β that is the rate at which infected people getting hospitalised is lesser then model will be stable.

Global Stability

Theorem 3 The pollution-free equilibrium point E_0 is globally asymptotically stable whenever $R_0 \leq 1$.

Proof Consider Lyapunov's function, $L_0(t) = A_1C_I(t) + A_2H(t)$.

$\therefore L_0^{'}(t) = A_1(B - \beta HC_I + \eta B_W - \mu_1C_I) + A_2(\beta HC_I - \gamma H - \mu_2H)$

$\therefore L_0^{'}(t) \leq \left(A_2(\gamma + \mu_2)\left(\frac{B\beta}{(\gamma+\mu_2)\mu_1} - 1\right) - \frac{A_1B\beta}{\mu_1}\right)H^0$

$\therefore L_0^{'}(t) = A_1C_I^{'}(t) + A_2H^{'}(t)$

$\therefore L_0^{'}(t) \leq \left(A_2(\gamma + \mu_2)(R_0 - 1) - \frac{A_1B\beta}{\mu_1}\right)H^0$

$\therefore L_0^{'}(t) \leq 0$ if $R_0 \leq 1$.

Hence, E_0 is globally asymptotically stable if $R_0 \leq 1$.

Theorem 4 The endemic equilibrium point E^* is globally asymptotically stable if $\frac{C_I}{C_I^*} = \frac{H}{H^*} = \frac{B_W}{B_W^*} = \frac{P}{P^*} < 1$.

Proof Let Lyapunov's function be, $L_1(t) = \varphi\left(\frac{C_I}{C_I^*}\right) + \varphi\left(\frac{H}{H^*}\right) + \varphi\left(\frac{B_W}{B_W^*}\right) + \varphi\left(\frac{P}{P^*}\right)$.

Such that, $\varphi(x) = x - 1 - \ln(x)$, $x > 0$ is an increasing function.

$\therefore L_1^{'}(t) = \left(1 - \frac{C_I^*}{C_I}\right)C_I^{'} + \left(1 - \frac{H^*}{H}\right)H^{'} + \left(1 - \frac{B_W^*}{B_W}\right)B_W^{'} + \left(1 - \frac{P^*}{P}\right)P^{'}$

$$\therefore L_1^{'}(t) = \left(B - \mu_1C_I^*\right)\left(1 - \frac{C_I^*}{C_I}\right) - \mu_2H^*\left(1 - \frac{H^*}{H}\right) - \mu_4P^*\left(1 - \frac{P^*}{P}\right) - \beta H^*C_I^*\left(\frac{H^*}{H} - \frac{C_I^*}{C_I}\right) - \eta B_W^*\left(\frac{C_I^*}{C_I} - \frac{B_W^*}{B_W}\right) - \varepsilon B_W^*\left(\frac{P^*}{P} - \frac{B_W^*}{B_W}\right) - \gamma_1H^*\left(\frac{B_W^*}{B_W} - \frac{H^*}{H}\right)$$

Here, $L_1^{'}(t) \leq 0$ at E^* that is $C_I = C_I^*$, $H = H^*$, $B_W = B_W^*$, $P = P^*$ and $\frac{C_I^*}{C_I} = \frac{H^*}{H} = \frac{B_W^*}{B_W} = \frac{P^*}{P} < 1$. Hence, E^* is globally asymptotically stable.

Optimal Control

Optimal control helps to optimise objective function over a few periods. Three controls are applied to the system. The first control (u_1) is on COVID-19 infected people to optimise hospitalisation. The second control (u_2) is treated on hospitalised individuals which decreases bio-waste and the third control (u_3) is a treatment applied to the bio-waste material that can optimise pollution. Therefore, the system seems,

$$\begin{aligned}
\frac{\mathrm{d}C_I}{\mathrm{d}t} &= B - \beta H C_I + \eta B_W - \mu_1 C_I + u_1 H \\
\frac{\mathrm{d}H}{\mathrm{d}t} &= \beta H C_I - \gamma H - \mu_2 H - u_1 H + u_2 B_W \\
\frac{\mathrm{d}B_W}{\mathrm{d}t} &= \gamma H - \varepsilon B_W - \eta B_W - u_2 B_W + u_3 P \\
\frac{\mathrm{d}P}{\mathrm{d}t} &= \varepsilon B_W - \mu_4 P - u_3 P
\end{aligned} \tag{17.2}$$

The objective function is,

$$\begin{aligned}
J(c_i, \Lambda) = \int_0^T &\left(A_1 C_I^2 + A_2 H^2 + A_3 B_W^2 + A_4 P^2\right. \\
&+ w_1 u_1^2 + w_2 u_2^2 + w_3 u_3^2))\mathrm{d}t
\end{aligned} \tag{17.3}$$

where, Λ denotes set of all compartmental variables, A_1, A_2, A_3, A_4 denote non-negative weight constants for compartments C_I, H, B_W, P respectively. w_1, w_2 and w_3 are the weight constants for each control u_i where $i = 1, 2, 3$, respectively.

Compute every values of control variables from $t = 0$ to $t = T$ such that,

$$J(u_i(t)) = \min\{J(u_i^*, \Lambda)/(u_i) \in \phi\}, \quad i = 1, 2, 3$$

where ϕ is a smooth function on the interval [0, 1].

The optimal control denoted by u_1, u_2 and u_3 are found by computing all the integrands of Eq. (17.3) using the lower bounds and upper bounds respectively with the results of Fleming and Rishel [11].

For minimising the cost function in Eq. (17.3), using the Pontryagin principle [12] by constructing Langrangian function consisting of state equations and adjoint variables $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ as follows:

$$\begin{aligned}
L(\Lambda, A_i) = {} & A_1 C_I^2 + A_2 H^2 + A_3 B_W^2 + A_4 P^2 + w_1 u_1^2 + w_2 u_2^2 \\
& + w_3 u_3^2 + \lambda_1 (B - \beta H C_I + \eta B_W - \mu_1 C_I \\
& + u_1 H) + \lambda_2 (\beta H C_I - \gamma H - \mu_2 H - u_1 H + u_2 B_W) \\
& + \lambda_3 (\gamma H - \varepsilon B_W - \eta B_W - u_2 B_W + u_3 P)
\end{aligned}$$

$$+ \lambda_4(\varepsilon B_W - \mu_4 P - u_3 P)$$

The adjoint equation variables, $\lambda_i = (\lambda_1, \lambda_2, \lambda_3, \lambda_4)$ for the system (2) is calculated by taking partial derivatives of the Langrangian function with respect to each compartment variable.

$$\begin{aligned}
\overset{\bullet}{\lambda}_1 &= -\frac{\partial L}{\partial C_I} = -2A_1 C_I + (\lambda_1 - \lambda_2)\beta H + \lambda_1 \mu_1 \\
\overset{\bullet}{\lambda}_2 &= -\frac{\partial L}{\partial H} = -2A_2 H + (\lambda_1 - \lambda_2)\beta C_I + (\lambda_2 - \lambda_3)\gamma + (\lambda_2 - \lambda_1)u_1 + \lambda_2 \mu_2 \\
\overset{\bullet}{\lambda}_3 &= -\frac{\partial L}{\partial B_W} = -2A_3 B_W + (\lambda_3 - \lambda_1)\eta + (\lambda_3 - \lambda_4)\varepsilon + (\lambda_3 - \lambda_2)u_2 \\
\overset{\bullet}{\lambda}_4 &= -\frac{\partial L}{\partial P} = -2A_3 P + (\lambda_4 - \lambda_3)u_3 + \mu_4 \lambda_4
\end{aligned}$$

The necessary conditions for Langrangian function L to be optimal are

$$\begin{aligned}
\overset{\bullet}{u}_1 &= -\frac{\partial L}{\partial u_1} = -2w_1 u_1 + (\lambda_2 - \lambda_1)H = 0 \\
\overset{\bullet}{u}_2 &= -\frac{\partial L}{\partial u_2} = -2w_2 u_2 + (\lambda_3 - \lambda_2)B_W = 0 \\
\overset{\bullet}{u}_3 &= -\frac{\partial L}{\partial u_3} = -2w_3 u_3 + (\lambda_4 - \lambda_3)P = 0
\end{aligned}$$

Hence, one can simplify as,

$$u_1 = \frac{(\lambda_2 - \lambda_1)H}{2w_1},\ u_2 = \frac{(\lambda_3 - \lambda_2)B_W}{2w_2} \text{ and } u_3 = \frac{(\lambda_4 - \lambda_3)P}{2w_3}.$$

Using Pontryagin max–min principle, the optimum value of each control is given by,

$$u_1^* = \max\left(a_1, \min\left(b_1, \frac{(\lambda_2 - \lambda_1)H}{2w_1}\right)\right),\ u_2^* = \max\left(a_2, \min\left(b_2, \frac{(\lambda_3 - \lambda_2)B_W}{2w_2}\right)\right)$$
$$\text{and } u_3^* = \max\left(a_3, \min\left(b_3, \frac{(\lambda_4 - \lambda_3)P}{2w_3}\right)\right)$$

For simulating result, this computation is done in this section analytically.

Numerical Simulation

In this section, results are simulated numerically wherein the parametric values are considered from Sect. Mathematical Modelling.

Figure 17.2 shows the compartmental behaviour of the model. COVID-19 is spreading day by day. COVID-infected individuals are getting hospitalised, and this interprets that, after approximately one-week bio-waste generated during the pandemic. This collection of bio-waste creates pollution after three and a half weeks if there is not taken any solution to prevent this thing by waste management.

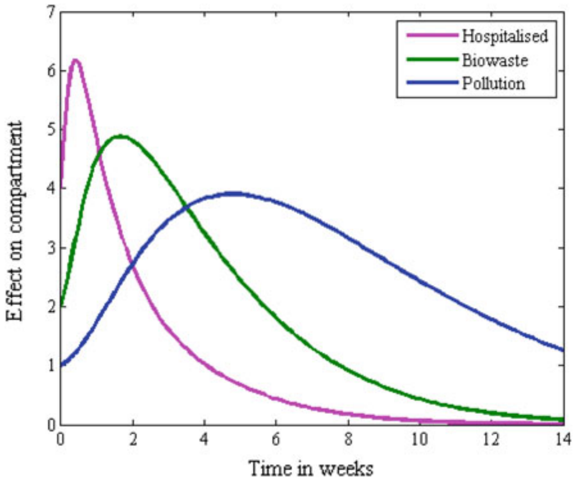
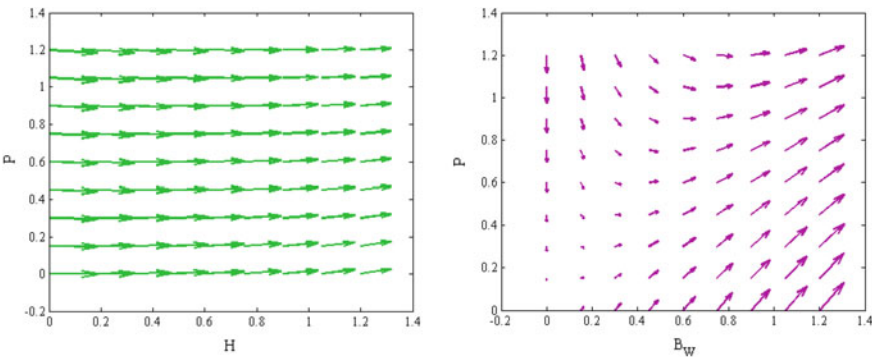
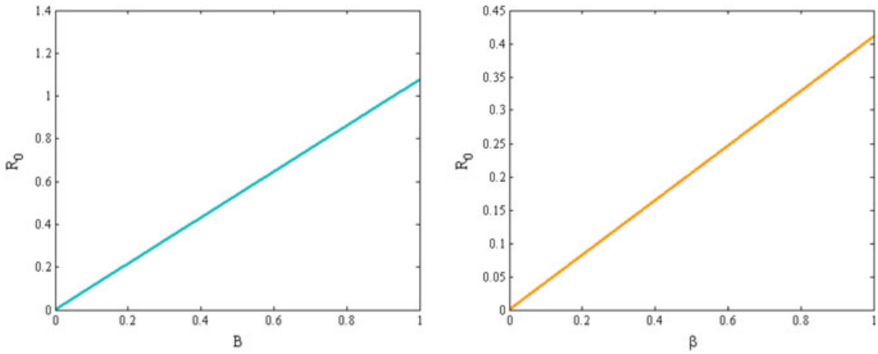


Fig. 17.2 Transmission in compartments. *Source* Own



(a) Through hospitalisation (b) Through bio-waste

Fig. 17.3 Intensity towards pollution. *Source* Own



(a) On growth rate B (b) On hospitalisation rate β

Fig. 17.4 Effect of R_0. *Source* Own

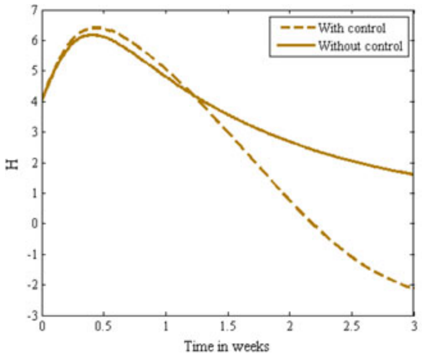
The figure depicts the directional behaviour of bio-waste (Fig. 17.3a) and hospitalised individuals (Fig. 17.3b) towards emerging pollution. As hospitalisation increases, medical staff has to use safety things for protection and hence tons of bio-waste have been produced in each month which increases pollution.

The direction of growth rate (Fig. 17.4a) and hospitalisation rate (Fig. 17.4b) with the basic reproduction number are plotted. Both figures illustrate that the threshold value increases with an increase in both the parametric values. These parameters are more sensitive to the threshold value and hence the model. Other parameters have negligible effect. Therefore, if both parameters have been undertaken care which means that infected people are getting cured by only home isolation then hospitalisation reduce which causes a decrease in pollution.

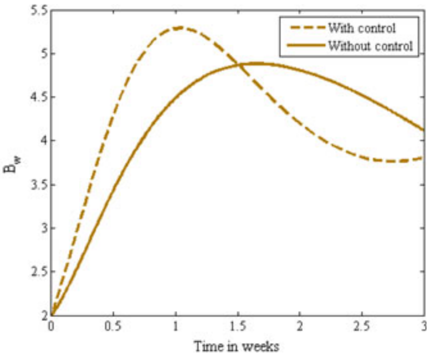
Three controls are applied to the system as mentioned in Sect. Optimal Control. One can inspects that if 21.7% hospitalisation (Fig. 17.5a) of COVID-infected people decreases then 15.56% of bio-waste (Fig. 17.5b) reduces from the medical sector which results in a reduction of 35.07% in pollution (Fig. 17.5c). This study advocates that control u_1 can be performed if individuals follow basic rules and regulation during this pandemic situation. During hospitalisation control u_2 is applicable if some changes have been taken care of COVID-19-infected people. General waste does not contaminate the environmental things hence control u_3 is beneficial when bio-waste is analysed and also obeys government guidelines.

Figure 17.6 interprets the area-wise distribution of three compartments; hospitalised individuals, bio-waste and pollution created by bio-waste, where the area of respective compartment shows its intensity. Analysis of intensity distribution of the respective compartment shows that, increasing hospitalised cases leads to an increase in bio-waste which accelerates the intensity of pollution.

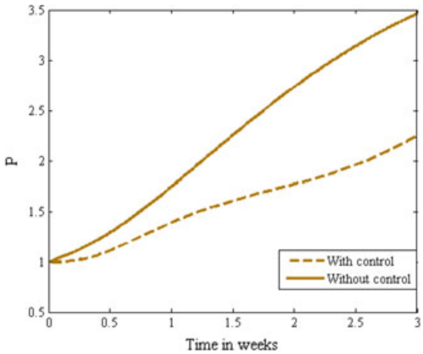
Result of Fig. 17.7 illustrates that, after getting hospitalisation of infected by coronavirus produces bio-waste which creates pollution. Here, black colour shows that, the everything becomes chaos and this scenario definitely a part of causing pollution.



(a) Hospitalised individuals



(b) Bio-waste



(c) Pollution

Fig. 17.5 After applying control. *Source* Own

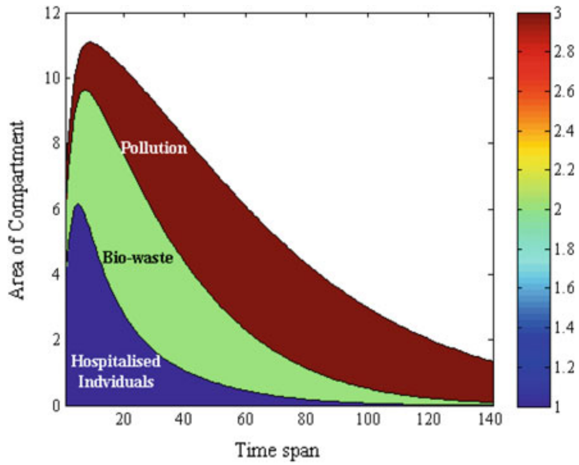


Fig. 17.6 Area plot. *Source* Own

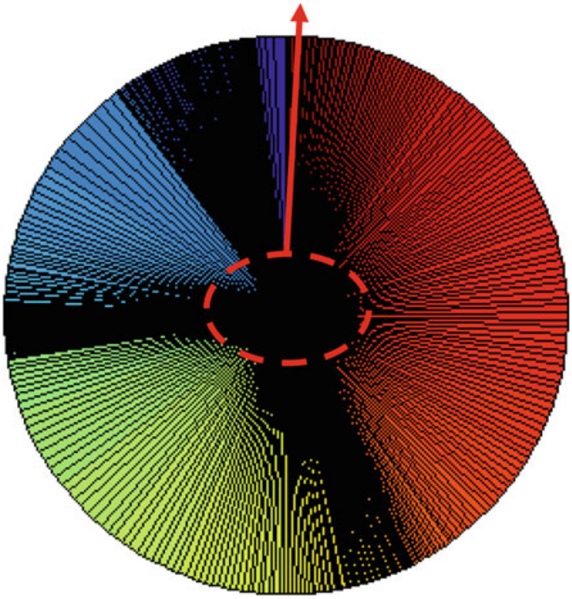


Fig. 17.7 Intensity pie-chart. *Source* Own

Conclusion

This study highlights how pollution due to bio-waste is regulated. Due to its adverse effect on human health, many organisations around the world are working in this direction during the current pandemic time. In an account of that, the compartmental model has been developed using some affected parameters and the data for simulation is taken from a recent ongoing COVID-19 outbreak. By solving the system, two equilibrium points are evaluated and both of them are stabilised locally and globally. The calculated threshold value suggests that 23.64% of pollution is created from biomedical waste from hospitalisation during the COVID-19 outbreak. This analysis recommends that if the rate at which infected people getting hospitalised is lesser, then this bio-waste is controlled and that reduces the pollution. Optimal control theory advices that, this bio-waste is started with having an infection coronavirus. Everyone has to get over it. Simulation suggests the reduction of pollution by 35.07%. Heartfelt thanks to all corona warriors. Its our prime duty to follow rules to fight again this contagious coronavirus and can contribute to make planet pollution-free and healthier.

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