Investigation of carbon emissions due to COVID-19 vaccine inventory

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Abstract Inventory model for vaccine of COVID-19 pandemic is the subject of analysis in the proposed article. The initial registration for vaccination and vaccination of registered individuals is taken during the period under consideration. The paper considers the utility of vaccine during storage, holding cost, purchase cost, manufacturing cost and inspection cost. A fraction of registered individuals who do not turn up for a vaccination is taken into account. All the actions by the player incur carbon emissions. During the whole procedure of vaccination starting from raw material to end user carbon emissions are observed. Carbon emissions in stocking raw material, during inspection, during purchase activity, during set-up and transportation phase and holding it at point of delivery. Maximum carbon emission of 28% occur during purchase activity followed by 21% during transportation at the point of delivery and stocking it at respective places. To follow green policy, carbon tax is levied. A non-linear formulation of the proposed problem is modelled to compute optimum cycle time without allowing shortages. The convexity of the objective function is established through the numerical data. Analysis of carbon emissions and carbon tax levied is carried out through the data. Research Objective: Carbon Emission is one of a cause for ozone layer depletion.

Moreover, it causes many ecological disturbances resulting into several environmental temperature variations. These all problem affect an individual's health. So, there arise a need to frame a mathematical model to decipher relationship between COVID-19 vaccine inventory and effect of carbon emissions.

Keywords Vaccine inventory · Quality inspection · Carbon emissions · Carbon tax · Spoilage of vaccine

1 Introduction

In late 2019, a novel infectious disease of the coronavirus family (COVID-19) was identified in Wuhan city of China, which has transformed quickly into a perplexity. The pandemic is a powerful warning of the capacity of infectious diseases to disturb the most advanced societies. Worldwide reports of the ongoing disaster show more than 113 million infected cases of the infection (worldometers).

Due to the effect of COVID-19 worldwide, several projects were shifted which focused on pandemic-related medications and it has primarily been a reason for financial growth for the pharmaceutical industry. Globally, both positive and negative effects are observed due to such pandemics. In the past, for developing vaccines, it went through several steps but due to the urgent need for COVID-19 vaccines, the process was happening parallelly while maintaining strict clinical as well as safety measures. Recent progression/invention of COVID-19 vaccine requires sustainable cooling technologies, transportation and preservation strategies, etc. which results in an increase in carbon emission.

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Carbon dioxide emission is attributed to both natural and human sources where natural sources include decomposition, respiration, etc. and human sources involve deforestation, burning of fossil fuels, etc. Additionally, it is rarely noticed that the pharmacy sector evokes images of pollution, smoke stack, environmental damages, etc. Proposed article is structured as follows: A succinct survey of prior literature is provided in Sect. 2. The assumptions and notations are demonstrated in Sect. 3. Section 4 represents the model description. Section 5 defines model development. Numerical solution is proposed in Sect. 5. Sensitivity analysis carried out in Sect. 6. Discussion of findings is presented in Sect. 7. Section 8 concludes the proposed model.

2 Literature survey

2.1 Inventory for growing items

In the literature of inventory, substantial attention has not been paid to the inventory model for growing items. In this context, Rezaei (2014) was the first to introduce the concept of growing items to inventory researchers by calculating the optimal order quantity at the start of the growing cycle. This model deliberates the situation in which newborn animals are purchased and after growth, these animals are slaughtered and sold out. For instance, Nobil et al. (2019) extended Rezaei (2014) model by taking linearly increasing growth function and shortages are fully backordered. After that Sebatjane and Adetunji (2019a, b, c) established an EOQ model for growing items with imperfect quality by assuming a quality screening process in which all the slaughtered items are checked before they are sold out. Khalilpourazari and Pasandideh (2019) proposed multi item economic order quantity for growing items with a limited management budget and available warehouse space. Malekitabar et al. (2019) investigated the inventory model for growing-mortal in a two-echelon supply chain with a supplier and a farmer. Furthermore, Sebatjane and Adetunji (2019a, b, c) formulated three echelon supply chain inventory model for growing items with farming, processing and retail operations. Hidayat et al. (2020) developed an EOQ model for growing items by considering unlimited capacity and an unlimited budget. Later on, this model was known as the Wilson model. Some research focused on the inventory model for growing items of quality aspects. Zhang et al. (2016) discussed the inventory model for growing items for carbon-constrained the total cost, carbon emission and the optimal slaughter time. Alfares and Afzal (2021) developed an inventory model for growing items

with a growth period and consumption period in which quality inspection and shortages are considerable.

2.2 Inventory for carbon emissions

In order to improve global warming, the total amount of carbon emission can be curbed because it is one of the most effective market-based mechanisms. So, organizations can optimize their strategic decisions in production, transportation and in inventory management to reduce carbon emission. There are some studies of operations decisions based on the carbon emission. Hereof, Hua et al. (2011a, b) proposed an inventory policy for managing carbon footprints with carbon emission. Asbi et al. (2013) studied carbon emission limitations in the multi-sourcing lot-sizing problem. Toptal et al. (2014) analyzed the joint inventory model and carbon emission reduction under carbon cap, tax and cap-and-trade policies. Lou et al. (2015) established a supply chain model for carbon emission technology investment. Dye and Yang (2015) studied the stability of the inventory model for default risk and demand which depends on the length of credit period under the carbon cap-and-trade policy. Moreover, this model is finished with carbon offset policy. Datta (2017) scrutinized the effect of green technology on a production inventory model by assuming price-sensitive demand under carbon tax policy. Mishra et al. (2020) proposed a sustainable economic production quantity model under carbon cap and carbon tax. For controlling carbon emission, green technology investment is applied in both cases: with shortages and without shortages and shortages are partially and fully backlogging. Mishra et al. (2021) analyzed a sustainable inventory model under carbon cap and tax regulation policies in which demand is price sensitive. This study includes the investment in green technology and preservation technology under different backorder situations for controlling carbon emission Table 1.

3 Problem statement, assumption and notations

In this section, problem statement is given. Next follows notations and assumptions for the proposed model formulation.

3.1 Problem statement

The aim of the research exhibited here is to analyze inventory of Vaccine for prevailing pandemic COVID-19.

Table 1 Literature survey

Title	Growing item	Carbon emissions	Demand pattern	Carbon regulation policy
Hua et al. (2011a, b)				Carbon trade and cap
Asbi et al. (2013)				
Toptal et al. (2014)				Carbon cap, tax and cap-and-trade
Rezaei (2014)				
Lou et al. (2015)				Carbon trade
Dye and Yang (2015)			Length of the credit period	Carbon cap-and-trade and carbon offset
Zhang et al. (2016)				
Datta (2017)			Price sensitive	Carbon tax
Nobil et al. (2019)				
Sebatjane and Adetunji (2019a, b, c)				
Khalilpourazari and Pasandideh (2019)				
Malekitabar et al. (2019)				
Sebatjane and Adetunji (2019a, b, c)				
Hidayat et al. (2020)				
Mishra et al. (2020)				Carbon cap and tax
Alfares and Afzal (2021)				
Mishra et al. (2021)			Price sensitive	Carbon cap and tax
Proposed article			Carbon emissions sensitive	Carbon tax

The process starts with buying raw material for vaccine production, manufacturing vaccine, stocking it in a specialized warehouse, transporting it to distribution center. Each of these processes observes carbon emission. The government started vaccinated program in phases. The registration is required for vaccination. It is evident that demand depends on the registration. The non-arrival of individuals even after registration and loss of utility of vaccine is considered in the formulation of the model. The focus of the study is to compute carbon emissions during the process of manufacturing by incurring raw material to vaccination at the distribution center. The vaccine is life-saving drugs at present so model does not consider shortages. The total cost which is sum of holding cost, purchase cost, inspection cost, ordering cost and carbon emissions cost is minimized.

4 Notations

In this section notations are exhibited which are used to construct the proposed model.

Cost parameters	
A	Set-up cost (\$ /order)
H	Holding cost (\$ /vaccine /unit of time)
C	Manufacturing cost (\$ /vaccine)
C_p	Purchase cost (\$ /vaccine)
C_i	Inspection cost (\$ /vaccine)
C_T	Carbon tax (\$)
A_{ce}	Amount of carbon emissions during manufacturing, set-up and transportation (in kg CO ₂)
h_{ce}	Amount of carbon emissions caused by holding vaccines in the inventory system (in kg CO ₂)
C_{rce}	Amount of carbon emissions produced during preparation time (in kg CO ₂)
C_{pce}	Amount of carbon emissions incurred during the purchase operation (in kg CO ₂)
C_{ice}	Amount of carbon emissions during inspection process (in kg CO ₂)
Demand and spoilage parameters	
r	Inspection rate
θ	Rate of health warriors who did not turn up for vaccination after registration
R	Scale demand in units
Functions	
X	Percentage of spoiled vaccine due to miss-handling

Cost parameters

$E[x]$	Expected value of percentage of spoiled vaccine
$1 - E[x]$	Expected value of percentage of quality vaccine
$f(x)$	Probability density function of percentage of spoiled vaccines

Constants

α	Constant > 0
β	Constant > 0
λ	Linear growth rate for vaccine registration /unit > 0
v_0	Rate of initial registration to get vaccine $0 \leq v_0 \leq 1$
v_1	Rate of vaccination at respective time

Time periods

t_1	Manufacturing period in weeks
t_2	Inspection time for Q -units in weeks
t_3	Utilization time of vaccine after inspection in weeks
T	Cycle time ($t_2 + t_3$) in weeks

Decision variables

Q	Order quantity of vaccines (units)
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Objective function

$TC(Q)$	Total cost per unit time (\$ /unit time)
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Problem

Minimize

$$TC(Q)$$

Subject to

$$Q > 0$$

5 Assumptions

The proposed inventory model of vaccine is based on the assumption listed below:

- (1) Only one type of vaccine is considered.
- (2) Registration to take vaccines increases linearly at an approximately constant rate. (<https://www.mohfw.gov.in/>)
- (3) The raw material cost of vaccine depends on demand of vaccine or the quantity of registration by the health warriors.
- (4) Inspection is carried out to identify the fault free vaccine.
- (5) The vaccine loses its utility due to maintenance at the rate θ ($0 \leq \theta < 1$).
- (6) Shortages are not allowed because health warriors are directly coming in contact with COVID-19 infectious patients.

6 Problem description

The objective of the proposed problem of vaccine inventory is to minimize the total cost of an inventory system per unit time which is sum of purchase cost (PC), ordering cost (OC), Manufacturing cost (RMC), holding cost (HC), inspection cost (IC) and carbon emissions cost (CEC).

7 Model development

The Indian COVID-19 vaccine needs to be stored at $2 - 8^\circ\text{C}$. The power cut or voltage fluctuation in the inventory system results in spoilage of vaccine. Let the fraction of spoilage of vaccine be x , which is a random variable with $f(x)$ as the probability density function and expected value $E[x]$. Therefore, the expected total cost is given by

$$E[TC] = PC + OC + RMC + E[HC] + IC + CEC \quad (1)$$

The registration for vaccine follows logistic curve with function $v(t) = \frac{\alpha}{1 + \beta e^{-\lambda t}}$, where α, β are positive constants and $\lambda > 0$ represents linear growth rate of registration.

During manufacturing period t_1 , registration is given by $v(t_1) = \frac{\alpha}{1 + \beta e^{-\lambda t_1}} = v_1$ (say).

So, the manufacturing time t_1 is

$$t_1 = -\frac{1}{\lambda} \ln \left[\frac{1}{\beta} \left(\frac{\alpha}{v_1} - 1 \right) \right] \quad (2)$$

These vaccines are thoroughly inspected at rate r . The inspection time t_2 is

$$t_2 = \frac{Qv_1}{r} \quad (3)$$

Under assumption that x fraction of spoilage vaccine is to be dumped, the utilization time of vaccine after inspection and dumping t_3 is given by

$$t_3 = \frac{Qv_1 - Rt_2 - E[x]Qv_1}{R} \quad (4)$$

Hence, the cycle time T is the sum of t_2 and t_3 . i.e.

$$T = t_2 + t_3 = \frac{Qv_1}{R} (1 - E[x]) \quad (5)$$

Next, we compute different cost components related to proposed problem.

Since, initial registration for vaccination is v_0 , the purchase cost is given by

$$\text{Purchase cost } PC = C_p Q v_0 \quad (6)$$

A fixed set-up cost occurs at the beginning of each cycle, thus the ordering cost per cycle is

$$\text{Ordering cost } OC = A \quad (7)$$

The vaccines are produced during 0 to t_1 with a manufacturing cost C per vaccine and so the manufacturing cost is given by:

$$\text{Manufacturing cost } RMC = CQ \left[\alpha t_1 + \frac{\alpha}{\lambda} (\ln(1 + \beta) e^{-\lambda t_1} - \ln(1 + \beta)) \right] \quad (8)$$

The organization invest in a holding cost for preserving vaccines. So expected holding cost is

$$E[HC] = h \left[\frac{Q^2 v_1 [E(1 - x)^2]}{2R} - \frac{Q v_1 (1 - E[x])}{R} + \frac{1}{2R} + \frac{Q^2 v_1^2 E[x]}{r} - \frac{Q v_1 E[x]}{r} + \frac{Q v_1}{r} \right] \quad (9)$$

During t_1 to t_2 an inspection process is carried out to inspect and separate the defective vaccine from the perfect ones. The organization acquires in an inspection with rate C_i per vaccine and the inspection cost is

$$\text{Inspection cost } IC = C_i Q v_1 \quad (10)$$

Next we compute carbon emissions. The carbon emissions occur from the beginning of manufacturing till it reaches to the customer. The carbon emission is caused due to procedures such as manufacturing, purchasing, set-up, holding inventories and inspection. Carbon emission caused by the purchasing activity is given below:

$$CEP = C_{pce} Q v_0 \quad (11)$$

$$\text{Carbon emissions due to setup activity } CES = A_{ce} \quad (12)$$

Carbon emission produced during the manufacturing process is

$$CRM = C_{rce} Q \left[\alpha t_1 + \frac{\alpha}{\lambda} (\ln(1 + \beta) e^{-\lambda t_1} - \ln(1 + \beta)) \right] \quad (13)$$

Carbon emission observed in holding inventory operations is CHC .

$$CHC = h_{ce} \left[\frac{Q^2 v_1 [E(1 - x)^2]}{2R} - \frac{Q v_1 (1 - E[x])}{R} + \frac{1}{2R} + \frac{Q^2 v_1^2 E[x]}{r} - \frac{Q v_1 E[x]}{r} + \frac{Q v_1}{r} \right] \quad (14)$$

Carbon emission spawned in the process of inspection.

$$CEI = C_{ice} Q v_1 \quad (15)$$

Carbon tax is one of the important policy which is imposed by government regulation on amount of carbon emissions.

$$CEC = C_T [CEP + CES + CRM + CHC + CEI] \quad (16)$$

From Eqs. (6) to (10) and (16), the expected total cost of an inventory system is:

$E[TC] = PC + OC + RMC + E[HC] + IC + CEC$ and expected cycle time $E[T] = \frac{Q v_1}{R} (1 - E[x])$ so expected total cost TC per time unit is

$$TC = \frac{E[TC]}{E[T]} = \frac{PC + OC + RMC + E[HC] + IC + CEC}{E[T]} \quad (17)$$

is a function of order quantity Q , for optimal value of Q , we need to set $\frac{dTC}{dQ} = 0$, where

$$\frac{dTC}{dQ} = \frac{1}{3(rQ^2 v_1 (-2 + a + b))} \left(\begin{aligned} & -C_T C_{pce} Q^2 v_1^2 a^2 r \theta - C_T C_{pce} Q^2 v_1^2 a b r \theta - C_T C_{pce} Q^2 v_1^2 b^2 r \theta \\ & -3C_T C_{pce} Q^2 R v_1^2 a \theta - 3C_T C_{pce} Q^2 R v_1^2 b \theta + 3C_T C_{pce} Q^2 v_1^2 a r \theta \\ & + 3C_T C_{pce} Q^2 v_1^2 b r \theta - C_T Q^2 v_1^2 a^2 h_{ce} r - C_T Q^2 v_1^2 a b h_{ce} r \\ & - C_T Q^2 v_1^2 b^2 h_{ce} r - C_p Q^2 v_1^2 a^2 r \theta - C_p Q^2 v_1^2 a b r \theta - C_p Q^2 v_1^2 b^2 r \theta \\ & - 3C_T C_{pce} Q^2 v_1^2 r \theta - 3C_T Q^2 R v_1^2 a h_{ce} - 3C_T Q^2 R v_1^2 b h_{ce} \\ & + 3C_T Q^2 v_1^2 a h_{ce} r + 3C_T Q^2 v_1^2 b h_{ce} r - 3C_p Q^2 R v_1^2 a \theta \\ & - 3C_p Q^2 R v_1^2 b \theta + 3C_p Q^2 v_1^2 a r \theta + 3C_p Q^2 v_1^2 b r \theta - Q^2 v_1^2 a^2 h r \\ & - Q^2 v_1^2 a b h r - Q^2 v_1^2 b^2 h r - 3C_T Q^2 v_1^2 h_{ce} r - 3C_p Q^2 v_1^2 r \theta \\ & - 3Q^2 R v_1^2 a h - 3Q^2 R v_1^2 b h + 3Q^2 v_1^2 a h r + 3Q^2 v_1^2 b h r - 3Q^2 v_1^2 h r \\ & + 6A_{ce} C_T R r + 6A_{ce} R r \end{aligned} \right)$$

8 Numerical validation

In this section, numerical example is demonstrated to show the applicability of the proposed model and explain the solution steps. The objective is to minimize the total cost which can be obtained by following steps:

Step 1: Differentiate total cost function given in Eq. (17) with respect to order quantity Q .

Step 2: Assign the values to all inventory parameters other than order quantity.

Step 3: Taking cost function is zero, in order to get solutions.

Step 4: Find the values of all cost functions and decision variable.

The following hypothetical data are considered to validate the model.

$\alpha = 2$, $C_p = \$1.2$ per vaccine, $\lambda = 0.60$,
 $A = \$1000$ per order, $C = \$1$ per vaccine,
 $h = \$0.40$ per vaccine,
 $C_i = \$4$ per vaccine, $C_T = 0.40$, $C_{pce} = 0.2$,
 $A_{ce} = 50$, $C_{rce} = 0.06$, $h_{ce} = 0.005$, $C_{ice} = 0.12$,
 $R = \$600$ per order, $r = 0.9$, $\theta = 0.1$, $v_0 = 0.9$,
 $v_1 = 0.8$

The percentage of spoilage vaccine follows a uniform distribution ($x \sim U[\gamma, \delta]$) with the probability density function $f(x)$ which is given below.

$$x \sim f(x) = \begin{cases} \frac{1}{\delta - \gamma} & \gamma \leq x \leq \delta \\ 0 & \text{otherwise} \end{cases}$$

Considering ($x \sim U[0, 0.04]$)

$$x \sim f(x) = \begin{cases} 25 & 0 \leq x \leq 0.04 \\ 0 & \text{otherwise} \end{cases}$$

The various optimal costs are:

As shown in Fig. 1, the various optimal costs are: raw material cost \$1280, inspection cost \$2449, purchase cost \$826.5, ordering cost \$2116, inventory holding cost \$2120 and carbon emission cost \$198.1 resulting total cost per unit time is \$8980 to procure 361 vaccine units. Each vaccine unit consists of 100 vaccines. The obtained total cost is minimum because $\frac{d^2TC}{dT^2} = 0.04 > 0$.

During the process of vaccination starting from raw material inventory in the pharmaceutical company, carbon emissions are observed. As per Fig. 2 carbon emission in stocking raw material \$30.5, during inspection \$29.79, during purchase action \$55.10, during set-up and transportation phase \$42.33 and holding it at point of delivery \$40.79. Then carbon tax levied is \$198.1. From Fig. 2, it is observed that maximum carbon emission of 28% occurs during purchase process followed by 21% during transportation at point of delivery and stocking it at respective places. This is obvious because of fuel consumption and cold storage which emits gases.

Fig. 1 xxx

9 Sensitivity analysis

In this section, the sensitivity analysis is carried out with different inventory parameters. When the value of one inventory parameter is changed by -20% , -10% , 10% and 20% at a time and keeping others parameters unchanged is shown in Table 2.

As depicted in Table 2, changes in purchase cost C_p , set-up cost A , manufacturing cost C , holding cost h , Inspection cost C_i and Scale demand R have a major impact on total cost. While constant α , growth rate λ , inspection rate r and v_1 have a revisable effect on total cost. Carbon tax C_T , carbon emissions during the purchase cost C_{pce} , amount of carbon emission during set-up cost A_{ce} , amount of carbon emission during preparation time C_{rce} , amount of carbon emissions during holding the inventory h_{ce} , carbon emission during the inspection process C_{ice} , rate of health warriors who didn't take vaccination θ and initial registration of vaccination v_0 have marginal effect on total cost. The order quantity Q gets positively affected by set-up cost and inspection rate while it decreases with increases in parameters C_p , h , θ and v_1 . The Rest of the inventory parameters have a negligible effect on order quantity. Carbon emission caused by purchasing cost increases with increases in carbon tax, C_{pce} , R and v_0 , while decreases with v_1 . Carbon emission due to set-up is positively affected by C_p , h , C_T , A_{ce} , R , θ and decreases with A and r . C_T , C_{rce} and R are the most sensitive parameters of carbon emission during manufacturing CRM . α and λ have a reversible impact on CRM . Carbon emission during holding the items CHC is increases when A , C_T , C_{pce} , h_{ce} , R and θ increases. Conversely CHC decreases with increases in C_p , h and r . The carbon tax and carbon emission during inspection has the most significant impact on carbon emissions generated during the inspection CEI . CEC is positively affected by C_T , C_{pce} , A_{ce} , C_{rce} , C_{ice} , R , θ and v_0 while it decreases with λ , r and v_1 . C_p , R and v_0 give rise to purchase cost whereas purchase cost reduces due to v_1 . Moreover, C_p , A , h , R and θ have a positive impact on

Fig. 2 yyy

Table 2 Sensitivity analysis

		Decision variable (in Units) and different costs (in \$)												
		Q	TC	CEP	CES	CRM	CHC	CEI	CEC	PC	OC	RMC	$E[HC]$	IC
Inventory parameters	α		↓			⇒						↓		
	C_p	⇒	⇒		↑		↓			↑	↑		↑	
	λ		↓			↓			↓				↓	
	A	↑	↑		↓		↑					↑	↑	
	C		↑									↑		
	h	↓	↑		↑		↓				↑		↑	
	C_i		↑											↑
	C_T		↑	↑	↑	↗	↑	↑	↗					
	C_{pce}		↑		↑		↑		↗					
	A_{ce}				↗				↗					
	C_{rce}					↗			↗					
	h_{ce}						↑							
	C_{ice}							↗	↑					
	R	↗	↗	↗	↗	↗	↑	↗	↗	↗	↗	↗	↗	↗
	r	↑	↓		↓		↓		↗			↗		
	θ	↗	↑		↑			↗		↗		↑		
	v_0		↑	↑					↑	↑				
	v_1	↗	↓	↗		↑			↓	↗		↑		
Symbol		Indication												
↑		Increasing												
↓		Decreasing												
↑		Linearly Increasing												
↓		Linearly Decreasing												
↗		Exponentially Increasing												
↘		Exponentially Decreasing												

ordering cost. Manufacturing cost gets increased with C , R and v_1 . Parameters α and λ have a negative impact on RMC . Holding cost increases when C_p , A , h , R and θ increases whereas it decreases with inspection rate. Inspection cost C_i and scale demand are the most sensitive parameters to inspection cost IC .

10 Discussion of findings

In Table 3, we carry out the analysis of critical parameters for the proposed problem of inventory of vaccines and carbon emissions due to process involved.

11 Managerial implication

From the sensitivity analysis Table 2, the following managerial insights are made:

Scale demand has major effect on order quantity, total cost, and carbon emissions during activity like purchase, holding set-up, manufacturing and inspection. Moreover, a bigger order size gives rise to carbon emissions but also increase the sell, so it is advisable to place larger order for a short period of time. Set-up cost and purchase cost increases manufacturing cost as well as total cost. Holding cost decreases the order quantity. A higher holding cost indicates better-quality storage condition and it increase the total cost. Hence, it is recommended that order in small lots so inventory can be handled, which is also reduce carbon emissions. As increase in carbon tax contributes to the total cost components which is unfavorably. Manufacturing cost is directly affected by demand. So proper technology should be employed. Rate of health warriors who did not turn up for vaccination after registration is directly increase total cost as well carbon emissions and also increase the risk of COVID-19 infection. Initial registration directly affect the manufacturing, transshipping and holding.

Table 3 Sensitivity analysis of critical parametersImpact of initial registration on *CEP*

In the adjacent figure, the impact of initial registrations on carbon emissions due to purchase action is shown. The purchase order directly reflects to the manufacturing, transportation and stocking. The carbon emission increases by 27.27%

Impact of λ on *CRM*

In the adjacent figure, the linear rate of registration is studied on carbon emissions due to raw material stocking. Here, the carbon emissions reduces by 33.16% when registration rate increases from 48 to 72%. This is because raw material is gone to production of vaccine phase

Impact of C_{rce} on *CRM*

In this figure, C_{rce} is varied from 0.048 to 0.072 which increases carbon emissions during manufacturing by 50%. So the proper technology investment should be deployed to reduce this

Table 3 continuedImpact of C_{ice} on CEI

In this adjacent figure when carbon emissions occurred during inspection is varied from -20% to 20%, to cost of carbon emission increases by 49.72%

Impact of purchase cost on CES and CHC

Here, when purchase cost is varied from \$ 0.96 to \$ 1.44, carbon emissions due to set-up increases by 4.66% and due to holding cost decreases by 7.35%

Impact of C_{pce} on CEP and CHC

Carbon emission cost due to purchasing; C_{pce} results 50% increase in carbon emission due to set-up and 37.84% in carbon emission during stocking

Table 3 continuedImpact of set-up cost on *CES* and *CHC*

Increase in set-up cost, decrease carbon emissions due to set-up by 18% and increase carbon emission due to holding cost by 21.95%

Impact of A_{ce} on *CES*When A_{ce} increases from \$ 40 to \$ 60, carbon emission cost due to set-up increases by 49.42%. This can be controlled by designing special vehicles for transporting vaccines to the point of delivery Impact of holding cost on *CHC*

– 20 to 20% variation holding cost results into 16.48% increase and 14.16% decrease in carbon emissions due to set-up and stocking operations respectively

Table 3 continuedImpact of v_1 on *CES* and *CHC*

Change in v_1 decreases carbon emission due to procurement by 27.28% and increases carbon emission due to raw material stocking 10.88%

Impact of θ on *CES* and *CHC*

The effect of spoilage of vaccines during storage or transportation on carbon emissions during set-up and stocking operations is exhibited here. It is 4.96% and 3.17% respectively. This is not affordable as it wastes raw material for vaccines and end-user will also not able to get vaccination which puts a good fraction of population at the risk of infection of COVID-19

12 Conclusion

Attributed to the invention of COVID-19 vaccines, people around the world were offered a hope that the pandemic may come to an end soon. But the gradual relief from this said pandemic will bring back to the biggest challenge currently faced by humans which is carbon emissions. This articles shows detailed analysis of carbon emissions during manufacturing, transportation and stocking. In order to reduce carbon emissions, it can be suggested vehicles which are used in transporting are well designed, the proper technology for manufacturing can be deployed and individuals should encourage for not to skip schedule second dose of vaccine. The spoilage of vaccine during storage is not affordable as it waste raw material and needed people are not get vaccine. The model is examined analytically

and graphically by minimizing the total cost. A sensitivity analysis is performed to scrutinize how each inventory parameters affects the total cost and carbon emissions cost.

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Declarations

Conflict of interest The authors does not have conflict of interest.

Human and animals participants Not applicable.

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