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Mathematical Model to Analyse the Effect of Quarantine on Spread and Containment of COVID-19

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Abstract:

Predictions, without mathematical approach and statistics appear bogus and simply drawn out of air. Hence applicability of mathematical modelling paves way for more authentic approach, the complexity of which depends on the number of parameters incorporated for use in the model. Analysing this, our work involved development of a model, labelled as SIQTRD model, which will signify its role and comprehensiveness in role prediction of quarantine in future containment of Covid19 disease as well as gain insights into the dynamics of disease transmission, based on the data available within a certain time frame. Predictions done this way in understanding the emergence effect and containment of epidemic are more effective and foster hind casting the event. The model predicts the number of active cases to reach 90,000 - 2,90,000 in India by mid-May to late June. In fact when the virus will enter the plateau phase, the number of active cases may monotonically increase even more depending on the relaxations implemented in lockdown and quarantine approach. This will be followed by a decreasing trend in the number of peak infective cases towards end August and after this the virus will fade out eventually although after effects may be visible in coming years. However the recovery rate may show an increasing trend due to the lockdown and quarantine policies in place providing ample time to the scientists, visionaries and medical practitioners to adopt implement and deploy anti-epidemic procedures including development of vaccines, testing kits etc. which will help out in dimming the disease.

INDEX TERMS: Novel Coronavirus, infection rate, quarantine, containment, prediction.

1. INTRODUCTION

Severe acute respiratory syndrome coronavirus (SARS-19COV-2) first emerged in Wuhan, China and since then this virus has taken the whole world by storm [1]. Approximately 3.66 million cases have been reported till date with death toll of 2, 59,000[2]. In the past years China has suffered a number of pandemological outbreaks such as Severe Acute Respiratory

Syndrome (SARS), H1N1, H7N9 etc. which alarmingly challenged the health management systems all over the world [3, 4]. Though there is a close similarity between the SARS virus and the Covid19 Virus and hence the name SARS-19COV-2, but several studies suggest COVID19 virus to be more dangerous than the usual SARS virus [5]. The spread of this newly emerging virus still holds uncertainty regarding the current and future behaviour despite the fact that numerous studies suggesting the trend all over the world have been reported. On 8th May 2020, Coronavirus cases in India crossed 56,000 mark and 3,390 new cases were reported in 24 hours. The death toll was recorded as 103 in a single day [6].

The Covid19 pandemic which has brought the whole world to a standstill stays a matter of grave concern even after months of its upsurge. In order to reduce the reproductive rate of the infection governments all over the world have implemented stringent lockdown and isolation measures but the pandemic seems far from over. This global pandemic not only has serious implications on people’s health but it is negatively impacting businesses and the economy as well. On an average the cumulative cases of Covid19 are increasing day by day although some countries like Canada, Taiwan, Iceland etc. have succeeded in flattening of the curve [7,8]. With the global race for vaccine intensifying and theories about plasma technology and herd immunity coming to surface, the apprehensions about its intensification seem to subside but for some it raises eyebrows [9]. There is a little knowledge of what challenges could arise during the development which could further delay the timelines.

The expeditious spread of the disease throughout the globe can be attributed to a number of factors. The strategies chalked out seem visibly to contain the virus in some areas of the world but the role of emergency committee seems to be somehow flawed. In spite of the declaration of Covid19 pandemic as Public Health Emergency of International concern, the monitoring and surveillance of which needed to be strengthened as per the recommendation, no restrictions on travel and trade at global level was initiated during earlier stages which worsened the case scenario[10]. The role of airline travel network seems to be pivotal, in spreading of Covid19 which has led to the development of several mathematical modelling techniques that enable us to examine the present status and demonstrate the future predictions of any eventuality [11, 12]. The possible outcomes in many of the already conducted researches show a positive relationship between global transportation network and the spread of the disease [13]. In this regard the decision making and implementation require certain adaptation and modification which are to be taken into consideration in terms of community structure, local epidemiology of disease, its risk assessment, social habits of area, juridical provisions and availability of financial – economic resources [14, 15,16]. Failure to control the disease even after months of its emergence clearly portrays disproportionate resources to health as are visible through dismaying results.

The epidemiological models provide a deep insight into the transmission dynamics by helping trace the path of infection so that appropriate measures can be deployed to contain the disease [17]. The SIQTRD model that has been proposed is a complex model than the earlier SI and SIR models that takes number of parameters into consideration [18, 19]. The study models the vital dynamics and envisions the effect of the COVID19 with and without quarantine to understand the future trend of the disease.

2. DATA AND METHODS

a) Data:

The data used in our Model is taken from https://www.kaggle.com/sudalairajkumar/covid19-in-india. It provides the latest epidemiological data including cumulative confirmed cases, deaths cases and cured cases, in various states of India. In our model we have taken data of Maharashtra state of India for analysis. The study has been restricted within time frame 06 March 2020 to 15 May 2020 to highlight the pattern of the spread of virus for Maharashtra and hence understand the progression of the disease based on the different parameters considered for the study.

b) Parameters used for the study:

To study pattern of COVID19 disease through the proposed mathematical model the number of confirmed Covid19 positive cases, recovered and death cases have been used as the parameters for study. Various graphs have been plotted to highlight the differences and similarities in spread of virus.

3. FORMULATION OF THE MODEL

The mathematical model labelled SIQTRD has taken quarantine and non-quarantine states of disease into consideration to study, evaluate and understand the vital dynamics of COVID19 disease and henceforth gain sufficient insights and predict the future trend of the infectious spread. Various differential equations have been proposed for analysing the effect on the no of active, recovered and death cases of COVID19 with and without quarantine. The total population denoted by N is divided into five sub-populations. The model consists of five compartments: S for population of susceptible, I for the population infected with the disease, Q for the population that has been quarantine, T for the population that was tested on the onset of symptoms, R for the population that recovered due to quarantine and treatment and D for the population that has been reported deceased or dead. Susceptible population class denoted by S refers to the class who are prone to get infected by COVID19 due to contact with infected individuals denoted by I and hence leave the susceptible compartment and join the I compartment. Quarantined class denoted by Q refers to the population that has been quarantined for a time period equal to the incubation period of the disease in order to contain the spread and this class will also consist of individuals who are coming from COVID19 affected countries and have the capability to spread the infection with the rate δ.If however the quarantined individuals do not show any symptoms they return to the susceptible compartment, S with the rate ρ.T denotes the population that was tested on the onset of symptoms during quarantine, wherein r denotes the rate of testing. If an individual is tested positive for COVID19, he will join the I compartment at the rate k. The population belonging to the I compartment may die and join the deceased compartment denoted by D either with a probability denoted by P_d or join the recovered compartment with a probability 1-P_d. Individuals in the susceptible compartment have the probability of contracting the disease at rate determined by an important driving factor called the reproductive rate or ratio of pandemic denoted by K_0 which in general can be calculated from the formula given below:

$$K_{0=}\ \sigma/\ \eta + \psi \qquad (1)$$

Also $\sigma = \tau_R\, P_c$ where σ signifies the rate of infection or transmission rate of pandemic, τ_R denotes the rate at which a healthy individual gets into contact with an infected individual and P_c denotes the probability of successfully contracting the disease.

If the state of quarantine is taken into consideration then equation (1) changes to

$$K_{1=} \sigma_1/ \eta_{1} + \psi_1 \qquad (2)$$

where K_1 is the reproductive number of pandemic with quarantine and σ_1,η_1 , ψ_1 denote the transmission rate, recovery rate and death rate respectively with the effect of quarantine.

Without quarantine equation (1) can be manipulated as given below:

$$K_{2=} \sigma_2/ \eta_2 + \psi_2 \qquad (3)$$

where K_2 is the reproductive number of pandemic without quarantine and σ_2,η_2 $\psi_{2,}$denote the transmission rate, recovery rate and mortality rate respectively without the effect of quarantine. The recovery rate is given by

η =1/ $\zeta_{\mathbf{d}}$ where $\zeta_{\mathbf{d}}$ represents the number of days required to recover from the infection.

The emphasis is on pulling out more no of individuals from I compartment and put them in R compartment at the rate determined by η. As can be seen from Table 2 η_1 i.e., the recovery rate of infected people with quarantine shows an increasing trend with time as compared to the η_2 i.e., he recovery rate of people who were not quarantined on getting infected and went on into spreading the infection further into population adding more number of individuals to the I compartment and hence increasing K_0 i.e., the reproductive rate of the pandemic overall.

The population has been assumed to be constant with no effect due to changes in other factors. The important fact that has been taken into due consideration is that the people who have recovered after contracting the disease have the probability of returning back to the susceptible compartment if immunity so developed is temporary at the rate given by λ . The model focuses on the long term control of COVID19 by taking vital dynamics into consideration. In order to understand and explain the recrudescence and subsistence of COVID19 disease, the proposed model works under the following assumptions:

i) Population is homogenously mixing.
ii) The disease induced immunity may be temporary or permanent.
iii) Vital dynamics have been taken into consideration with respect to the no of deaths only.
iv) People coming from COVID19 affected countries are quarantined for a time period equivalent to the breeding period of the disease.
v) $\eta_1 > \eta_{2.}$ i.e.; recovery rate of an infected quarantined individual is greater than that for an infected non-quarantined individual.
vi) Individuals who develop symptoms test positive.
vii) Individuals can develop infection during quarantine i.e., backward bifurcation is taken into account.
viii) Testing of infants born to mother’s infected with COVID-19 has been overlooked.
ix) $\boldsymbol{\psi_1} < \boldsymbol{\psi_2}$ i.e., the mortality rate of infected quarantined person is less than that of infected non-quarantined individual.
x) Ꝁ0 the reproductive ratio or rate of the epidemic falls in the range of 1<=Ꝁ0<=0.
xi) Pc i.e., the probability of getting infected can have the value 0 or 1.
xii) Only horizontal transmission i.e., transmission through direct or indirect contact with an already infected individual has been taken into consideration. Vertical transmission

i.e., transmission from an infected mother to an offspring has been overlooked.

Table 1: Various parameters and variables used in the model

Symbol	**Description**
S	Population that is yet to catch infection.
I	Population denoting the infectives
Q	Population that has been quarantined for time period equal to incubation period of COVID19
T	Population denoting the individuals who are tested.
R	Population that recovered successfully after disease
D	Population that has been reported deceased or dead
K_0	Reproductive ratio or rate of the pandemic
K_1	Reproductive ratio or rate of the pandemic with quarantine
K_2	Reproductive ratio or rate of the pandemic without quarantine
Σ	Infection rate or transmission rate of the pandemic
l	Birth/Death rate
σ_1	Infection rate or transmission rate of the pandemic with quarantine
σ_2	Infection rate or transmission rate of the pandemic without quarantine
$\boldsymbol{\tau}_{\mathbf{R}}$	Contact rate with an already infected individual
P_c	Probability of getting infected.
$\zeta_{\mathbf{d}}$	Number of days required to recover from the disease.
α	Natural mortality rate.
$\psi_{\mathbf{1}}$	Mortality rate of an infected quarantined individual
$\psi_{\mathbf{2}}$	Mortality rate of an infected non-quarantined individual
$\Psi_{\mathbf{3}}$	Mortality rate of people who died few days prior to testing positive.
η	Rate of recovery
$\eta_{\mathbf{1}}$	Rate of recovery of an infected quarantined individual
$\eta_{\mathbf{2}}$	Rate of recovery of an infected non-quarantined individual
k	Rate at which people who were found COVID19 positive after testing, join the I compartment.
r	Rate at which people who were quarantined for latent period show symptoms and hence are tested.
δ	Rate of immigration from COVID19 affected countries.
z	Rate at which individuals tested negative.
μ	Rate of undetected infected individuals
$\boldsymbol{\Omega}$	Rate of detected infected individuals.
ρ	Rate at which quarantined individuals who did not show symptoms of the disease return to the susceptible compartment
$P_{\mathbf{d}}$	Probability that people with infection die and join the deceased class.
$1- P_{\mathbf{d}}$	Probability that people who are infected recover and join the recovered class.
λ	Rate at which people who recover join the susceptible compartment again if the immunity so developed is temporary.

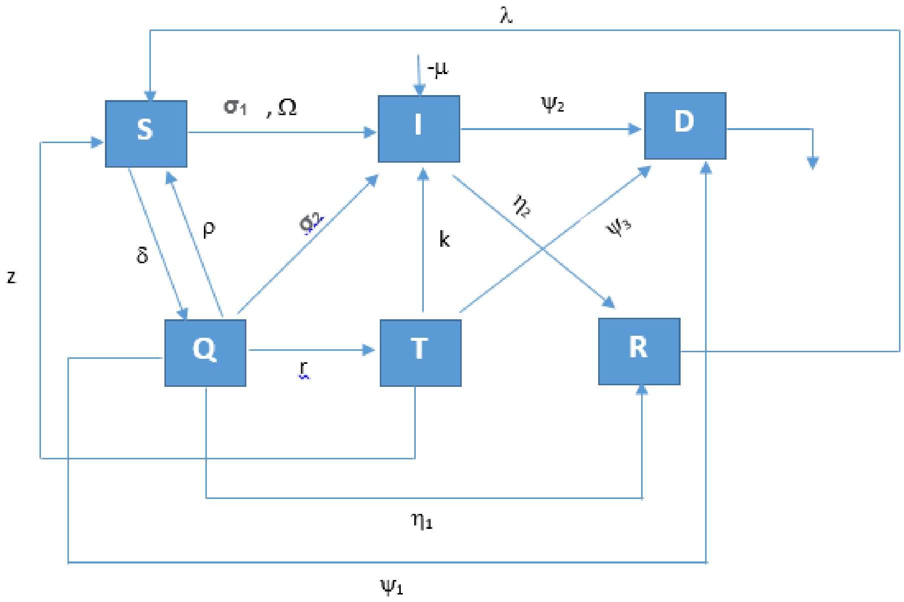

Fig. 1: Flow diagram showing the progression into various compartments at different stages of SIQTRD model

From the model parameters in Table 1 and flow diagram in Figure 1, the following system of deterministic differential equations governs the SIQTRD model.

$$\frac{dS}{dt} = \eta R - \sigma \frac{SI}{N} + \rho Q + (l- \alpha)\, S+\lambda \qquad (4)$$

$$\frac{dI}{dt} = \sigma \frac{SI}{N} - (\eta_1 + \eta_2)\, I - \alpha I + kT-\mu \qquad (5)$$

$$\frac{dQ}{dt} = \delta - Q(\rho+\psi_1) + \tau_R S + rT \qquad (6)$$

$$\frac{dT}{dt} = (\mu+\Omega+k)I + rQ - zS \qquad (7)$$

$$\frac{dR}{dt} = (1- P_d)\, (\eta_1+\eta_2)I - \eta R + \eta_1 Q \qquad (8)$$

$$\frac{dD}{dt} = P_d\, (\psi_1+\psi_2)I + \psi(Q+1) + \psi_3 T \qquad (9)$$

The above given system of differential equations (4) to (9) has a unique solution given by

$$l=\{(S,I,Q,T,R,D) \in R5+:N<=\delta/\ \psi\}$$

The above solution confirms the meaningfulness and the validity of the proposed model in the region defined by l. Also

S+I+Q+T+R-D=N=Constant Population.

Table 2: Sample table showing calculated values for model parameters

Date	σ_1	σ_2	ψ_1	ψ_2	η_1	η_2	K_1	K_2	K_0
6 March	0.970	0.996	0.831	0.988	0.021	0.01	1.079	1.088	1.981
11 March	0.957	0.981	0.713	0.979	0.054	0.03	1.084	1.099	1.962
16 March	0.905	0.992	0.736	0.928	0.081	0.032	1.045	1.098	1.902
21 March	0.800	0.911	0.749	0.904	0.093	0.048	0.963	1.043	1.833
26 March	0.754	1.000	0.631	0.873	0.106	0.049	0.834	1.038	1.776
31 March	0.699	0.838	0.788	0.938	0.133	0.051	0.864	1.010	1.721
5 April	0.655	0.931	0.804	0.817	0.334	0.011	0.792	0.909	1.702
10 April	0.546	0.986	0.832	0.876	0.338	0.010	0.781	0.983	1.738
15 April	0.544	0.813	0.801	0.991	0.438	0.028	0.738	0.976	1.588
20 April	0.561	0.726	0.932	0.986	0.500	0.010	0.813	0.950	1.546
25 April	0.573	0.834	0.912	0.917	0.531	0.040	0.621	0.901	1.5903
30 April	0.559	0.813	0.938	0.987	0.682	0.048	0.601	0.863	1.631
5 May	0.581	0.793	0.908	0.963	0.719	0.031	0.701	0.813	1.501
10 May	0.568	0.888	0.913	0.833	0.971	0.018	0.788	0.891	1.431
15 May	0.558	0.801	0.920	0.918	0.915	0.021	0.632	0.811	1.563

4. STABILITY ANALYSIS OF SIQTRD MODEL

Axiom 1: Using sensitivity analysis, If $\sigma S0<=1$, then I will decrease to 0 as time denoted by t will approach to infinity. If, however $\sigma S0>1$, then I will increase monotonically and reach its peak value given by

$$1-K_0-1/\sigma-[\ln(\sigma S0)]/\sigma \qquad (9)$$

i.e., the disease enters the plateau phase. As t->∞, I shows a decrease until it finally reaches 0.S (∞) is the unique root of equation

$$1-K_0-S(\infty)+[\ln(S(\infty)/S0)]/\sigma=0 \qquad (10)$$

With K_1 the equation (10) can be modified as follows

$$1-K_1-S(\infty)+[\ln(S(\infty)/S0)]/\sigma=0 \qquad (11)$$

Replacing K_1 by K_2 equation (11) becomes

$$1-K_2-S(\infty)+[\ln(S(\infty)/S0)]/\sigma=0 \qquad (12)$$

5. RESULTS AND DISCUSSION

Different global patterns may emerge in infection outcomes driven by the dynamics between deaths and immunity. $\sigma S0$ in axiom 1 denotes the threshold number or the initial substitution numeral. If the threshold number is greater than 1, then a pandemic is reported, as the number of clinical peak infective cases first increase and then monotonically decrease to zero. If, however the number is less than 1, there is no epidemic at all. Also limit I=0 as S tends to 0 i.e., as S(t) tends to zero, rate of spread of infection tends to zero, but S is never negligible i.e.; $S(\infty)$is not equal to 0.In case ,there is no vaccination available during the pandemic ,the epidemiological data can prove useful in estimation of σ using probabilistic modelling and analysis. The effective number K_0, called the reproductive ratio helps in predicting the future trend of the pandemic. K_0 not only determines number of infective cases generated on an average by an infected person but also measures the potential of spread of infection. Lower the value of K_0, lower is the spread and vice versa.K_1 and K_2 representing the reproductive rate of the disease with and without quarantine have been computed (Table 2) from the available epidemiological data to study the effect of quarantine on the spread of the disease. The plots of Figure 2(a), Figure 2(b), Figure 3(a), Figure 3(b), Figure 4(a), Figure 4(b) clearly show a decreasing trend with quarantine as the effective K_1 values are 1.2, 1.5, 1.7 whereas without quarantine the K_2 values are somewhat higher as 1.4,1.6, 1.9. The emphasis is on keeping value of K_0 below 1 so that the disease eventually dies out. However K_0 is not the only important measure. Although, the graphs plotted show value of K_1 reducing with quarantine but it is just delaying the spread of the disease. It can be clearly seen that the effective K_1 values with quarantine still measure above 1, although the graphs show decreasing trend with decreasing K_1 value for quarantine. The uncertainty analysis of the proposed model shows the failure to bring the reproductive number K_1 below 1 even with strict enforcement of quarantine. Reducing K_0 in general will also allow healthcare systems to cope up better with the influx of patients. This is the reason why the number of recoveries has increased since implementation of quarantine or lockdown. However the number of peak infective cases continues to rise even with implementation of quarantine. K_1 determined by equation (2) is dependent on σ_1, η_1 and ψ_1. Clearly σ_1 should show a decreasing trend and η_1 should show an increasing trend in order to skew K_1 below 1.Also greater the value of ψ_1, greater will be the number of people removed from the susceptible compartment and less number will be exposed to the disease. Initially η_1 will be negligible as less number of people will recover from the disease. Skewing σ_1 to a measurable extent is a rule out criterion at the beginning. The reproductive ratio, denoted by K_2 (without quarantine), given by equation (3) shows the dependency on σ_2, η_2 and ψ_2. σ_2 should show a decreasing trend while η_2 and ψ_2 should show an increasing trend. Table 2 clearly highlights the fact that $\eta_2 > \eta_1$ and $\sigma_2 < \sigma_1$ which implies $K1<K2$. This implies flattening of the epidemic curve. Flattening of the curve does not indicate suppression of the disease; it ensures that the healthcare systems do not become overwhelmed with the patients. The daily count of COVID19 cases has risen sharply in May than last week of April. This can not only be attributed to easing of the lockdown but also other factors like higher number of testing kits and better reporting of cases. The doubling rate in India stands at 13 days as is clear from the plots of Figure 2(a) and Figure 2(b). Doubling rate every two weeks assumes growth rate is somewhat constant, although the cases reported in late May, further spike suggesting a difference in the opinion. The plots for number of active cases in Figure 2(b) with quarantine show extrapolations until 15 May due to uncertainty regarding the change in no of cases once the lockdown ends.

The comparison between the graphs of Figure 2(a) and Figure 2(b) shows the delay in number of active cases reported for April but for May the growth rate is accelerating faster even with quarantine. The graph of Figure 2(b) clearly shows the positive effect of quarantine on the number of recoveries, as quarantine provided ample time for the healthcare systems to prepare for the inevitable. The plots of 3(a) and 3(b), however continue to show surge with quarantine. The model predicts the number of active cases to reach 90,000 -290000 in India by mid-May to late June. In fact when the virus will enter the plateau phase, the number of active cases may monotonically increase even more depending on the relaxations implemented in lockdown and quarantine approach. The immediate effect of lockdown is delay in number of active cases. Whatever is done-drastic or non-drastic, it will not shift the peak by a week or so.

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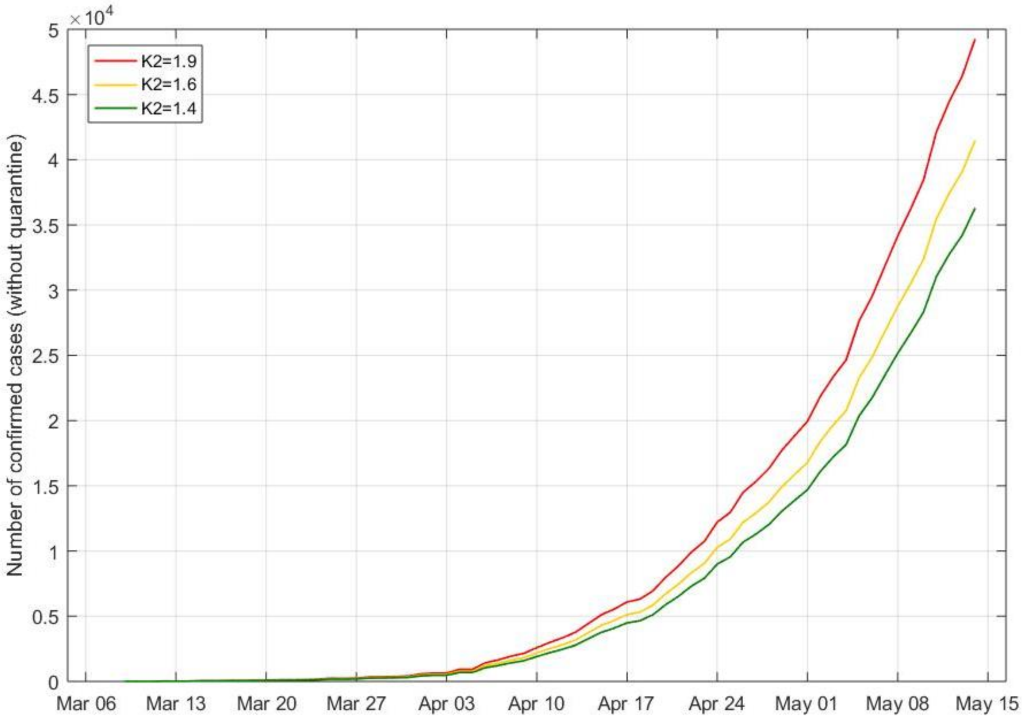

Fig.2 (a): The different coloured lines indicating growth of COVID19 without quarantine at K2 = 1.9, 1.6 and 1.4

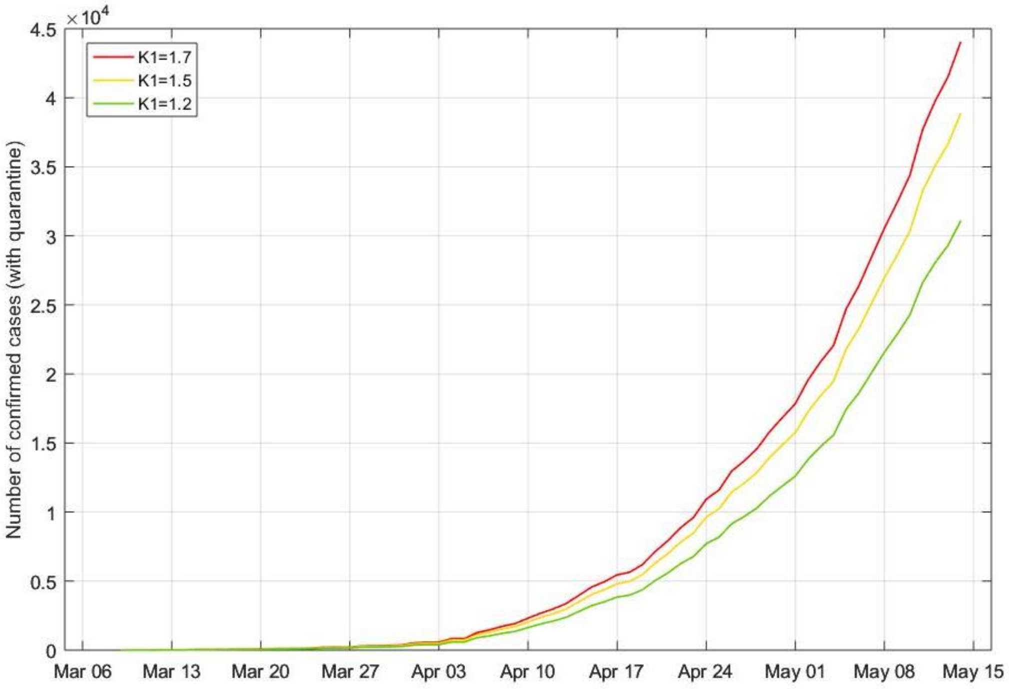

Fig. 2(b): The different coloured lines indicating growth of COVID19 with quarantine at K1 =1.7, 1.5 and 1.2

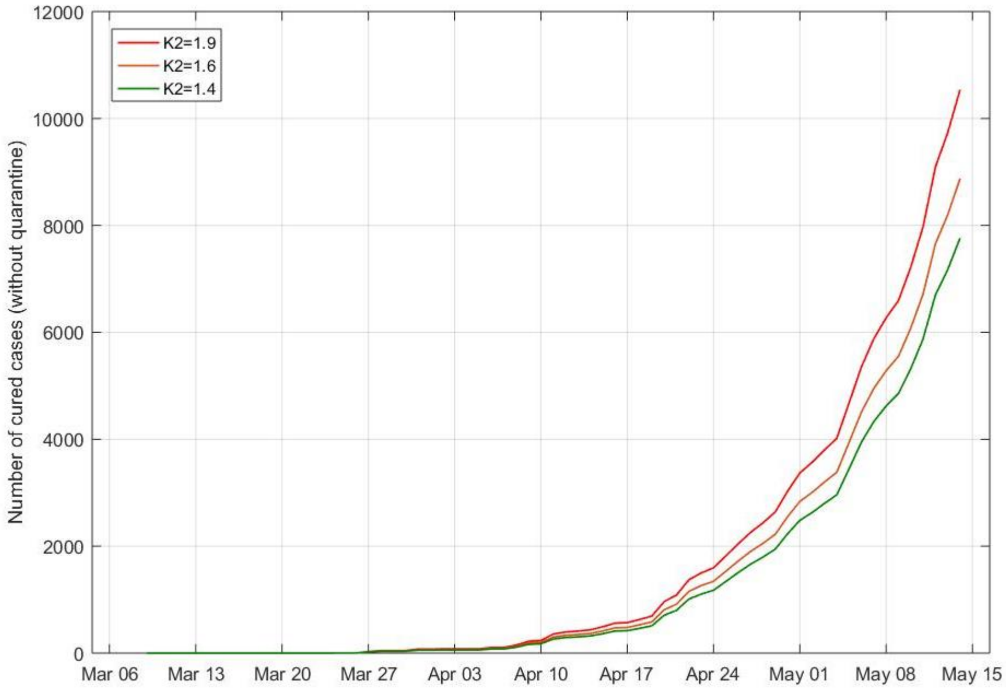

Fig. 3 (a): The different coloured lines indicating recovery trend from COVID19 without quarantine at K2 =1.9, 1.6 and 1.4

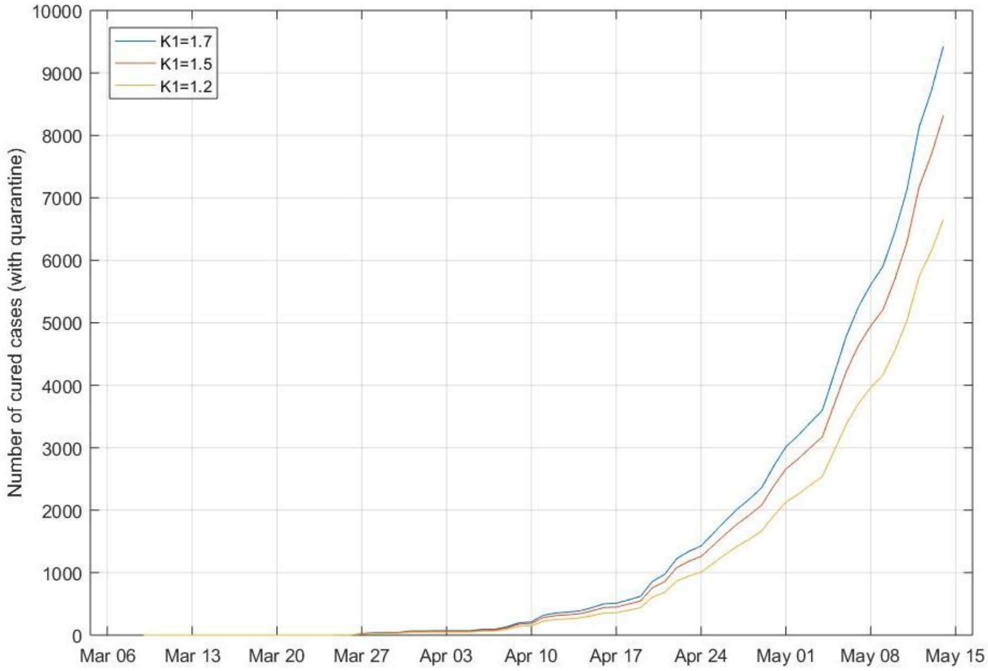

Fig. 3 (b): The different coloured lines indicating recovery trend from COVID19 with quarantine at K1 = 1.7, 1.5 and 1.2

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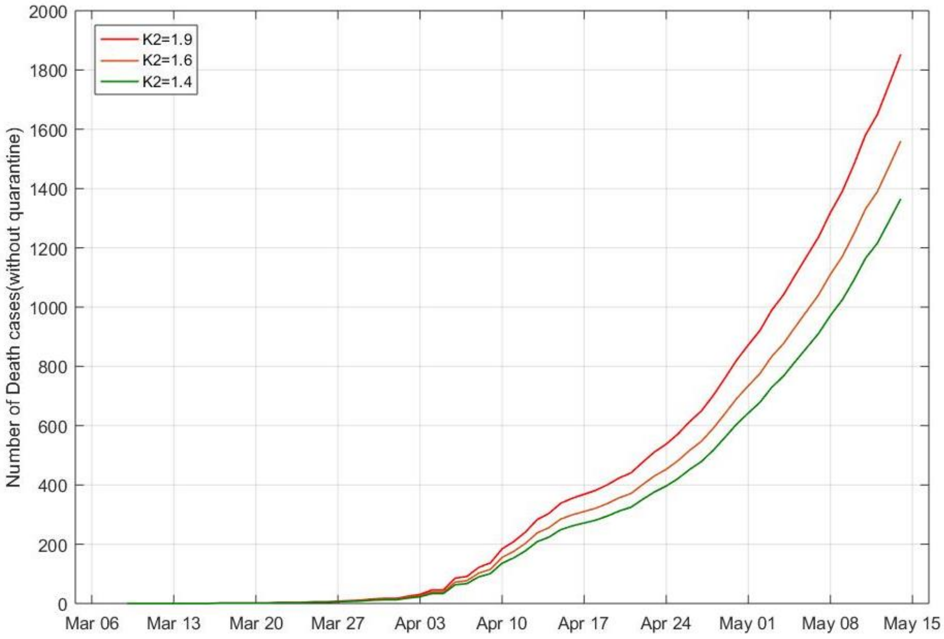

Fig 4(a): The different coloured lines indicating death trend of COVID19 without quarantine at K_2 =1.9, 1.6 and 1.4

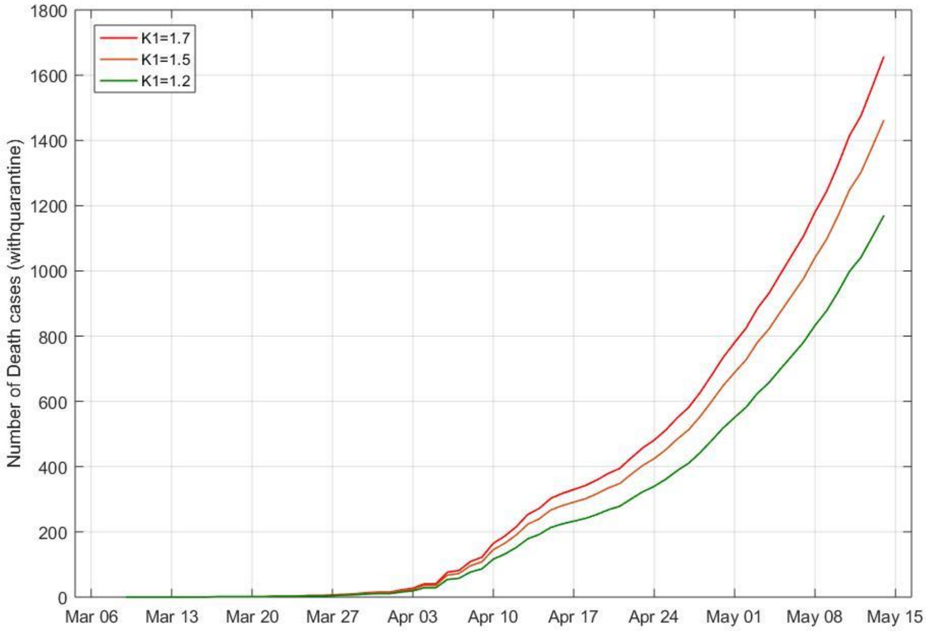

Fig 4(b): The different coloured lines indicating death trend of COVID19 with quarantine at K1 = 1.7, 1.5 and 1.2

CONCLUSION

The recognition of root problem and acceptance of failure even on part of so called developed countries needs to be humbly accepted. Proper funding and redirection of the same for meeting out such challenges seems to be lacking. While glancing at the mathematical model to understand the future trend we start to realise the paucity of situation and get a clear picture of its impact on population as well as economy. Huge population, lack and widespread inaccessibility of proper healthcare system or infrastructure furthermore sparks the fears. Since first week of May the cases have seen a sudden accelerating trend. If this trajectory continues, it will overwhelm India's hospital capacity and strain an already weak health system. The need of the hour is the creation of digital health sector which can improve efficiency and quality of healthcare and can prove to be a stepping stone for any of the future incidents. Comprehensive testing and quarantine regime needs to be followed until vaccine is developed for the disease. Prevention & suppression seem to be the only way out for us right now.

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