

Assessing the Macroeconomic Impact of COVID-19 Pandemic on the Nigerian Economy through the Lens of SIR-Macro Model

Nwosu Chinedu Anthony ¹; Samuel Nnamdi Marcus ²; and Onogbosele Donatus Otaigbe ³

¹Department of Economics, Alvan Ikoku Federal University of Education, Owerri, Nigeria. ²Department of Economics, Abia State University, Uturu, Nigeria. ³Department of Economics, University of Africa, Toru-Orua, Nigeria.

Corresponding author: chinedu.nwosu@alvanikoku.edu.ng

DOI: <https://doi.org/10.62154/ajmbr.2025.018.010613>

Abstract

The COVID-19 pandemic caused economic and social disruptions in Nigeria forcing the government to implement certain containment measures to reduce the severity of the epidemic. The containment measures triggered economic recession leading the government into a policy dilemma of choosing between reducing fatalities and stabilizing the economy. Thus, the key objectives of this research focused on analyzing the macroeconomic impact of COVID-19 pandemic on the Nigerian economy and evaluating the effectiveness of government containment policies in reducing the infection rates and their attendant trade-off with economic performance. To achieve the objectives, this study implemented the SIR-macro model to study the interaction between agents' economic decisions and COVID-19 epidemic. The parameters of the models were calibrated based on the characteristics of Nigeria's economic structure to analyze the implications of containment policies on the severity of economic recession and the dynamics of the epidemics. The result showed that the population of those infected peaked at 5.56 % in week 34 while economic activities dipped by 5.18% in the no-containment model. However, in the benchmark containment model with treatment and vaccination, the population of the infected peaked at 3.09 percent in week 42 while economic activities declined by 22.32%. The study found that government containment policies were effective in reducing the severity of the epidemic in terms of the spread of the disease and number of deaths. The containment policies on the other hand exacerbated the severity of the economic recession. Given the findings, it was concluded that the predictions of the model are qualitatively sufficient in explaining the macroeconomic outcomes in Nigeria during this period. The study suggest that government should consider socio-demographic characteristics of the country in the selection of policies in an epidemic condition. The government should strengthen the health care system with adequate infrastructure to prevent large case fatalities.

Keywords: COVID-19, Epidemics, SIR-Macro Model, Recession, Containment Policy.

JEL Code: C51, C63, E71, I12, I18

Introduction

On the 5th of May 2023, the World Health Organization (WHO) declared the end of the pandemic phase of COVID-19 but the economic shock induced by the pandemic around the world is yet to completely disappear (Sarker et al., 2023) . The economic structure of

developing countries limits their pace of recovery following the effect of the pandemic in their economies (Takyi et al., 2023). Like many other countries, the Nigerian economy witnessed negative growth as result of disruptions and restrictions which imposed considerable hardship on the populace. Many households were unable to carry on with market activities which prompted the government to create social safety measures to reduce the hardship (Farayibi & Simplice, 2020; Nwosu et al., 2020; Yunusa et al., 2020).

Governments around the world implemented lockdowns and social distancing measures to contain the virus which affected economic activities. The measures appear to be uniform across countries despite country-specific peculiarities in terms income, demography, weather and large informal economy. Lin et al. (2022) argues that weather conditions affect the spread of COVID-19 while Tilmann von Carnap et al. (2020) had argued that factors like population and comorbidity structure and income levels affect policy prescriptions. Africa have high proportion of young people with greater percentage of the population living at low-income levels. Moreso, majority of developing countries have very robust informal sectors. Alon et al. (2020) and Hausmann & Schetter (2022) had argued that workers in the informal sector cannot be completely shielded from the disease by social distancing and lockdowns. These factors raise the utility cost of any containment restrictions. Therefore, adoption of similar policy responses for developing countries may not yield expected result (Barnett-Howell et al., 2021; Ravallion, 2020; Susskind & Vines, 2020).

Several studies focusing on the economic implication of the COVID-19 pandemic in Nigeria exist. The consensus of the findings points to the downturn in economic well-being of the populace. For instance, Amusan & Agunyai (2021) avowed that the lockdown policy of the government was effective in controlling the spread of the virus but worsens household crisis in terms of hunger, food shortage and their purchasing power. Nwosu et al. (2020) argued that lockdowns created supply disruptions and scarcity of essential commodities which triggered increase in prices. Ozili (2020) opined that a combination of dwindling oil price and spillovers from government containment policies caused businesses to suffer as economic agents could not freely engage in economic activities due to COVID-19 outbreak. Farayibi & Simplice (2020) concluded that COVID-19 had adverse macroeconomic impact on variables like inflation, employment, exchange rate and the growth rate of GDP. Yunusa et al. (2020) explained that the lockdown policy occasioned by the pandemic caused the output of transport and hospitality industry to decline.

Different approaches have been used to study the effect of COVID-19 around the world. The central framework for studying the spread of disease is the SIR epidemiological model where the population is divided into three categories - Susceptible, Infected and Recovered (Removed) (Kermack & Mckendrick, 1927). This framework is mainly applied in developed countries. The application of SIR model to study COVID-19 in developing countries is not popular. In Nigeria, SIR studies concentrated on modeling the infection trend (Abioye et al., 2021; Okuonghae & Oname, 2020). Generally, the major drawback of the SIR model was the non-inclusion of agents' economic decisions in the framework. From policymaking

point of view, understanding the interaction between economic agents' decisions and the rate of infection is important for policy design. Consequently, many extensions of the SIR model evolved where economic agents' decisions on consumption and work are incorporated.

The SIR-macro model by Eichenbaum et al. (2021) being an extension of the SIR model incorporated the equilibrium interaction between the decisions of economic agents and the epidemic dynamics. In this SIR-macro model, there is both aggregate demand and aggregate supply effects. The aggregate supply effect occurs because workers are exposed to the risk of contracting the virus. The workers respond to this risk by cutting back on their labour supply. The aggregate demand effect occurs because the consumers are also exposed to the risk of contracting the virus and they respond to the risk by reducing consumption. The demand and supply effects interact to generate a recession. Thus, adjustments in agents' behaviour affects economic activities.

The adjustments in behaviour creates economywide externality. This arises because agents are exposed to the risk of infection when working or consuming but upon realizing this danger, reduce economic activity as the risk escalates. However, the agents' do not consider the effect of their own work and consumption decisions on the spread of the disease. This generates externality which the government seeks to internalize (Eichenbaum et al., 2021). In order to deal with the externality, the government implements policies that leads to maximization of present value of societal utility that balances the utility of the agents from consumption and leisure; the disutility of foregone consumption due to reduced productivity when infected; and disutility of dying from the infection (Tilman von Carnap et al., 2020). The policy is aimed at reduction of consumption and hours worked to minimize interaction among agents and raise the welfare of people by reducing death toll from the epidemic. This policy predictably exacerbates the economic recession.

Developing countries particularly in Africa are assumed to be more vulnerable to pandemics because of poor healthcare system, high population density, low fiscal capacity and high informal sector. Existence of high disparities between developed and developing countries implies that implementation of blanket restrictions will be less effective in developing countries (Alon et al., 2020). Nigeria implemented blanket containment measures as widely done by other countries. The questions then arises whether the containment measures have a trade-off effect between the epidemic and aggregate economic activities and what is the optimal policy path to deal with the externality from economic decisions of agents? The Nigerian economy witnessed negative quarterly growth rates in 2020 indicating an economic recession. Like other countries, a wave of studies on the economic implications of the pandemic emerged (Amusan & Agunyei, 2021; Ozili, 2020; Farayibi & Simplice, 2020). However, none of these studies presented an integrated model of the evolution of the pandemic and the macroeconomy. A close observation shows that epidemiological and macroeconomic models had focused on developed countries (Atkeson, 2020; Borelli & Góes, 2021; Eichenbaum et al., 2021; Giagheddu & Papetti, 2023; Morato et al., 2020; Wang et al., 2020). Application of the SIR-macro model in African countries is very rare. Tilman

von Carnap et al. (2020) is an exception for Ugandan economy. Therefore, there is need to integrate epidemiological models with economic analysis to provide data-driven policy insights. No such approach in the COVID-19 research exists in Nigeria. This constituted a research gap which this study filled. Thus, the objectives of this research are (1) to analyze the macroeconomic impact of COVID-19 pandemic on the Nigerian economy using the SIR-macro model (2) to evaluate the effectiveness of government containment policies in reducing the infection rates and their attendant trade-off with economic performance (3) to examine the role of behavioral adjustment of economic agents in response to the epidemic (4) to provide policy recommendations for optimizing future epidemic response strategies.

Literature Review

Nigeria's economic performance during the peak of the pandemic in 2020 followed the global trend of economic downturn. At the aggregate level, Nigerian economy witnessed negative growth rates in the major economic sectors due to measures implemented to contain the pandemic both at the domestic and international level. According to National Bureau of Statistics (NBS, 2020) the quarterly growth rate of the real GDP in the second quarter of 2020 was -6.1% while that of the third quarter was -3.62%. The fourth quarter growth rate was rather very mild at 0.11%. The average growth rate of the real GDP in entire 2020 was -1.92% which showed weak performance. At the sectoral level, the COVID-19 shock led to negative growth rate in all the real sectors except the Agricultural sector with very moderate growth of 1.58%, 1.39% and 3.42% in the second, third and fourth quarters of 2020 respectively (NBS, 2021). The industrial sector grew by -12.05%, -6.12% and -7.30% between the second to the fourth quarter of 2020. The services sector grew by -6.78% and -5.49% in the second and third quarters respectively. Due to global economic slowdown occasion by the pandemic, energy demand dwindled which affected oil exporting countries like Nigeria as oil sector growth in the second, third, fourth in 2020 stood at -6.63%, -13.89% and -19.76% respectively. This negative growth of the oil sector continued throughout the year 2021 showing weak oil demand and slow global economic recovery. Just like many other countries, the above statistic confirmed that the Nigerian economy decelerated as a result of the COVID-19 outbreak.

Research on COVID-19 pandemic and its effect on all facets of human existence is still ongoing. Several modeling approaches have also been implemented in this regard. However, the application of the SIR-macro model in the study of the pandemic is still evolving particularly for developing countries. In this section, we reviewed selected empirical studies related to application of SIR-macro model and COVID-19 pandemic. Tilmann von Carnap et al. (2020) applied the SIR-macro model to Ugandan data to assess how containment policies differ with other countries. Their result showed that differences in demography, comorbidities and state of health systems influence mortality risk. In the model without containment for Ugandan infection and fatality rate, the infection peaked

at 6.0% with a fatality of 0.17% with an output loss of 3.0%. In the model's optimal containment policy, the infection reduced to 5.0% with a fatality of 0.15% with output loss of 10.0%. They further found that income levels influence agents' willingness to give up consumption and work which affect the disease risk. In the study of macroeconomics of epidemics in Brazil, Rabelo & Soares (2020) implemented the SIR-macro model. Their result show that the adjustment in behaviour of economic agents affected the dynamics of the epidemic and the economic activities in Brazil. In their SIR-macro model without containment, the infection peaked at 4% with associated mortality of 0.15% and output loss of 4.79%. In their SIR-macro model with containment, the peak of the infection was reduced to 2.5% while the fatality was reduced to 0.1%. Output loss due to optimal containment policy increased to 16%.

Katuwal et al. (2021) assessed the macroeconomic impact of COVID-19 in Nepal using the SIR-macro model. Their result showed that in the no-containment scenario, the infection rate peaked at 8% while the rate of fatality stood at 0.78%. The implementation of the optimal containment policy reduced the peak infection and fatality rate to 5% and 0.65% respectively. Their result confirms the effectiveness of containment policy in flattening the infection curve. Eichenbaum et al. (2021) applied the SIR-macro model for US economy. Their result indicates that the interaction between economic activity and the transition probabilities significantly altered the dynamics of the epidemic and associated impact on the economy. In the SIR-macro model without containment, the output loss within the first 52 weeks of the epidemic is 4.7% while the peak of the infection is 5.2% and a death toll of 0.27%. In the SIR-macro model with containment, the peak of the infection was reduced to 3.2% while the fatality was reduced to 0.21%. Output loss due to optimal containment policy increased to 17%. Using the benchmark SIR-macro (treatment, vaccination and medical preparedness) model with the best containment policy, the economic recession rose to 22% against the 7% without containment measures. However, the severity of the infection reduced from 4.7% to 2.5%. This finding confirms the trade-off effect between the epidemic and aggregate economic activities following government containment measures. Borelli & Góes (2021) applied the SIR-macro model to study the macroeconomics of COVID-19 epidemic in Brazil with consideration of interstate heterogeneity among five selected states. They calibrated the model based on the intrinsic characteristics of each state. In the model without containment, the highest peak of the infection in a state was 4.95% while the lowest was 3.83%. In the optimal containment policy, the highest peak of the infection in a state was 3.50% while the lowest was 2.09%. The highest fatality rate was 0.53% against the lowest of 0.20%. In terms of recession, the state with the highest output loss stood at 18.11% without containment while it rose to 22.58% with containment. The result showed that there are relevant differences in the dynamics of the epidemic, the containment policies and their implementation on the magnitude of the recession in each state. Giagheddu & Papetti (2023) developed an SIR-age macro model by extending the SIR-macro model of Eichenbaum et al. (2021) that captured age-heterogeneity in social and economic interactions to study the role of demographic factors in determining the

evolution of COVID-19 epidemic, its macroeconomic effects and containment measures in Italy. They emphasized the social aspect of the interaction between the socially active young people and vulnerable elderly people in the spread of the infection. Their no-containment model showed a fatality rate of 0.29 % with 1.9% output loss in the first year of the pandemic. The containment in their model can either be a social or economic restrictions. They found that a generalized social distancing reduces output by 0.8% and fatality by 0.08% while young-old people interaction restriction causes output loss of 1.1% and 0.05% fatality. Without social distancing, optimal economic containment policy yields 0.17% fatality and 19.2% output loss. Their finding indicates that social distancing measures for the elderly people above 70 years of age saved lives and reduced significant output losses. However, their result showed that optimal economic shutdown saved small numbers of lives but with large output losses. The empirical literature reviewed so far agree that there is a trade-off of between social welfare in terms of low mortality from the disease and economic activities.

Model Specification: SIR Model and SIR-Macro Model

The SIR modelling framework emerged as the workhorse for studying COVID-19 epidemic and the economy (Atkeson, 2020). The modeling framework in this study follow the SIR-macro model by Eichenbaum et al. (2021) which is an extended version of the SIR model. We adapted this model because it is the main reference model incorporating the interaction between the epidemic dynamics and economic decisions of agents (Borelli & Góes, 2021). The economy that preceded the epidemic is presented first followed by the actual SIR-macro model.

The SIR Model: Pre-epidemic Economy

Before the epidemic, the population is made up of identical people whose objective is to maximize utility function given as

$$U = \sum_{t=0}^{\infty} \beta^t u(c_t, n_t) \quad (1)$$

Where the discount factor is denoted by $\beta \in (0,1)$. The momentary utility of the population is given as

$$u(c_t, n_t) = \ln c_t - \frac{\theta}{2} n_t^2. \quad (2)$$

c_t and n_t represent consumption and hours worked respectively. The representative agent's budget constraint is given as

$$(1 + \mu_t)c_t = w_t n_t + \Gamma_t \quad (3)$$

w_t stands for real wage rate, Γ_t is lump-sum government transfers while μ_t denotes tax rate on consumption used to capture containment policy to minimize social interactions among the economic agents. So, μ_t is the containment rate.

The first order condition of this representative agent's problem yields

$$(1 + \mu_t)\theta n_t = c_t^{-1}w_t \quad (4)$$

The competitive representative firms produce consumption goods (C_t) by making use of (N_t) hours worked following the technology

$$C_t = AN_t \quad (5)$$

The firms maximize profit Π_t by choosing work hours according to

$$\Pi_t = AN_t - w_t N_t \quad (6)$$

The government's budget constraint is

$$\mu_t C_t = \Gamma_t \quad (7)$$

In equilibrium, individual consumption and hours worked equals the aggregates. Thus, $c_t = C_t$ and $n_t = N_t$.

The SIR-Macro Model: Epidemic Economy

The major drawback of the SIR model was the assumption that epidemic transmission probabilities are independent of economic decisions. To deal with this drawback, the SIR model was extended to incorporate the connection between transmission probabilities and economic decisions of the agents (Eichenbaum et al., 2021). There are three modes of transmission of the infection to the susceptible people. $\pi_1(S_t C_t^S)(I_t C_t^I)$ is consumption related transmission, $\pi_2(S_t N_t^S)(I_t N_t^I)$ is work related transmission, $\pi_3 S_t I_t$ is random transmission. Thus, the total number of infected people is given as

$$T_t = \pi_1(S_t C_t^S)(I_t C_t^I) + \pi_2(S_t N_t^S)(I_t N_t^I) + \pi_3 S_t I_t \quad (8)$$

Where S_t = susceptible, I_t = infected, R_t = recovered. C_t and N_t are as defined in equation (4).

π_i denotes transmission probabilities. In the pre-epidemic economy, $\pi_1 = \pi_2 = 0$.

The number of susceptible people in period $t + 1$ is given as

$$S_{t+1} = S_t - T_t \quad (9)$$

while the number of people who get infected in period $t + 1$, is given as

$$I_{t+1} = I_t + T_t - (\pi_r + \pi_d)I_t \quad (10)$$

where $\pi_r I_t$ denote number of recovered people and $\pi_d I_t$ denote number of people who died. Effectively, π_d represent the case fatality rate (CFR) showing the probability of dying from the infection.

The total number of recovered people in period $t + 1$ is the number of people who recovered in time period t and the number of infected people who recovered at moment ($\pi_r I_t$). It is given as

$$R_{t+1} = R_t + \pi_r I_t \quad (11)$$

The total number of deaths in period $t + 1$ is the number of deaths in period t plus the number of newly deceased ($\pi_d I_t$). This is given as

$$D_{t+1} = D_t + \pi_d I_t \quad (12)$$

The evolution of total population follows the expression $Pop_{t+1} = Pop_t - \pi_d I_t$ where the initial population is normalized to one ($Pop_0 = 1$), the initially infected people, $I_0 = \varepsilon$, and initially susceptible people $S_0 = 1 - \varepsilon$.

The optimization problem of the j_{th} person depends on the group where he belongs. Thus, we take U_t^j as the lifetime utility of j_{th} person ($j = s, i, r$) in time t . The budget constraint of the j_{th} person is given as

$$(1 + \mu_t)c_t^j = w_t \phi^j n_t^j + \Gamma_t \quad (13)$$

Where c_t^j and n_t^j denote the j_{th} person's consumption and hours worked respectively. The parameter ϕ^j measures the labour productivity which is equal to one for susceptible and recovered people ($\phi^s = \phi^r = 1$) and less than one for those still infected ($\phi^i < 1$).

Utility of Susceptible People

The lifetime utility of susceptible people is given as

$$U_t^s = u(c_t^s, n_t^s) + \beta[(1 - \tau_t)U_{t+1}^s + \tau_t U_{t+1}^i] \quad (14)$$

Where τ_t denotes the probability of the susceptible to become infected

$$\tau_t = \pi_1 c_t^s (I_t C_t^i) + \pi_2 n_t^s (I_t N_t^i) + \pi_3 I_t \quad (15)$$

Here, the susceptible people know that reducing consumption and hours worked will reduce their probability of getting infected.

The first-order condition for consumption and hours worked for susceptible people yields the following

$$u_1(c_t^s, n_t^s) - (1 + \mu_t)\lambda_{bt}^s + \lambda_{rt}\pi_1(I_t C_t^i) = 0 \quad (16)$$

$$u_2(c_t^s, n_t^s) + w_t \lambda_{bt}^s + \lambda_{rt}\pi_2(I_t N_t^i) = 0 \quad (17)$$

Where λ_{bt}^s and λ_{rt} represent Lagrangian multiplier for constraints (13) and (15) respectively. The first-order condition for τ_t is given as

$$\beta(U_{t+1}^i - U_{t+1}^s) - \lambda_{rt} = 0 \quad (18)$$

Utility of Infected People

The infected person's lifetime utility is given as

$$U_t^i = u(c_t^i, n_t^i) + \beta[(1 - \pi_r - \pi_d)U_{t+1}^i + \pi_r U_{t+1}^r] \quad (19)$$

The first-order condition for consumption and hours worked for an infected person yields the following

$$u_1(c_t^i, n_t^i) = (1 + \mu_t)\lambda_{bt}^i, \quad (20)$$

$$u_2(c_t^i, n_t^i) = -\phi^i w_t \lambda_{bt}^i, \quad (21)$$

Where λ_{bt}^i represent Lagrangian multiplier for constraints (13).

Utility of Recovered People

The lifetime utility of a recovered person is given as

$$U_t^r = u(c_t^r, n_t^r) + \beta U_{t+1}^r \quad (22)$$

Solving for the first-order condition for consumption and hours worked yields the following

$$u_1(c_t^r, n_t^r) = (1 + \mu_t)\lambda_{bt}^r, \quad (23)$$

$$u_2(c_t^r, n_t^r) = -w_t \lambda_{bt}^r, \quad (24)$$

Where λ_{bt}^r represent Lagrangian multiplier for constraints (13).

The government budget constraint is given

$$\mu_t(S_t c_t^s + I_t c_t^i + R_t c_t^r) = (S_t + I_t + R_t)\Gamma_t, \quad (25)$$

The market clearing equilibrium for goods, labour and government is given as

$$S_t C_t^s + I_t C_t^i + R_t C_t^r = AN_t, \quad (26)$$

$$S_t N_t^s + I_t N_t^i \phi^i + R_t N_t^r = N_t. \quad (27)$$

In equilibrium $c_t^j = C_t^j$ and $n_t^j = N_t^j$ for $j = s, i$ and r .

So far, the model operates in an environment where there is absence of treatment and vaccination. The SIR-macro model can be extended to incorporate medical preparedness where the CFR depends on the number of infected people. Furthermore, the probability of developing a cure for the disease or vaccine to vaccinate susceptible people can be incorporated. This we pursue in the relevant sections.

Model Calibration

In this section, we present how the parameters of the model were calibrated. It is important to note that due to paucity of accurate statistics and lack of empirical studies in this area for Africa and indeed Nigeria, we adopted some parameter values from other SIR-macro models. We note that the timing of the model is based on weekly reports. According to the Nigerian center for Disease Control (NCDC, 2022), the CFR of COVID-19 in Nigeria was 0.3% which is similar to that of Borelli & Góes (2021) and Tilmann von Carnap et al. (2020). So, we adopted a CFR of 0.3%. Tables 1 and 2 reports key variables and parameters of the model. Following Atkeson (2020) and Wang et al. (2020), we assume that people who are infected will either die or recover within the first 18 days of infection. Given a CFR of 0.3%, the probability of dying is 0.0012 ($\pi_d = 7 \times 0.003/18 = 0.0012$) while probability of recovering is 0.3877 ($\pi_r = 7 \times 1/18 = 0.3877$). The initial SIR-Macro model parameters by Eichenbaum et al. (2021) was calibrated based on US dollars. This affected the implementation of the model and its attendant results when exchange value of Nigerian currency was introduced. In order to overcome this, we utilized the US dollar (\$) exchange rate to Nigerian Naira (₦). For this purpose, we used the Central Bank of Nigeria CBN (2019) official rate of \$1 to ₦306.95. We chose $\beta = 0.96^{1/52}$ and computed the pre-epidemic steady state statistical value of life to be ₦305,170,058.34 which is equivalent to \$994,201.2. Value of statistical life indicate how much people are willing to pay to reduce the risk of death. In pre-epidemic steady state, the technology parameter A , is chosen to be 4.215 while disutility of labor parameter, $\theta = 0.000625$. Nigerians work officially 40 hours per week (ie. 8 hours times 5 days) to earn an income target of ₦51,751 (\$168.6). We arrived at this figure by taking average salary between formal and informal sectors at all levels (i.e. ₦150000+₦30000+₦27000=207000/4) given by Nigerian Salaries, Income and Wages Commision (NSIWC, 2019). The parameter ϕ , measuring productivity of infected people was calibrated to 0.8. Following Eichenbaum et al. (2021), we assume that 30% of transmission takes place at home, 33% takes place in the general community while 37% occur in school and workplaces. We retain mapping of US data so that 2/3 of transmission occur in the general community activities related to consumption. According to Lee et al. (2010), the average daily contact at school was 10 while average daily contact at work was 4. Bearing in mind that 37% of transmissions are related to school and work, we assigned weight of 10 to population of students in 2019 while weighting population of workers by 4. For population of workers in Nigeria, we utilized the labour force data from the first quarter of 2020 which stood at 80.3 million (NBS, 2020). We chose the entire labour force data to reflect the possibility of missing out huge number of informal sector workers. The population of students of 42.6 million was obtained from the Federal Ministry of Education (FME, 2019). Using these data, we found that approximately 1/6 (sixteen percent) transmission is related to work. That is $80.3 \times 4 / (80.3 \times 4 + 42.6 \times 10) = 43\%$. Multiplying 0.37 by 0.43 gives 0.1591. The remaining transmission which is neither work nor consumption

related belong to the random category. Thus, the values of π_1, π_2 and π_3 were selected to march

$$\frac{\pi_3}{\pi_1 C^2 + \pi_2 N^2 + \pi_3} = 2/3$$

$$\frac{\pi_2 N^2}{\pi_1 C^2 + \pi_2 N^2 + \pi_3} = 0.16$$

$$\frac{\pi_1 N^2}{\pi_1 C^2 + \pi_2 N^2 + \pi_3} = 1 - 2/3 - 0.16$$

Where C and N represent pre-epidemic steady state of consumption and hours worked respectively.

Table 1: Key Variables for Determination of Parameter Calibration

Variables	Value	Source
Exchange rate	\$1/₦306.95	CBN (2019)
Weekly Income Target	₦51,751 (\$168.6).	Calculated by author
Weekly Hours worked	40 Hours	NBS (2020)
Number of Workers	80.3 million	NBS (2020)
Number of Students	42.6 million	FME (2019)
Case fatality rate (CFR)	0.3 %	NCDC (2022)

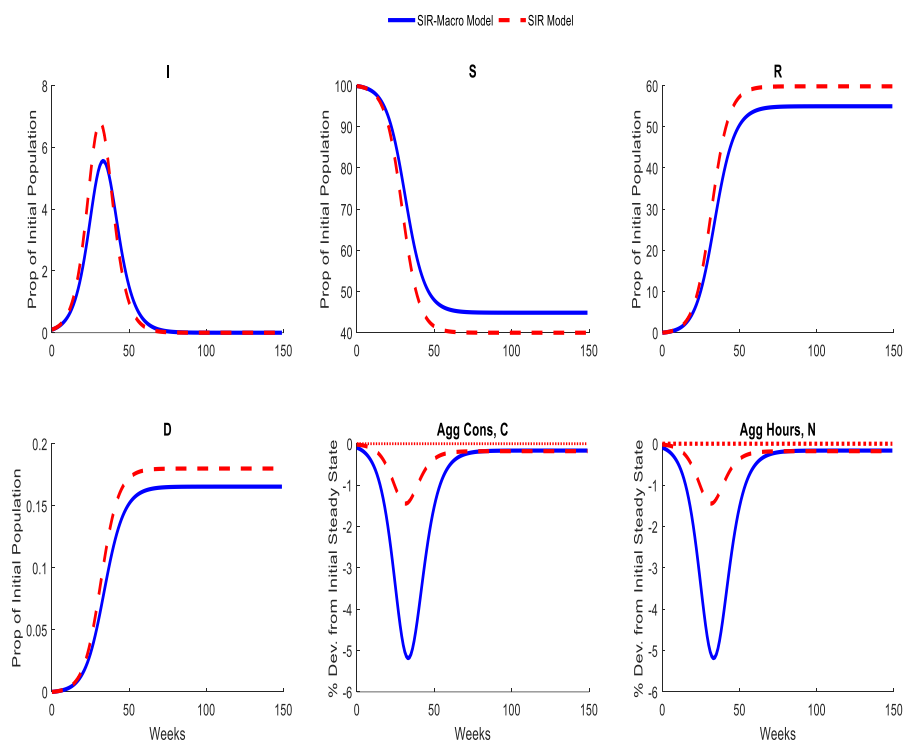
Table 2: Key Calibrated Parameters

A		β	θ	ϕ	ε	π_1	π_2	π_3	κ	π_d	π_r
4.21		$0.96^{1/52}$	0.000625	0.8	0.001	$3.431e-06$	$6.096e-05$	0.3902	0.6	0.0012	0.387

Results

The SIR Model versus SIR-Macro Model

After assigning the calibrated values to the parameters, we simulated the model to obtain the relevant results. We start by presenting the competitive equilibrium model. In Figure 1, the equilibrium population dynamics of SIR model is represented by the red dashed line while that of the SIR-macro model is represented by the solid blue line. In this competitive equilibrium model, there is no government intervention (no containment measure). The infection runs until a greater proportion of the population acquires immunity, leading to a lesser exposure to the remaining susceptible people. Thus, the epidemic ends when sufficient proportion of the population acquire immunity, 'the herd immunity level'.



Prop = Proportion; I = Infected; S = Susceptible; R = Recovered; D = Dead; Agg Cons = Aggregate Consumption; Agg Hours = Aggregate Hours

Fig 1 Competitive SIR-Macro Model and SIR Model

Source: model result

In the SIR model, the proportion of the initial population infected peaks at 6.82 percent in week 32 but falls gradually until week 52 when herd immunity would have been attained and fewer people are susceptible. Aggregate consumption declined by 1.44 percent following 20% reduction in the productivity of the infected people ($\phi = 0.8$). In the SIR-macro model, rationally optimizing agents adjust their consumption and work. This reflected in the epidemics dynamics as the initial proportion of infected population peaks at 5.56 percent in week 34 which is smaller and occur later than the SIR model. This implies that the severity of the infection is reduced because of the endogenous behavioural response of people to lower their consumption and work hours in order to avoid being infected. This caused the epidemic to spread more slowly leading to a flatter and prolonged susceptible and recovered curve. Expectedly, the recession is more severe in the SIR-macro model. The average aggregate consumption dipped by 5.18 percent in relation to the steady state value in the first year of the epidemic when compared to the SIR model of 1.44 percent. Within the first year of the epidemic, the model predicted that about 0.16 percent of the infected dies from the virus while 53 percent recovers without treatment or vaccination. This prediction of our SIR-macro model without containment compares closely

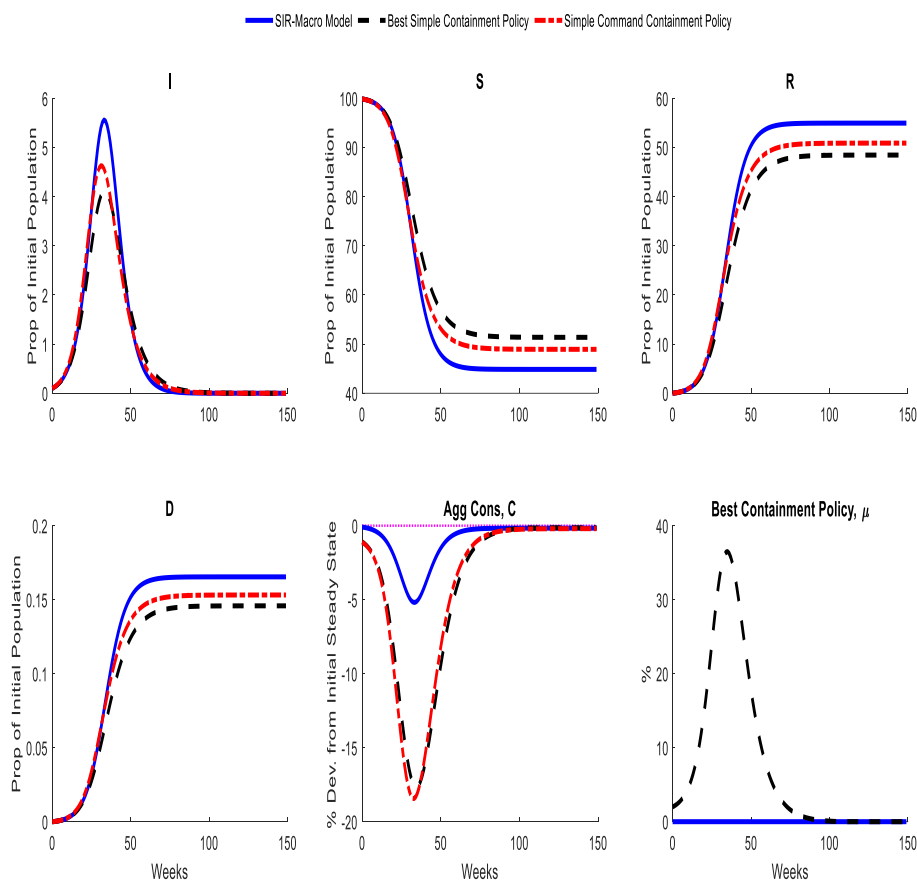
with that of Tilmann von Carnap et al. (2020) for Uganda with 6.0% peak infection and 0.17% mortality rate. This may be because of similar economic structure between Nigeria and Uganda. This result, however, corroborates the main prediction of SIR-macro model that behaviour adjustment of optimizing agents causes a decrease in both infection rate and economic activities (Eichenbaum et al., 2021).

Containment Policies in the SIR-Macro Model

Figure 2 explains the dynamics of the epidemic and economy with and without containment policy. Government intervenes to internalize the externality imposed on the economy by the adjustment in behaviour of infected people by either implementing a policy instrument of Ramsey type or choose the same amount of consumption and hours worked for all the people (susceptible, infected and recovered) to maximize the social welfare. The Ramsey problem is solved by imposing a tax on consumption that follows capital control (Eichenbaum et al., 2021). This tax is referred to as the best simple containment rate in our model. In order to arrive at the optimal containment rate, a sequence of 250 containment rates $\{\mu_t\}_{t=0}^{249}$ were computed which maximizes the social welfare U_0 given as

$$U_0 = S_0 U_0 + I_0 U_0 \quad (28)$$

Equation (28) is the weighted average of the lifetime utility of both the susceptible and infected at time zero. The result is explained in Figure 2. The solid blue line remains the initial baseline SIR-macro model without government intervention. The dashed black line is the best simple containment policy while the dashed red line is the simple command containment policy. At the beginning of the infection, fewer people are infected which makes the externality insignificant. However, introducing initial high containment rate raises social cost relative to social benefit. Figure 2 shows that the containment rate starts at 2 percent in week zero but gradually increase as the epidemic curve rises and the externality becomes very significant. Thus, as more people are getting infected, it becomes more optimal to increase the rate of containment until it reaches a peak value of 36 percent in week 37. This slows down the spread of the infection. The containment policy reduced the peak of the infection from 5.56 percent to 4.11 percent (cutting it by 1.45 percent) in week 34. However, the reduction in the peak of the infection came at a cost as the size of the recession increases due to implementation of a prolonged containment policy. As the containment rate is being raised, consumption becomes more expensive leading to reduced spending and hours worked. This heightens the severity of the recession as average aggregate consumption in the first year of the epidemic dipped by about 18 percent from the steady state, more than three times the value in the model without containment (5.2 percent). Comparatively, our SIR-macro model with containment prediction is closer to that of Eichenbaum et al. (2021) with 17% of economic decline. This finding corroborates SIR-macro model's prediction that optimal containment policy greatly reduces the infection rate but exacerbate economic recession (Borelli & Góes, 2021; Eichenbaum et al., 2021).



Prop = Proportion; I = Infected; S = Susceptible; R = Recovered; D = Dead; Agg Cons = Aggregate Consumption; Agg Hours = Aggregate Hours

Fig 2 SIR-Macro Model with Containment vs No Containment

Source: model result

The red line of Figure 2 shows that implementing the simple command containment rate by choosing the same amount of consumption and hours worked for all the agents (susceptible, infected and recovered) to maximize the objective social welfare is costlier. The infection rate peaked at 4.5 percent in week 34 which is above the best simple containment policy. The aggregate consumption in the first year of the epidemic for a simple command containment policy dipped by about 19 percent which is higher than the best simple containment policy. Despite the economic cost, the best simple containment policy reduces the impact of the epidemic and minimizes long term economic recession experienced in the absence of any containment policy. Within the first year of the epidemic, the implementation of the best containment reduced the percentage of death from 0.16 percent of the infected to 0.14 percent resulting in fewer fatalities. The best containment policy equally limits the impact of the virus by stabilizing the susceptible population at 55 percent from week 54 while 45.2 percent recovers by week 59.

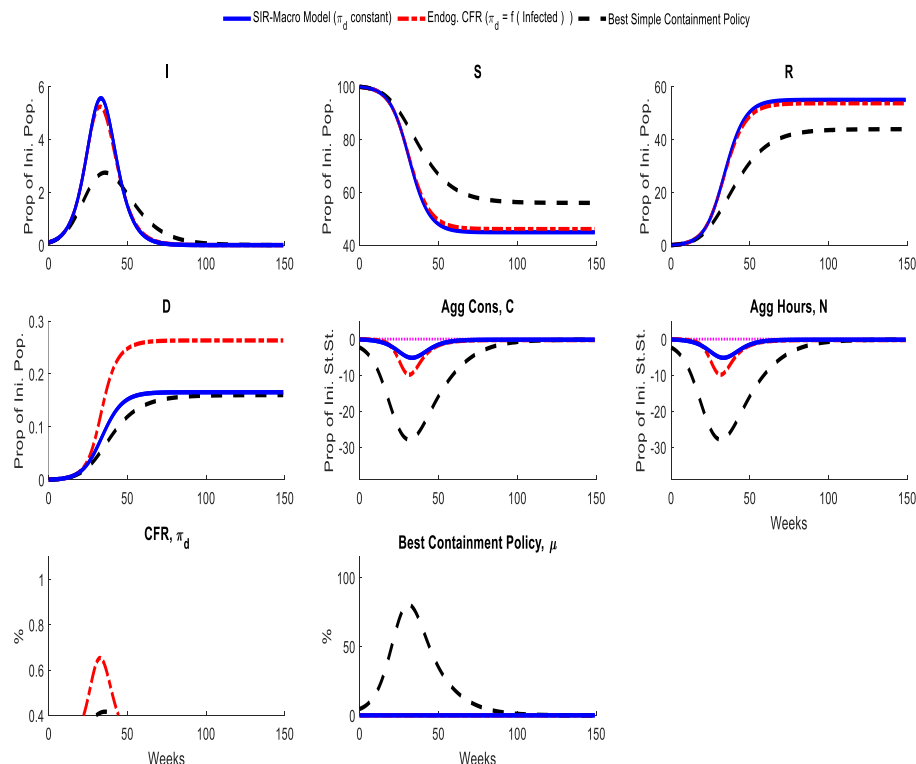
Medical Preparedness Model

The SIR-macro model assume that CFR is independent of the number of infected people which implies that the probability of dying (π_d) is constant. However, there is possibility that the health care system can become overwhelmed by increase in the population of infected people which is a test of the strength of the healthcare system and level of medical preparedness. In order to model this scenario, we assumed that the CFR depends on the number of infected people, I_t .

$$\pi_{dt} = \pi_d + \kappa I_t^2 \quad (29)$$

Here, $\kappa > 0$ whereas in the initial SIR-macro model, $\kappa = 0$.

In the medical preparedness model, the rate of containment policy depends on the case fatality rate (CFR). We endogenize the CFR to depend on the number of infected as a consequence of the state of health facilities available during the epidemic. Moreover, the effectiveness of the medical system diminishes when greater proportion of the population gets infected with likelihood of higher fatality rate. In order to capture this alongside the containment policy, we adapted the values of Tilmann von Carnap et al. (2020) for Uganda and calibrated κ to 0.6. The impact is reported in Figure 3.



Prop = Proportion; I = Infected; S = Susceptible; R = Recovered; D = Dead; Agg Cons = Aggregate Consumption; Agg Hours = Aggregate Hours; CFR = Case Fatality Rate

Fig 3 Medical Preparedness Model

Source: model result

The red dashed line indicates the endogenous CFR curve. The infection peaks at to 5.13 percent as proportion of the initial population by week 35. The associated death as proportion of the initial population of 0.26 percent is higher than the initial SIR-macro model showing inability of medical facilities to contain the spread. The average aggregate consumption and work hours declined by 10.7 percent from steady state in week 34 showing a milder recession. The cost of poor health system and increasing fatalities causes the authorities to intervene by ramping up the containment rate to a peak of 70 percent which is about double the size in containment model without medical preparedness. The best simple containment policy (black dashed line) in this model reduces the peak of the infection from 5.13 percent to about 2.7 percent. However, this came at a cost as the recession become more severe as average aggregate consumption in the first year of the epidemic declined further by about 28 percent from the steady state. This is expected because, in addition to containment measures being implemented by the authorities, people are aware of the higher CFR and inability of the healthcare system to cater for all the infected people. Since the cost of becoming infected is higher, people take the option of reducing their consumption and work to avoid being infected. The aggressive containment measure reduced the proportion of death to 0.12 percent within the first year of the epidemic. The implies that lack of robust health system increases fatality rate.

Treatment and Vaccine in SIR-Macro Model

Treatment Model

In the SIR-macro model, there is possibility that a cure to the virus can be discovered which can change the dynamics of the epidemic. To accommodate this scenario in the SIR-macro model, we assume that the probability of discovering an effective treatment in each period is δ_c . Upon discovery, treatment of infected people starts immediately which subsequently transforms the infected people to recovered people so that the number of deaths from the disease moves to zero.

The lifetime utility of a person who is infected prior to discovery of treatment is given as

$$U_t^i = u(c_t^i, n_t^i) + (1 - \delta_c)[(1 - \pi_r - \pi_d)\beta U_{t+1}^i + \pi_r \beta U_{t+1}^r] + \beta \delta_c U_{t+1}^r \quad (30)$$

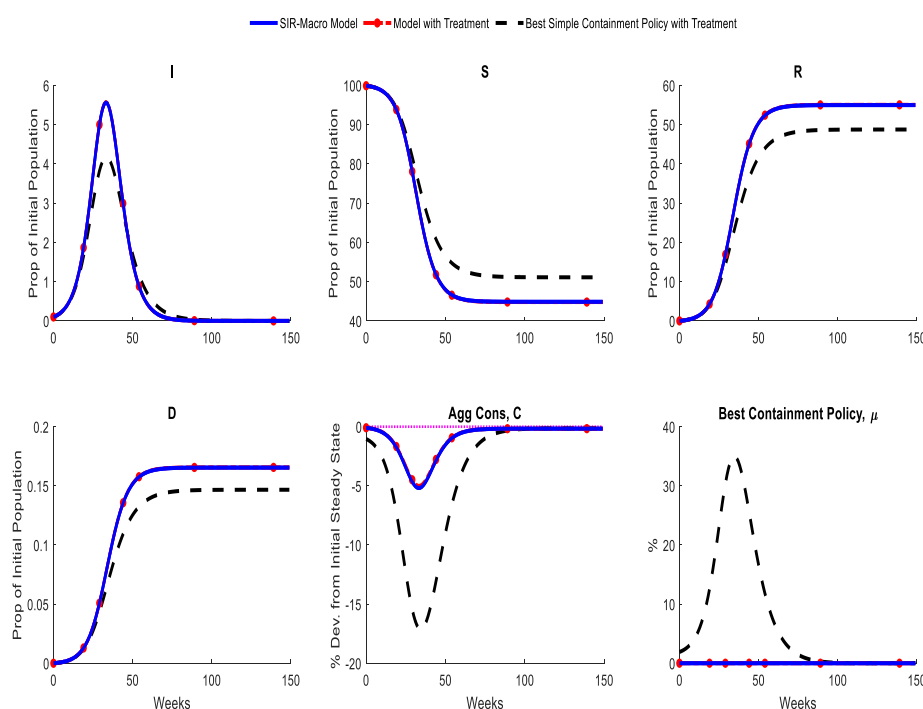
Equation (30) shows that an infected person in period t remains infected in period $t + 1$ with the probability of $1 - \delta_c$. But this person can then receive treatment and recover from the disease with a probability of δ_c . The discovery and implementation of effective treatment stabilizes the population dynamics. Prior to discovery of effective treatment, the population dynamics change based on equations (8),(9),(10),(11) and (12). If the treatment was discovered at the beginning of period t^* , all the infected gets treatment and recovers. Thus, the number of deceased people stabilizes as soon as treatment arrives so that $t \geq t^*$,

$$D_t = D_{t^*}.$$

This implies that all the infected people get instant cure. The number of susceptible persons is normalized to zero for $t > t^*$, so that the number of recovered people is now

$$R_t = 1 - D_t.$$

The result is reported in Figure 4. In order to include availability of treatment in the SIR-macro model with containment policy, we calibrate δ_c to 1.92 percent (i.e 1/52) in anticipation that treatment arrives within the first 52 weeks of the epidemic. People understand that treatment cures the infected when available even though the duration of the infection and the timeline of the arrival of treatment is not certain. The expectation of recovering from treatment encourages people to engage in market activities. When treatment is delayed, the treatment model behaves more like the SIR-macro model and the case-by-case management of the infected is not optimal.



Prop = Proportion; I = Infected; S = Susceptible; R = Recovered; D = Dead; Agg Cons = Aggregate Consumption; Agg Hours = Aggregate Hours

Fig 4 SIR-Macro Treatment Model

Source: model result

As some members of the population decide to engage in market activities, others still maintain the decision to reduce economic activities. This is why the infection curve did not change much between the SIR-macro model and the treatment model. As the infection continue to rise due to delayed treatment, the authorities increase the rate of containment from 2 percent to about 36 percent in week 34 until the peak of the infection. This reduces the proportion of initial population infected from 5.56 percent to 4.16 percent in week 34. This confirms the finding of Eichenbaum et al. (2021) that treatment in the SIR-macro model does not have much effect on optimal policy design.

Vaccination Model

Just as in the SIR-macro model with treatment, there is a possibility that a vaccine against the virus can be developed. To model this scenario, we assume that the probability of developing a vaccine in each period is δ_v . Vaccination of susceptible people starts immediately to prevent them from contacting the virus. The lifetime utility of a susceptible person in this scenario is given as

$$U_t^s = u(c_t^s, n_t^s) + (1 - \delta_v)(1 - \tau_t)\beta U_{t+1}^s + \delta_v(1 - \tau_t)\beta U_{t+1}^r + \tau_t\beta U_{t+1}^i. \quad (31)$$

Equation (31) shows that a susceptible person in period t will remain susceptible in period $t + 1$ with a probability of $1 - \delta_v$. But this person can be vaccinated with a probability of δ_v , and acquires immunity from the virus so that in period $t + 1$, the person's health condition is the same with the recovered. The health status of the infected or recovered is not affected by the vaccine. So, their lifetime utility still follows equation (19) and (22) respectively. Prior to the development of vaccines, the population dynamics change based on equations (8),(9),(10),(11) and (12). If the vaccine was developed at the beginning of period t^* , all the susceptible get vaccinated and thus immune to the virus. Since no nobody is susceptible, there will be no new infections. If we denote the number of susceptible and recovered persons right after the introduction of the vaccines at period t^* as S_{t^*}' and R_{t^*}' , we have

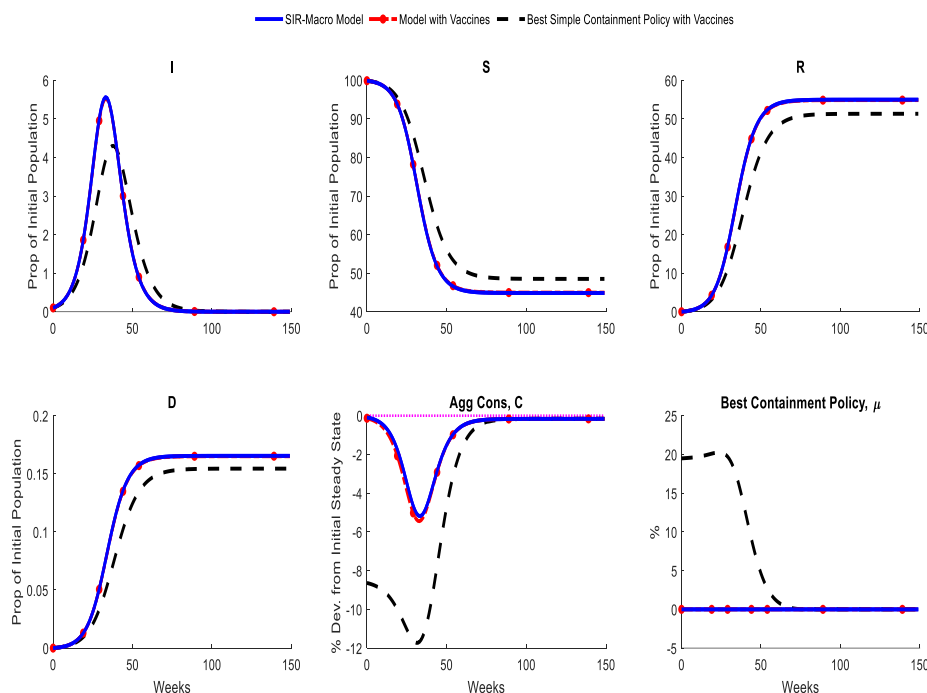
$$\begin{aligned} S_{t^*}' &= 0 \\ R_{t^*}' &= R_{t^*} + S_{t^*} \end{aligned}$$

when $t \geq t^*$, we obtain the following

$$R_{t+1} = \begin{cases} R_t' + \pi_r I_t & \text{for } t = t^* \\ R_t + \pi_r I_t & \text{for } t > t^* \end{cases}$$

The law of motion for I_t and D_t follows equation (10) and (12).

As with the treatment model, the behaviour of people changes with the expectation that vaccines will arrive within the first 52 weeks of the epidemic. We calibrate δ_v to 1.92% in the vaccine model to capture vaccination. Even though vaccines do not cure the infected, it prevents susceptible people from getting infected. The expectation of vaccination in future causes people to cut back on market activities while expecting the vaccines. In Figure 5, the best simple containment policy (dashed black line) shows that it is optimal to immediately enforce the containment rate from 20 percent at the onset of the epidemic (week 0) with the expectation that vaccines will arrive soon. This reduces fatality. With this, the magnitude of the recession is high as the percentage average aggregate consumption reduced at impact in week zero by 8.5 percent until about 12 percent in week 34. The ensuing recession is worth it because the early arrival of the vaccine will minimize the infection rate and grant the susceptible immunity from the virus. Thus, reducing and delaying the peak of the infections while anticipating the arrival of vaccines is optimal (Borelli and Goes, 2021)



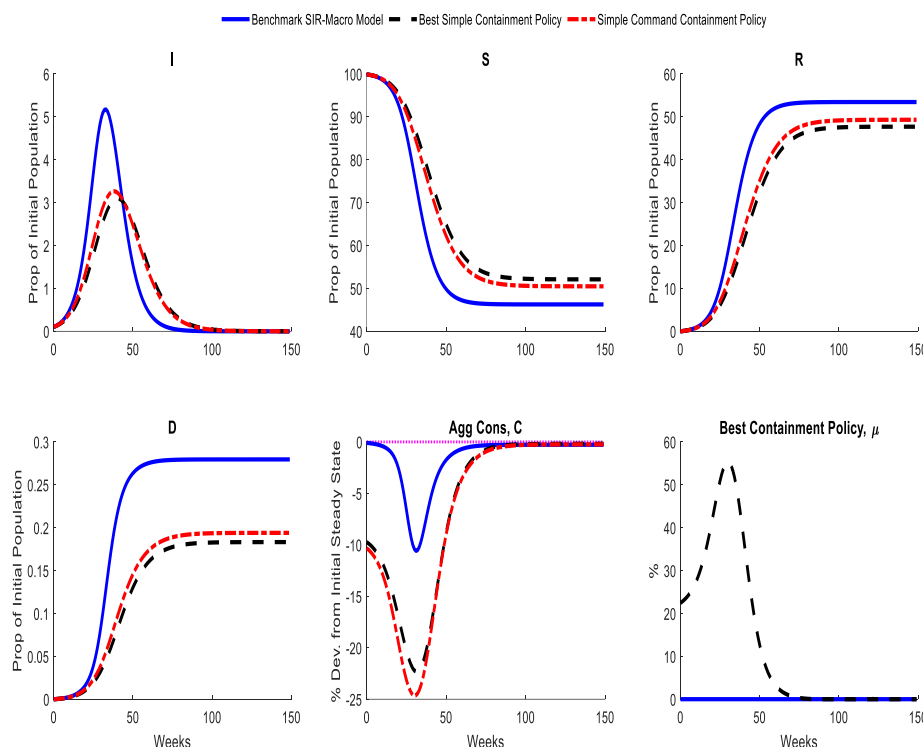
Prop = Proportion; I = Infected; S = Susceptible; R = Recovered; D = Dead; Agg Cons = Aggregate Consumption; Agg Hours = Aggregate Hours

Fig 5 Vaccines in the SIR-Macro Model

Source: model result

Benchmark SIR-Macro Model

The results presented earlier handled the predictions of the SIR-macro model based on different scenarios. This aided the understanding of the potential measures being pursued. In this section, we combine treatment, vaccines and medical preparedness models. This version of the model becomes the benchmark model. Figure 6 presents the result of the benchmark SIR-macro model. The solid blue line represents the benchmark SIR-macro model, the dashed black line is the best simple containment policy while the dashed red line depicts the simple command containment policy.



Prop = Proportion; I = Infected; S = Susceptible; R = Recovered; D = Dead; Agg Cons = Aggregate Consumption; Agg Hours = Aggregate Hours

Fig 6 Benchmark SIR-Macro Model

Source: model result

The probability of treatment and vaccine (δ_v and δ_c) arriving in the first year of the epidemic was calibrated to 1.92 percent (1/52). Even though there is expectation of the arrival of treatment and vaccine which affected the economic behaviour of agents to be more willing to engage in market activities, we present the result of worst-case scenario where vaccines and treatment were not discovered within the first year of the epidemic. Following the anticipation of vaccination and treatment, Figure 6 shows that it is optimal for early implementation of best simple containment policy. In week zero, the containment rate is 24 percent. As with the treatment and medical preparedness models, it is optimal to keep increasing the containment rate as the infection rises. The peak containment rate reaches 55 percent in week 33 against 70 percent in the medical preparedness model. The early introduction of this containment strategy came with a more severe economic cost. The magnitude of the recession measured by average aggregate consumption dipped by 22.32% below the steady state in week 35 compared to 22% in Eichenbaum et al. (2021) and 22.58% in Borelli & Góes (2021). This is 11.74 percent higher than the SIR-macro-model without containment. Figure 6 shows that the proportion of initial population infected peaked at 3.09 percent in week 42 while the death rate is 0.15 percent. These values are

lower than simple command containment and SIR-macro model. This shows that the best simple containment policy in the benchmark model was successful in limiting fatalities. We note that eventual arrival of vaccines and treatment will further cause more lives to be saved alongside the implementation of the optimal policy. Thus, we conclude that the best containment policy of the benchmark model is more effective in reducing the peak of the infection, number of deaths and spread of the virus by keeping higher proportion of the population uninfected and susceptible overtime. But this policy worsens the economic recession when compared to other strategies (Eichenbaum et al., 2021).

Discussion of Findings and Model Performance

We have discussed the SIR-macro model results in different scenarios. Even though the result from these models is tentative, the validity of the findings depends on the model performance relative to actual data. In this section, we attempt a comparison of the model predictions with both aggregate and disaggregate data on economic performance in the COVID-19 period and discussed its implication in Nigeria. The timing of the model is in weeks but there are no available weekly GDP growth rates. So, we discussed based on quarterly data. In order to make this analysis, we concentrate on the model prediction and actual data without emphasizing the timing and nature of the containment measure. Firstly, the model predicted that economic activities would undergo a sharp decline due to the epidemic before a slow recovery. The result of the model supported this prediction when compared to actual data in Nigeria. The model predicted that the peak-to-trough decline in Nigeria's GDP as represented by average aggregate consumption is 5.18% in the initial SIR-macro model. The quarterly growth rate of the real GDP in the second and third quarters of 2020 averaged -4.86 %. This is quite close to the model prediction in terms of aggregate economic decline. Judging from the model performance with phased government containment policies, the model predictions closely march some of the actual sectoral performances in Nigerian economy as reported by the NBS (2021). The benchmark SIR-macro model with best containment policy predicted a 22.32% economic decline. Comparing this result with the -12.05% growth of industrial sector and -19.76% of the oil sector shows that the model prediction is quite close. The wide difference between the prediction of the SIR-macro model and the benchmark model with containment reinforces the trade-off effect between containing the spread of the disease (reducing number of death) and economic activity. The finding is in line with expected empirical predictions of SIR-macro model (Borelli & Góes, 2021; Eichenbaum et al., 2021; Giagheddu & Papetti, 2023; Tilmann von Carnap et al., 2020).

In terms of disease spread and fatality, we utilized COVID-19 data on weekly total number of infections and deaths sourced from Our World in Data (OWID, 2024) to compare our model performance. Figure 7 shows the actual infection and death rates. By comparison, the infection rate in the benchmark SIR-macro model with containment predicted a peak infection of 3.09% of initial population whereas the actual data showed a peak infection rate of 0.14 %. The model predicted a peak death rate of 0.16% against actual observed data of

0.0017%. This showed that the SIR-macro model over-predicted both the infection rate and the death rate in Nigerian case. The discrepancy in the model prediction and actual data may be connected to other factors such as high youthful population and low comorbidities. Nigeria has high population of young people with minimal comorbidities when compared to countries like US and Italy with high mortalities (Alon et al., 2020). This is supported by Giagheddu & Papetti (2023) who explained that age is an important factor in COVID-19 mortality while Tilmann von Carnap et al. (2020) attached fatality rate to existence of comorbidities in the population. Again, Nigeria's weather condition may have contributed in limiting the disease spread and fatality (Lin et al., 2022). Even though actual data due to COVID-19 in Nigeria may be unreliable, the model's prediction of declining infection and death rates when containment measures were introduced is true in our model.

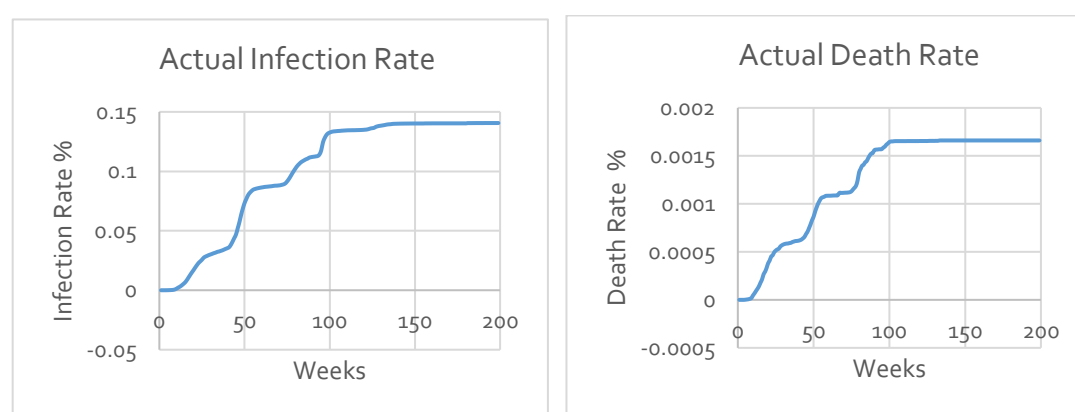


Fig 7 Actual Infection and Death Rates

Source: OWID (2024)

We adduce to other reasons outside the model for low mortality in Nigeria. A cursory observation showed peoples' hesitance in complying to government-imposed restrictions due to resultant escalation of poverty and hunger. Many households rely on daily income to survive which inadvertently affect compliance to restrictions and increase the vulnerability of people to the disease. In addition, the dominance of contact-intensive informal sector suggest that the infection mortality should have been higher than the observed but lack of access to adequate healthcare and government-imposed restrictions combined to force the behavioural adjustments that slowed the spread of the disease. Thus, our result agrees with the SIR-macro model's prediction that the adjustment in behaviour of economic agents in Nigeria helped to flatten the infection curve. However, government should balance public health measures and economic sustainability to deal with the effect of prolonged restriction on lower-income groups and informal sector workers by implementing social safety measures in form of cash transfers, food distribution programs and incentives to small businesses.

Conclusion

We calibrated the SIR-macro model of Eichenbaum et al. (2021) using Nigerian data. We took into account the peculiarity of the epidemic dynamics in the context of a developing country to check if the result we obtained matches the stylized findings obtained in SIR-macro models. Our main findings are in congruence with the predictions of the SIR-macro model where adjustment in behaviour of agents changes the course of the disease in terms of its spread and societal utility. The intervention of the government to internalize the unpriced cost of adjustment in behaviour was effective in reducing the spread and fatality of the epidemic but increases the size of the recession. We recommend the consideration of the socio-demographic characteristics of developing countries in policy prescriptions in case of future epidemic of COVID-19 nature in order to minimize the negative economic impact on the populace. This will ensure that demographic and environmental factors relevant for the survival of the people are not ignored. The government should strengthen the health care system to be able to cater for pressure from epidemic outbreaks. This is necessary because the pandemic revealed the fragile health system in developing countries. We equally recommend investments in the health sector to create a robust healthcare infrastructure. These include funding of pharmaceutical and medical research that will benefit the developing countries towards the discovery of vaccines and medication without prolonged wait for the international community for assistance.

References

- Abioye, A. I., Peter, O. J., Ogunseye, H. A., Oguntolu, F. A., Oshinubi, K., Ibrahim, A. A., & Khan, I. (2021). Mathematical model of COVID-19 in Nigeria with optimal control. *Results in Physics*, 28(2021), 1–10. <https://doi.org/10.1016/j.rinp.2021.104598>
- Alon, T., Kim, M., Lagakos, D., & Vanvuren, M. (2020). *How Should Policy Responses to the COVID-19 Pandemic Differ in the Developing World?* <https://www.nber.org/papers/w27273>
- Amusan, L., & Agunyai, S. C. (2021). The COVID-19 pandemic and the crisis of lockdowns in Nigeria: The household food security perspective. *Africa's Public Service Delivery and Performance Review*, 9(1), 1–10. <https://doi.org/10.4102/apsdpr.v9i1.484>
- Atkeson, A. G. (2020). *What Will be the Economic Impact of COVID-19 in the US? Rough Estimates of Disease Scenarios*. <https://doi.org/10.21034/sr.595>
- Barnett-Howell, Z., Watson, O. J., & Mobarak, A. M. (2021). The benefits and costs of social distancing in high- And low-income countries. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, 115(7), 807–819. <https://doi.org/10.1093/trstmh/traa140>
- Borelli, L., & Góes, G. S. (2021). The macroeconomics of epidemics: Interstate heterogeneity in Brazil. *Economía*, 22(3), 164–197. <https://doi.org/10.1016/j.econ.2021.11.001>
- CBN. (2019). *Central Bank of Nigeria 2019 Statistical Bulletin*. <http://statistics.cbn.gov.ng/cbn-onlinestats/DataBrowser.aspx>
- Eichenbaum, M. S., Rebelo, S., & Trabandt, M. (2021). *The Macroeconomics of Epidemics*. <https://tinyurl.com/ERTcode>
- Farayibi, A., & Simplice, A. (2020). *The Economic Consequences of the Covid-19 Pandemic in Nigeria*. <https://mpira.ub.uni-muenchen.de/107098/>
- FME. (2019). *Federal Ministry of Education Nigeria Digest Of Education Statistics*. <https://education.gov.ng/wp-content/uploads/2021/09/2019-Nigeria-Digest-of-Education-Statistics.pdf>

- Giagheddu, M., & Papetti, A. (2023). The macroeconomics of age-varying epidemics. *European Economic Review*, 151, 1–28. <https://doi.org/10.1016/j.eurocorev.2022.104346>
- Hausmann, R., & Schetter, U. (2022). Horrible trade-offs in a pandemic: Poverty, fiscal space, policy, and welfare. *World Development*, 153, 1–22. <https://doi.org/10.1016/j.worlddev.2022.105819>
- Katuwal, K., Prakash, M., Adhikari, N., Raut, N. K., & Adhikari, S. R. (2021). An Assessment of the Macroeconomic Implications of COVID-19 in Nepal: Evidence from SIR –Macro Model Analysis. *Economic Journal of Nepal*, 44(1–2), 1–18. <https://doi.org/10.3126/ejon.v44i1-2.55024>
- Kermack, W. O., & Mckendrick, A. G. (1927). A Contribution to the Mathematical Theory of Epidemics. In *Source: Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* (Vol. 115, Issue 772). <http://www.jstor.org/stable/94815>
- Lee, B. Y., Brown, S. T., Cooley, P. C., Zimmerman, R. K., Wheaton, W. D., Zimmer, S. M., Grefenstette, J. J., Assi, T. M., Furphy, T. J., Wagener, D. K., & Burke, D. S. (2010). A Computer Simulation of Employee Vaccination to Mitigate an Influenza Epidemic. *American Journal of Preventive Medicine*, 38(3), 247–257. <https://doi.org/10.1016/j.amepre.2009.11.009>
- Lin, R., Wang, X., & Huang, J. (2022). The influence of weather conditions on the COVID-19 epidemic: Evidence from 279 prefecture-level panel data in China. *Environmental Research*, 206. <https://doi.org/10.1016/j.envres.2021.112272>
- Morato, M. M., Bastos, S. B., Cajueiro, D. O., & Normey-Rico, J. E. (2020). An optimal predictive control strategy for COVID-19 (SARS-CoV-2) social distancing policies in Brazil. *Annual Reviews in Control*, 50, 417–431. <https://doi.org/10.1016/j.arcontrol.2020.07.001>
- NBS. (2020). *Nigerian Gross Domestic Product Report*. <https://nigerianstat.gov.ng/elibrary/>
- NBS. (2021). *GDP Q4 2021_Report*. <https://nigerianstat.gov.ng/elibrary/read/1241137>
- NCDC. (2022). *Covid-19 Situation Report Bi-Weekly Epidemiological Report 01*. <https://ncdc.gov.ng/>
- NSIWC. (2019). *The Presidency Annual Report*. <https://nsiwc.gov.ng/information-center/reports/>
- Nwosu, C. A., Marcus, S. N., & Metu, A. G. (2020). COVID-19 Lockdown, Supply Disruptions and Inflationary Pressure In Nigeria. *Socialscientia Journal*, 5, 84–95. <https://journals.aphriapub.com/index.php/SS/>
- Okuonghae, D., & Oname, A. (2020). Analysis of a mathematical model for COVID-19 population dynamics in Lagos, Nigeria. *Chaos, Solitons and Fractals*, 139(2020), 1–18. <https://doi.org/10.1016/j.chaos.2020.110032>
- OWID. (2024). *Nigeria: Coronavirus Pandemic Country Profile*. <https://ourworldindata.org/coronavirus/country/nigeria>
- Ozili, P. K. (2020). *Covid-19 pandemic and economic crisis: The Nigerian experience and structural causes*. <https://mpira.ub.uni-muenchen.de/103131/>
- Rabelo, M., & Soares, J. (2020). *The Macroeconomics of Epidemics: results for Brazil The Macroeconomics of Epidemics: results for Brazil **. <https://www.researchgate.net/publication/340984435>
- Ravallion, M. (2020). *Pandemic Policies in Poor Places*. <https://www.cgdev.org/publication/pandemic-policies-poor-places>
- Sarker, R., Roknuzzaman, A. S. M., Nazmunnaahar, Shahriar, M., Hossain, M. J., & Islam, M. R. (2023). The WHO has declared the end of pandemic phase of COVID-19: Way to come back in the normal life. *Health Science Reports*, 6(9). <https://doi.org/10.1002/hsr2.1544>
- Susskind, D., & Vines, D. (2020). The economics of the COVID-19 pandemic: An assessment. *Oxford Review of Economic Policy*, 36(1), 1–13. <https://doi.org/10.1093/oxrep/graa036>
- Takyi, P. O., Dramani, J. B., Akosah, N. K., & Aawaar, G. (2023). Economic activities' response to the COVID-19 pandemic in developing countries. *Scientific African*, 20. <https://doi.org/10.1016/j.sciaf.2023.e01642>

- Tilman von Carnap, Almås, I., Bold, T., Ghisolfi, S., & Sandefur, J. (2020). The Macroeconomics of Pandemics in Developing Countries: An Application to Uganda. In *DC* (Vol. 416). www.cgdev.org
- Wang, H., Wang, Z., Dong, Y., Chang, R., Xu, C., Yu, X., Zhang, S., Tsamlag, L., Shang, M., Huang, J., Wang, Y., Xu, G., Shen, T., Zhang, X., & Cai, Y. (2020). Phase-adjusted estimation of the number of Coronavirus Disease 2019 cases in Wuhan, China. *Cell Discovery*, 6(1), 1–8. <https://doi.org/10.1038/s41421-020-0148-0>
- Yunusa, T., Obi, S. E., Ezeogueri-Oyewole, A. N., Sekpe, S. S., Egwemi, E., & Isiaka, A. S. (2020). The Socio-Economic Impact of Covid-19 on The Economic Activities of Selected States in Nigeria. *Indonesian Journal of Social and Environmental Issues (IJSEI)*, 1(2), 39–47. <https://doi.org/10.47540/ijsei.v1i2.10>