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Statistical Approaches to Infectious Diseases Modelling in Developing Countries: A Case of COVID-19

Ezra Gayawan
Federal University of Technology, Akure (FUTA)

Adeshina I. Adekunle, Anton Pak, and Oyelola A. Adegboye
James Cook University

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38.1 Introduction

Emerging infectious diseases remain public health challenges with serious socioeconomic and political consequences [1,2]. COVID-19, a highly contagious viral infection caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was first detected in

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the city of Wuhan, China, in December 2019. The disease is mainly transmitted between people through direct or indirect (through contaminated objects or surfaces), or close contact with infected people via mouth and nose secretions [3–5]. Although many countries closed their borders to international travellers at the onset of the pandemic, this was not before the virus was transmitted outside of China [6,7]. The majority of the initially reported cases in most countries were linked to China, prompting countries to increase detection, surveillance and evaluate the risk of importations. Similar to the 2009 pandemic of avian influenza H1N1 (swine flu), COVID-19 was declared a pandemic by the World Health Organization (WHO) on March 11th 2020 [8]. As of September 13th 2020, COVID-19 pandemic has spread to all regions of the world, infecting more than 28.6 million people and causing 917,417 deaths (case fatality ratio, CFR = 3.2%) across 217 countries [9].

The scope of this chapter focuses on approaches to COVID-19 pandemic, especially in low- and lower middle-income countries (L-LMICs). We first explore the early transmission of the disease outside the initial Wuhan epicentre. Secondly, we take a closer look at various responses to COVID-19 in L-LMICs and give specific examples from India, the Republic of Mauritius and Nigeria. Thirdly, we introduce different mathematical models used in most of these countries. Fourthly, we synthesize various economic responses considered in some L-LMICs. Lastly, we conclude with a discussion of how several countries and regional areas are joining resources to fight the disease, how researchers are collaborating to provide a scientific explanation to the spread of the disease and assess the effectiveness of the mitigation strategies used in these countries.

38.1.1 Early Transmission of COVID-19 in the Low and Lower Middle-Income Countries (L-LMICs)

The literature on early estimates of the transnational spread of COVID-19 is extensive and mostly based on air travel data. Air-travel volumes were keys to evaluate the risk of importation to other regions. It is unclear why the arrival of COVID-19 to many L-LMICs was delayed. L-LMICs are not new to disease outbreaks; the majority of the outbreaks in the last decade occurred in the L-LMICs (Table 38.1). Some studies have linked the slow arrival of COVID-19 in these countries to low detection, preparedness, resources, capacity, travel volume, younger population and perhaps an unidentified genetic factor [6,10–15].

Using early-confirmed cases reported in Wuhan, a study suggested that once there are at least four independently introduced cases, the likelihood that an outbreak will be established in the population is almost certain [16]. Thailand, Cambodia, Malaysia, Canada, the United States and Australia and some pan-European countries were found to have a high risk of importation from China, while Africa and South America had very low risk [10]. Similarly, whereas Asia-Pacific is more at risk (high risk to extreme) from the China epicentre, South America and Africa are more at risk from the Italian epicentre [6]. Preparedness and vulnerability of African countries were linked to the risk of importation from China; African countries with the highest importation risk have moderate to high capacity to respond to such outbreaks [12].

Although COVID-19 pandemic has caused disruptions to health services in most countries, L-LMICs have experienced the greatest difficulties [9]. Prior to the COVID-19 pandemic, L-LMICs have already been dealing with concurrent outbreaks of infectious diseases and were more vulnerable to continuous political instabilities [17–21]. Additionally, routine immunization in L-LMICs is the lowest globally [22,23]. Together, these factors

TABLE 38.1

Major Recent or Ongoing Outbreaks (or Unusual Large Cases of Infection), 2010–2020[a]

Disease	Pathogens	Transmission	Year[b]	Country
Avian influenza	H1N1[c]	Direct contact with infected animals or contaminated environments	2009/2010	Pandemic
	H7N9		2013–2017	China
Chikungunya	*Chikungunya virus*	Bite of an infected female mosquito (*Aedes* spp.)	2013	St. Martin
			2015	Senegal
			2016	Argentina
			2017	France, Italy
			2018	Kenya, Sudan
			2019	Congo
Cholera	*Vibrio cholerae*	Ingestion of contaminated food/water	2010	Central Africa, Haiti, Pakistan
			2011	Congo and DRC
			2012	Sierra Leone and DRC
			2013	Mexico
			2014	South Sudan
			2015	DRC, Iraq, Tanzania
			2017	Kenya and Zambia
			2018	Zimbabwe, Nigeria, Algeria, Cameroon, Somalia, DRC, Mozambique, Tanzania
COVID-19	SARS-CoV-2	Direct, indirect (through contaminated objects or surfaces), or close contact with infected people via mouth and nose secretions[d]	2019/2020	Pandemic
Dengue	Dengue virus	Bite of an infected female mosquito (*Aedes* spp.)	2012	Portugal
			2015	Egypt
			2016	Burkina Faso, Uruguay
			2017	Burkina Faso, Cote d'Ivoire, Sri Lanka
			2018	Reunion
			2019	Sudan, Pakistan, France, Jamaica
			2020	Mayotte, French Guiana, Guadeloupe, Martinique, and Saint-Martin

(Continued)

TABLE 38.1 (*Continued*)

Major Recent or Ongoing Outbreaks (or Unusual Large Cases of Infection), 2010–2020[a]

Disease	Pathogens	Transmission	Year[b]	Country
Ebola	Ebola virus	Direct contact with infected animals, body fluids of an infected individual (dead or alive) or contaminated environments. Sexual transmission from semen of men who have recovered from the disease	2011/2012	Uganda
			2012	Democratic Republic of Congo (DRC)
			2014	West Africa, DRC
			2017	DRC
			2018	DRC
			2019	DRC, Uganda
			2020	DRC
Lassa fever	Lassa virus	Direct contact with body fluids of an infected individual, urine or faeces of *Mastomys* natalensis rats or contaminated environment	2012–2020	Nigeria
Measles	Measles virus	Direct, indirect (through contaminated objects or surfaces), or close contact with infected people via mouth and nose secretions	2011	Regions of the Americas, Europe and Africa
			2015	The Americas, Europe
			2018	Brazil and Japan
			2019	Global situation
			2020	Palestinian territory, Central African Republic, Mexico, Burundi
Meningococcal	*Neisseria meningitidis*	Direct or close contact with infected people via the mouth and respiratory secretions	2010/2011	Chad
			2012	African Meningitis Belt
			2013	African Meningitis Belt
			2015	Niger, Nigeria
			2017	Liberia, Nigeria, Togo
Middle East respiratory syndrome	MERS-CoV	Direct, indirect (through contaminated objects or surfaces), or close contact with infected people via mouth and nose secretions[d]	2012	Saudi Arabia
			2013-2020	Middle East
			2015	South Korea
Plague	*Yersinia pestis*	Bite of an infected flea, contact with contaminated fluid or tissue, infectious droplets	2010	Peru
			2014/2015/2017	Madagascar
			2020	DRC
West Nile virus infection	West Nile Virus	Bites of an infected mosquito (*Culex* spp.), direct contact with body fluids/tissues of infected animals or *In-utero* transmission	2011	Europe

(Continued)

TABLE 38.1 (*Continued*)

Major Recent or Ongoing Outbreaks (or Unusual Large Cases of Infection), 2010–2020[a]

Disease	Pathogens	Transmission	Year[b]	Country
Poliomyelitis	Wild poliovirus	Faecal-oral route or ingestion of contaminated water or food	2011	Pakistan
			2010	Angola
			2011	China
			2011	Chad
			2010	Tajikistan
			2010	DRC
			2010	The Republic of Congo
			2010	Central Asia and the Russian Federation
			2013	Syrian
			2013	Niger
Yellow fever	Yellow fever virus	Bite of an infected female mosquito (*Aedes* spp., *Haemogogus* spp.)	2011	Senegal
			2010	The Democratic Republic of the Congo
			2011	Sierra Leone
			2010/2011	Côte d'Ivoire
			2010/2011/2012	Uganda
			2010	Guinea
			2010/2012	Cameroon
			2012	Ghana
			2010	Senegal
			2012	Sudan
			2012	The Republic of Congo
Zika	Zika virus	Bite of an infected female mosquito (*Aedes* spp.), in-utero transmission, or contact with genital fluids of an infected individual	2015	Americas

[a] *Source*: WHO disease outbreaks (https://www.who.int/csr/don/archive/year/en/) Assessed 16 September 2020.

[b] Confirmed date and not necessarily start/end of the outbreak.

[c] Occasional outbreaks around the world.

[d] Ongoing.

have further weakened the already fragile healthcare system, making it very difficult for these countries to provide adequate and timely measures to mitigate the current pandemic. Moreover, unlike most L-LMICs, Africa has been spared the scale of devastation experienced in some L-LMICs, particularly in Asia and South America, perhaps because Africans are not new to confronting epidemics [24] (Figure 38.1). Thus far, India is the second most severely affected by COVID-19 globally and the worst affected in L-LMICs (accounting for more than 68% of the total COVID-19 cases in L-LMICs). The trajectory of COVID-19 pandemic in L-LMICs has been described as a "slow burn" [25].

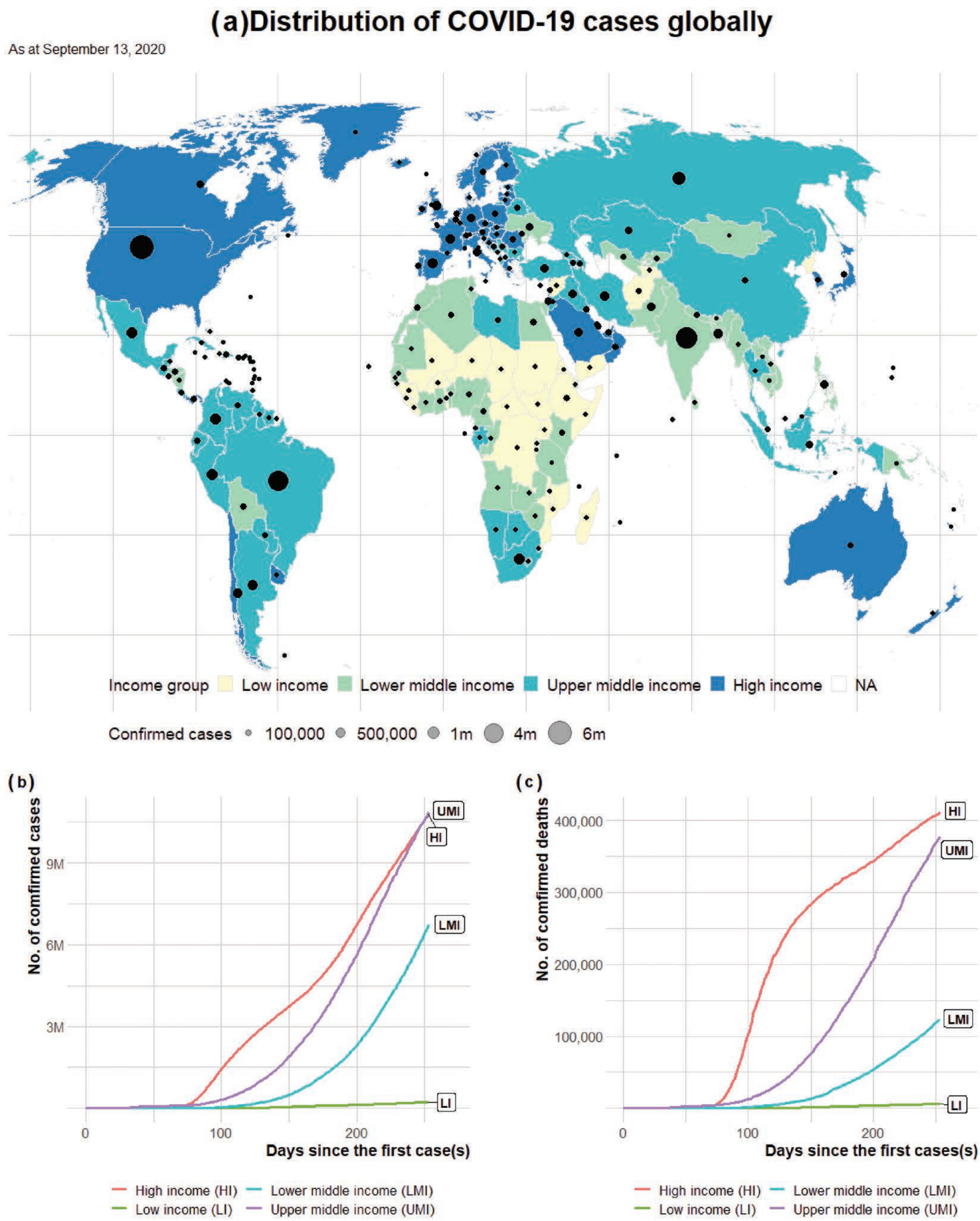

FIGURE 38.1
(a) World map showing the geographical distribution of COVID-19 cases globally, (b) response system of low-income countries could be [26]. Time-series plot of COVID-19 cases from days since the first cases, (c) time series plot of COVID-19 deaths from days since the first cases by World Bank income group.

38.1.2 Responses To and Challenges of COVID-19 in L-LMICs

The COVID-19 pandemic has demonstrated how people from different parts of the world are connected. The global nature of the impact of the pandemic has attracted a global response from public health professionals and experts across disciplines to ensure the disease was brought under control. However, a tremendous increase in cases was still recorded, with most countries experiencing an exponential rise in cases and deaths within a short period. In the absence of an effective vaccine, compliance with WHO recommended public health guidelines for prevention, case identification, quarantine, and treatment remains the effective way of containing the virus.

Before the advent of COVID-19, most L-LMICs have already been facing public health challenges, of which the most devastating ones include Ebola, cholera, malaria, measles, haemorrhagic fever, and meningitis (Table 38.1). The outbreak of Ebola virus diseases and the case fatality rate recorded in some West African countries demonstrate how weak the infectious disease surveillance and response system of low-income countries could be [26].

Collaborative efforts and commitments of national and international governments and agencies were consequently deployed to prevent the global calamity that could have been caused by the virus [27]. However, the continued remnant of the virus in places such as the Democratic Republic of Congo demonstrates that the considerable experience of local health services to identify and deal with emerging pathogens can be hampered by geographical and sociopolitical instability [28].

Prior to the spread of COVID-19 to L-LMICs, the health systems of most of the countries were operating at maximum capacities with the huge workload on their hospital, clinics and health workers [29]. In Table 38.2, we present some healthcare capacity indicators for

TABLE 38.2

Comparison of Some Health Capacities of Selected L-L-LMICs

Country	Density of Medical Physicians[a, b]	Density of Nursing and Midwifery Personnel[a, b]	Density of Pharmacists[a, b]	Hospital Beds[b, c]
Afghanistan	2.8	3.2	0.5	3.9 (2017)
Bangladesh	5.3	3.1	1.6	7.9 (2016)
Benin	1.6	6.1	<0.1	5.0 (2010)
Brazil[d]	21.5	97.1	6.8	20.9 (2017)
Cameroon	0.9	9.3	0.1	13.0 (2010)
Egypt	7.9	14.0	4.3	14.3 (2017)
Ethiopia	1.0	8.4	0.1	3.3 (2016)
Ghana	1.8	12.0	3.6	9.0 (2011)
Haiti	2.3	6.8	0.3	7.1 (2013)
India	7.8	21.1	6.8	5.3 (2017)
Kenya	2.0	15.4	0.5	14.0 (2010)
Liberia	0.4	1.0	0.1	8.0 (2010)
Mauritius	20.2	33.8	3.9	34.0 (2011)
Nigeria	3.8	14.5	0.9	5.0 (2004)
Philippines	12.8	33.3	6.2	9.9 (2014)
South Africa	9.1	35.2	1.5	23.0 (2010)
Zimbabwe	0.8	1.2	0.3	17.0 (2011)

[a] *Source*: WHO World Health Statistics 2019, Annex 2, Part 4.
[b] 10,000 Population, 2009–2018.
[c] *Source*: WHO Global Health Observatory data repository: Hospital bed density.
[d] The recent World Bank income group definition classified Brazil as a middle high-income country.

selected L-LMIC countries. The 2005 International Health Regulation (IHR) indicated a list of actions to be carried out by international organizations and individual countries and regions in order to be prepared for any unfolding public health threat [30]. Several countries were considered to have limited IHR capacities, and a universal improvement was required across the majority of the sub-Saharan African countries [31]. The identified areas of improvement by the report, coupled with the lessons learned from previous outbreaks such as Ebola virus disease and massive investments in surveillance and preparedness, could have positioned most of the countries in a better states to deal with the outbreak of COVID-19.

In responding to the threat posed by the COVID-19 pandemic, most countries of the world adopted the measures implemented in Wuhan, China, where the pathogen was first reported. This includes strict lockdown, social distancing and control of mobility, economic and social activities, all of which were in line with the recommendations of the WHO. However, considering the wide differences in preparedness to public health issues, specific responses by countries are bound to differ. In what follows, we review the responses to COVID-19 pandemic in selected L-L-LMIC countries, namely India, Nigeria and The Republic of Mauritius. India was selected because of its large population, high burden of COVID-19 and proximity to China. Similarly, we considered Nigeria because of its population size in Africa and large traffic between China and sub-Saharan Africa, while the Republic of Mauritius was considered to showcase how a small and Island country responds to the pandemic.

38.1.2.1 India

Countries in the Southeast Asia region have been prone to climate change and emerging infectious diseases, partly because the region is characterized and shaped by differing environmental, ecological and economic factors [32,33]. In the recent past, the region was considered a hotspot for emerging infectious diseases, including those with the potential to transform into a pandemic [33,34]. They are also more susceptible to COVID-19 because of their proximity to China, where the pandemic was first reported. Consequently, to enhance their surveillance, response and other contingency plans against public health challenges, member countries of the Southeast Asia region conduct regular simulation exercises and annual self-assessment with external partners. In September 2019, the countries adopted the "Delhi Declaration" to strengthen their preparedness to respond to emerging public health challenges [35]. The key components of the declaration evolve around collaboration between and among individuals and sectors when responding to public health issues. The four key components include (1) identify risk by mapping and assessing vulnerability for evidence-based planning; (2) invest in people and systems for risk management; (3) implement plans; and (4) interlink sectors and networks to engage and involve all, beyond the sector, who can and have a role in responding to public health emergencies.

The first case of COVID-19 in India was reported on January 30th 2020, the same day that WHO declared the virus a public health emergency of international concern. Earlier, India implemented surveillance measures on January 17th 2020, even before the first case was reported, followed by a series of travel advisories and restrictions [36]. However, it was not until March 25 that the first major control measure that ensured a complete lockdown was put in place. By this time, there were 320 cases and 10 deaths from COVID-19, mostly confined to a few regions [37]. The lockdown was imposed by the Central Government, invoking the Disaster Management Act 2005, which empowers the government to adopt rapid policy decisions and impose restrictions on people to manage any disaster. India also put in place a "five P" response measure for the pandemic. These include (1) proof of concept with a social environment: this ensures complete lockdown with proper experimentation and communication; (2) a proactive approach to ban international flights and screening all international passengers arriving in the country; (3) people management: a "#9PMfor9Minutes" challenge was declared on April 5th 2020 by the Indian Prime Minister to turn off lights and lighting of diyas "oil lamps" and candles for 9 minutes beginning 9 p.m. to demonstrate resolve and resilience for every Indian in the collective fight against COVID-19, and to indicate the country's gratefulness to the frontline workers battling the virus; a cause that was widely supported; (4) partnerships: regular interaction between stakeholders, state governments and the G20 groups that ensured exchanges of ideas and knowledge that further empowered local authorities to confront the pandemic; (5) preparation and collaboration: the country devised and implemented several strategies to contain further spread and death. The health facilities were equipped with personal protective equipment (PPE), ventilators and establishment of isolation wards and COVID-19 care centres. Further, the country, through the National Informatics Centre, came up with an open-source COVID-19 app, "Aarogya Setu" deplored for contact tracing, syndromic mapping and self-assessment. The app tracks the movements of infected persons, alerting a nearby person of their presence, and provides updated travel advisory and containment measures [32,38]

While Indian's proactive efforts at containing COVID-19 might not be adjudged as completely successful going by the astronomic rise in numbers of cases and death around July 2020, the efforts helped to get time for preparation to handle possible widespread situations and were applauded by the WHO [38,39].

38.1.2.2 The Republic of Mauritius

The outcome of the responses to COVID-19 in Mauritius demonstrates that a well-implemented and early "hard lockdown" backed by a strong political will could be effective in managing a highly contagious infectious disease outbreak [40]. Mauritius is an African island nation in the Indian Ocean, with about 1.3 million people, and is considered among the most densely populated countries in the world [41]. Long before any case was reported in the island country or even in Africa, the government of Mauritius began the screening of people on arrival at its international airport on January 22nd 2020, introducing fever measurements and separation of people considered to have travelled from countries considered to be at-risk, especially China [42]. The government moved further on February 28th 2020, to quarantine visitors from countries with a high number of cases, even though there was yet any reported case locally. At the same time, the authorities increased accommodation capacity to quarantine suspected COVID-19 cases [43].

The first three cases were detected on March 18th 2020, and the following day, the Mauritius instituted some stringent measures that ensured the closure of all schools and all its borders to travellers, including its citizens [43]. Beginning March 20th 2020, a national lockdown was enforced by the authorities and this was transformed into a curfew that lasted until May 30th 2020. Following WHO recommendations, all confirmed cases were moved to isolation facilities and were closely monitored. The health authorities prioritized contact tracing of people who had been in physical contact with infected patients to identify and test [42]. The country set up a National Communication Committee (NCC) led by the Prime Minister with stakeholders mainly from the Ministry of Health, Ministry of Commerce and the Police Force, who worked collaboratively, addressing the nation regularly, providing COVID-19 statistics and informed the population about the measures put in place and the need for everyone to play their role in the fight against COVID-19. The Ministry of Information and Communication also developed a mobile app called "beSafeMoris" that provided updates and useful tips on the virus and was available for download and used free of charge. The daily data communication by the NCC was used to quantify the effectiveness of measures put in place to contain COVID-19 outbreak in the country. By May 11th 2020 (Day 55 from the date the first cases were reported), there was no active case of COVID-19 in Mauritius [43]. Thus, the Mauritian government was able to achieve the objectives of containing a surge in positive cases of COVID-19 in the country to save the lives of the citizens and prevent the available healthcare facilities from being overwhelmed. The country's prompt interventions and the evident success recorded were highly applauded by WHO and other international organizations [44].

38.1.2.3 Nigeria

Nigeria was one of the West African countries affected by the outbreak of Ebola virus disease in 2014, but the country was notable for its swift action, which demonstrated the importance of adequate preparation and coordinated response in containing infectious disease outbreaks [45]. The successes drawn from the containment of polio and Ebola strengthened the country's healthcare capacity in deploying high-quality surveillance and temperature screening machines at the major ports of entry using equipment acquired during the Ebola outbreak [45]. The human resources, technical expertise, disease surveillance, community networks and logistical capacity used in curtailing polio in the country were equally available for deployment to curtail COVID-19 [46].

Nigeria was prompt in recognizing the risks posed by COVID-19 a few days after the first case was reported in Wuhan, China. The country is seen as a major destination of movements between China and sub-Saharan Africa, as the number of such movements rapidly increased over the past decade [6]. Consequently, a multi-sectoral National Coronavirus Preparedness Group was set up by the Nigeria Centre for Disease Control (NCDC) on January 7th 2020, a week after China's case was reported [47]. The Group met daily to assess the risk COVID-19 posed to the country and review its response to it. The diagnostic capacity for COVID-19 was promptly established in three laboratories. The country's Ministry of Health equally activated Emergency Operation Centres (EOCs) to coordinate the outbreak response activities. The EOCs were organized under six functional units, following the patterns that were adopted for the Polio EOC, namely: Management and coordination, epidemiology, and surveillance, case management, laboratory services, risk communication and point of entry. The EOCs' priorities were to develop the capacities of clinicians, port health officials, point of entry crews and other relevant groups on infection prevention and control, decontamination and contact tracing [46]. Further, the Polio programme has an SMS-based application called "AVADAR" short for "auto-visual AFP detection and reporting" which was used by a network of health workers and community volunteers in hard to reach areas to support disease surveillance through filling in a simple form after receiving a notification [46,47]. This device was deployed by adding relevant disease surveillance questions on COVID-19 to the mobile app.

The index case of COVID-19 was reported in Nigeria on February 27th 2020, and within 2 days, a laboratory diagnostic test for SARS-CoV-2 was set up [48]. Rapid response teams were deployed within the states to lead contact tracing and response activities, while the index case was evacuated to a health facility for treatment and close monitoring [48]. At the onset of the response efforts, the testing capacity of the country was low and limited to symptomatic cases but the number of testing laboratories was increased from 5 to 13 across the six geopolitical zones of the country, leading to more decentralized testing [49]. The testing capacity was also enhanced by donations of testing kits by an individual and a private Biotech company, 54Gene [50,51]. All these efforts notwithstanding, the number of reported cases in the country surged within a few days.

Nigeria initially placed a travel ban on 13 countries considered to be a high risk of COVID-19 and subsequently suspended all international flights in and out of the county on March 23rd 2020. Through a presidential proclamation, two states, Lagos and Ogun, and the Federal Capital Territory, Abuja, considered hotspots during the early outbreak, were placed on total lockdown, and governors of other states implemented similar measures to curb the spread [52]. Restrictions were placed on inter-and intrastate movements, and social and religious gatherings of all forms were banned. All schools and universities were also hurriedly closed. A multi-sectoral and intergovernmental Presidential Task Force on COVID-19 was also put in place. The Task Force ensures the enforcement of all presidential directives related to COVID-19 and equally issues guidelines and regulations weekly. Contact tracing and other public health measures were intensified while the NCDC further deployed an open-source mobile web application for disease outbreak detection, notification, management and response called Surveillance Outbreak Response Management and Analysis System [53]. Daily data collection from all the states, analysis and reporting were equally prioritized by the NCDC to inform the citizens of events around their neighbourhood and to adjudge the progress being made. However, the impact of the lockdown on the economy and, in particular, on the majority of the citizens, especially the most vulnerable became harder by the day as the majority of Nigerians are artisans who depend on daily wages and the daily survival sustenance provided by the government, was grossly inadequate. The lockdowns were consequently relaxed in phases, and citizens were instructed to use face masks and maintain social distance in public places. Despite increasing the number of testing laboratories within the country, low levels of testing to identify infected cases remained an issue in most Nigerian states. Thus, the reported cases, considered fewer when compared with what was reported for some developing countries, may not be true reflections of the number of cases.

38.1.3 Different Mathematical Models Used in L-LMICs

Implementation of public health interventions to mitigate the impact of COVID-19 in developing and developed countries has largely relied on disease spread and its mathematical projections. Mathematical models are essential tools for assessing the underlying mechanisms that govern the spread of infectious diseases, in particular COVID-19 [54]. They were extensively used during Ebola outbreaks from 2013 to 2016 and were instrumental to the development of control policies that helped in curtailing the outbreaks [55]. The Ebola outbreak was mainly in West-African countries, which are all low-income countries. Despite the challenges that face the applicability of mathematical modelling in this region, adjusting for such challenges in modelling exercises still allows mathematical modelling to be readily adapted for changing policies. In the case of COVID-19, there have been limited mathematical models developed to understand the underlying dynamics of the pandemic in L-LMICs [56]. However, those models developed still cover the main modelling types that can be used to determine the epidemic spread and estimate key parameters that aid intervention implementation.

There are two popular modelling approaches that have been adopted for modelling COVID-19. They are deterministic and statistical modelling methods. Deterministic models are mostly compartmental models, while statistical models require the formulation of probability distribution to capture the disease dynamics. The models used in L-LMIC range from simple linear regression to metapopulation models. Also, a single application may require combining more than one modelling approach. We discussed the two approaches below and how they have been applied to COVID-19 in L-LMICs and the model complexities and validity.

38.1.3.1 Compartmental Models

Compartmental models are the most widely used approaches for COVID-19 epidemic modelling [57–59]. In this approach, the population is divided into infection status classes and the disease spread through the population via infection, contact and recovery processes. One commonly used compartmental model is the Kermack and McKendrick SIR (S – susceptible, I – Infectious, and R – recovery) model [60]. This model applies to infectious diseases where individuals become immune after treatment or natural recovery, for example, each strain of flu, measles and COVID-19. Early in the COVID-19 outbreak in February 2020, the decisions of most governments were based on the risk of importation and changing in epicentres [6,12]. Adegboye et al. [6] used a compartmental model to determine where the next epicentre will be and the risk of importation of COVID-19 to Africa. The compartmental model used was a SE1E2I1I2R (S – susceptible, E1 – early exposed, non-infectious, E2-late exposed stage and infectious, I1-early infectious stage, I2-late infectious stage, R – recovered individuals) model. The model used 2014 air travel data between countries to determine the rate of movement of people from one country to another. The dynamical equations for movement between two countries developed were:

$$\frac{dS^1}{dt} = \frac{-\left(\beta_1^1 E_2^1 + \beta_2^1 I_1^1 + \beta_3^1 I_2^1\right)S^1}{N^1} + c_d^1 \gamma_2^1 I_2^1 - \frac{m_{12}S^1}{N^1} + \frac{m_{21}S^2}{N^2} \tag{10.1}$$

$$\frac{dE_1^1}{dt} = \frac{\left(\beta_1^1 E_2^1 + \beta_2^1 I_1^1 + \beta_3^1 I_2^1\right)S^1}{N^1} - \sigma_1 E_1^1 - \frac{m_{12}E_1^1}{N^1} + \frac{m_{21}E_1^2}{N^2}$$

$$\frac{dE_2^1}{dt} = \sigma_1 E_1^1 - \sigma_2 E_2^1 - \frac{m_{12}E_2^1}{N^1} + \frac{m_{21}E_2^2}{N^2}$$

$$\frac{dI_1^1}{dt} = \sigma_2 E_2^1 - \gamma_1^1 I_1^1 - \frac{m_{12}I_1^1}{N^1} + \frac{m_{21}I_1^1}{N^2}$$

$$\frac{dI_2^1}{dt} = \gamma_1^1 I_1^1 - \gamma_2^1 I_2^1$$

$$\frac{dR}{dt} = \left(1 - c_d^1\right)\gamma_2^1 I_2^1 - \frac{m_{12}R}{N^1} + \frac{m_{21}R}{N^2}$$

The parameters in the model are described in Table 38.3. With this modelling effort, the risks of importation of COVID-19 from China and Italy – the then-new epicentre – were determined. The analysis showed that the risk of travellers infected with COVID-19 coming to the L-LMICs was higher from Italy than from China. These prompted many L-LMICs to consider closing their borders and cancelled international flights [52,61].

TABLE 38.3

Description of the Parameters Used in the Model

Parameter	Description
$\beta_1, \beta_2, \beta_3$	Transmission rates for E_2, I_1, I_2 classes
σ_1	First stage incubation rate
σ_2	Second stage incubation rate
γ_1	First stage of recovery
γ_2	Second stage of recovery
c_d	COVID-19 case fatality

The compartmental modelling approach was also used in evaluating non-pharmaceutical intervention controls for COVID-19. COVID-19 is unique in its transmission dynamics, and there were no vaccines for preventing infection and disease. Thus, non-pharmaceutical control measures such as social distancing, contact tracing and lockdowns were introduced [62]. For example, Iboi et al. [63] used this model to investigate the effects of various social distancing measures on reducing COVID-19 cases in Nigeria, where the authors found a moderate level of social distancing and face mask could help control COVID-19 in Nigeria.

38.1.3.2 Statistical Modelling

Another common COVID modelling approach is the statistical models. Early dynamics of COVID-19 in many L-LMICs were evaluated to check the effectiveness of the non-pharmaceutical control measures implemented. One of the parameters for examining this is the effective reproduction number (R_t). An $R_t<1$ implies that the control measures are effective and ineffective if $R_t>1$ [64]. This parameter has been estimated for many developed and L-LMICs [62,64–69]. There are many approaches to estimating R_t. Some researchers used compartmental models [68], while others used a probabilistic modelling approach [64]. For example, Adekunle et al. [65] used a Bayesian approach to estimate the R_t for Nigeria between February 27th and May 7th 2020. The model assumed a Poisson distribution for the number of locally observed cases adjusting for imported COVID-19 cases. The estimate showed that as of May 7th, 2020, Nigeria needs to re-evaluate their control measures as R_t was above one. The Bangladesh estimate also shows a similar pattern [70]. For this approach, we let $L(t)$ be locally acquired infections and $\lambda(t)$ be the rate of infection. Thus,

$$\lambda(t) = \left(R_t \sum_{s=1}^{t} \varphi(s)\, C(t-s) \right) \tag{10.2}$$

$C(t)$ is the total daily cases, which includes the imported cases, and $\varphi(s)$ is the serial interval distribution. Using equation (10.2), the conditional likelihood via Poisson distribution can be formulated for estimating R_t.

38.1.3.3 Model Complexity and Parameter Sensitivity

Apart from the modelling choice, level of complexities can be added to get robust estimates of disease parameters. The WHO multi-model comparison guide identified the required criteria in adopting a particular model choice to solve real-life problems [71]. However, most of these models are mechanistic with age distribution in transmission but not accounting for sub-populations and comorbidities [72]. The models vary in how COVID-19 transmission, contact patterns and interventions are incorporated. These models are either deterministic or stochastic [72]. For example, Prem et al. [73] used synthetic contact data in a deterministic compartmental model to characterize COVID-19 epidemics in 177 countries, including many L-LMICs. They evaluated three intervention scenarios: 20% physical distancing, 50% physical distancing and shielding, and compared with the unmitigated epidemic [73].

Similarly, the modelling work of Walker et al focused L-LMICs [74]. The model is also a dynamic compartmental model that incorporates age classes and contacts, health system challenges and comorbidities. In most L-LMICs, prior to COVID-19 pandemic, there were other diseases such as malaria, tuberculosis, yellow fever that were weakening the health systems. These existing challenges play a critical role in whether mitigation measures will be effective or not. Walker et al. [74] have to a greater extent, incorporated such factors in their modelling work.

Parameter sensitivity is another aspect that could influence modelling results. Estimated model parameters will vary from setting to setting. For instance, age-dependent contact rates, health capacities and infection fatality rates will differ from country to country or geographically within a country. There are many mathematical methods for conducting parameter sensitivity analysis [75]. This aspect has not been extensively explored for COVID-19 by many modelling groups as the disease is evolving, and detailed information about the dynamics of the virus is still unknown. Conducting country-dependent robustness analysis of the uncertainty surrounding COVID-19 key parameters will be important for future usage of the developed mathematical models for policy change.

38.1.3.4 Disease Mapping

According to Tobler's [76] first law of geography, "everything is related to everything else, but near things are more related than distant things". Geographical locations are important components in decision-making when it comes to prioritizing support systems for emergency health services or situating emergency health facilities, particularly in the face of meagre resources available to most developing countries. Consequently, detecting spatial clusters in disease is an essential component that allows for evidence-based response in containing infectious diseases [77,78]. The goal of disease mapping (also referred to as spatial epidemiology) is to produce spatially smoothed maps that display the variation in disease risk [79]. Apart from helping to determine locations of potential disease clusters, the approach helps to ascertain if the clusters at the different locations are due to the magnitude of the outbreak or resulting from random fluctuations in case count. Approaches to disease mapping can range from a simple mapping of observed disease rate (number of observed cases per unit population) from the different geographical entity to the use of a variety of Bayesian spatial models or other spatial smoothing techniques that estimate risks at different geographical settings.

A number of disease mapping techniques have been deployed to understand the spread of COVID-19 in L-LMICs, ranging from a simple method that maps the incidence and fatality rates to more complex approaches that smooth the spatial variations. In an extensive review of disease mapping approaches to COVID-19, Franch-Pardo and colleagues [80] categorized the approaches into the following groups: spatiotemporal analysis, health and social geography, environmental variables, data mining and web-based mapping. For instance, Arab-Mazar et al. [81] map the incidence and fatality rates for the first 20 days of COVID-19 in Iran using the provinces of the country as the spatial units. On their part, Gayawan et al. [82] used a two-parameter hurdle Poisson model to investigate the spatio-temporal pattern during the first 62 days of COVID-19 in Africa. The Bayesian approach adopts a Markov random field prior for the spatial components that ensure spatial continuity among the spatial units and split the spatial variations into structured and unstructured random effects.

With respect to collaboration in infectious disease modelling, models used for COVID-19 are very diverse. The two models mentioned in this chapter are typical examples of such modelling efforts. Each of these modelling approaches present has its advantages and disadvantages. For instance, compartmental models will give an average representation of disease dynamics in a population, but stochastic models will show the posterior distribution of the parameters. Seeking the average representation of disease dynamics is not as computationally intensive as seeking the posterior distribution. As there are many epidemiological mathematical models employed by many countries to inform policy and control of COVID-19, there are tendencies for such a wide range of modelling efforts to lead to conflicting results and generate alternative opinions. Hence, depending on the researchers' interest and computational power, any of these modelling choices will serve well in helping to understand the dynamics of infectious diseases, as seen in the case of COVID-19.

This implication has led to lead the WHO, the World Bank, the Bill and Melinda Gates Foundation and, the international Decision Support Initiative to form the COVID-19 multi-model comparison collaboration (CMCC) [83]. This initiative was hosted by the Centre for Global Development, the Royal Thai Government and other partners, including the Department for International Development and the following modelling teams: the University of Basel, Institute of Metrics and Evaluation, Imperial College London, Institute for Disease Modelling, London School of Hygiene and Tropical Medicine and the University of Oxford Modelling Consortium came together to form the COVID-19 Multi-model CMCC [83]. They aimed to identify key policy decisions that can benefit from epidemic modelling, resource requirement under different modelling scenarios, data requirement and key assumptions-driven potential differences in predictions, and selecting meaningful models.

38.1.4 Economic Responses to COVID-19 in L-LMICs

Statistical modelling and mathematical projections of the COVID-19 spread have been useful in designing and implementing public health responses by the governments aiming at limiting the spread of the virus and saving lives. As earlier mentioned, common measures deployed at the onset of the pandemic included travel restrictions, bans on mass gatherings, social distancing requirements, school closings and a temporary shutdown of businesses [1,84–86]. Consequently, these containment measures have led to significant economic costs arising from the reduction in economic activities, increase in unemployment, supply chain disruptions and a high level of uncertainty [87,88].

While the COVID-19 pandemic has created economic challenges worldwide, L-LMICs might be particularly vulnerable due to their limited health systems capacity, lack of resources and low economic resilience. In this section, we examine economic challenges and policy responses in developing countries, discuss emerging empirical evidence and stress the importance of cooperation and support from international organizations.

38.1.4.1 Challenges to Economic Policies and Public Finances in L-LMIC

COVID-19 pandemic has negatively affected the demand and supply for goods and services. Companies and workers, especially in the industries in which social distancing requirements are difficult to maintain, such as travel and entertainment, have reduced production and work activities. The health crisis has also raised economic uncertainties for economic agents and reduced household income, thus lowering consumer spending and capital investments [89].

To prevent a spiralling economic crisis into a deep economic recession, most governments quickly adopted fiscal and monetary measures. In many developed countries, central banks quickly provided ample liquidity to financial organizations, and some reduced their interest rates easing borrowing constraints [90]. Targeted discretionary fiscal measures were also essential. In March- April 2020, G20 governments committed to provide fiscal support and financial assistance of over US$7.3 trillion to people and firms most affected by the COVID-19 crisis [91]. Expansion of healthcare provisions, unemployment benefits and social assistance payments were among the most common measures to support citizens. Governments of most L-L-LMICs also supported businesses from affected sectors, such as hospitality and transportation, by providing temporal wage subsidies and tax deferrals, as well as supporting businesses through loan relief programmes and credit holidays [92]. The summary of main economic responses by country is described by the International Monetary Fund (IMF) Policy Tracker [93].

These aggressive fiscal and monetary measures were targeted to avoid the economy spiralling by keeping workers in employment and preventing the destruction of valuable economic linkages between businesses. However, the ability to deploy fiscal stimulus measures and deliver broad economic support programmes in L-L-LMICs has been primarily limited by their insufficient fiscal space and capacity [94]. Thus, the economic government assistance in response to the pandemic in developing countries have translated to around 4% of GDP on average, and countries with better fiscal position have averaged 2% of GDP higher in stimulus spending [92].

To finance these new expenditures, governments need to borrow money. However, L-LMICs might experience severe borrowing constraints. Developing countries borrow at higher interest rates due to lower credit ratings and have more significant exposure to exchange rate and maturity risks. Borrowing costs are also increasing in developing economies as public and private debt reached record numbers and now corresponds to 170% of GDP [92]. Less developed financial markets also limit domestic sovereign borrowing. Funding from foreign investors may also be less available for developing countries, as investors tend to move the capital to safer investments during times of high uncertainty and recession. This further raises the cost of borrowing for developing countries. Constraint on public finances makes it critical to use a targeted approach in providing financial support. However, with many developing countries having large informal sectors, less efficient tax administration and lacking social protection systems, the implementation of policy measures aiming to support the most affected firms and people is much more complex to implement than in developed economies.

38.1.4.2 Labour Market and Household Income

Labour markets in developed countries have been quickly responsive to public health measures. For example, in the United States, the weakness of the labour market was evident by the large spikes in unemployment insurance claims across states and a steep drop in job postings [95]. Fiscal stimulus measures for both firms and workers have provided financial support to survive the pandemic and prevent the country from falling into a deep recession. Wage subsidies offered by many governments were targeted to keep workers employed even during the lockdowns when firms were not able to operate. This measure prevents the destruction of many valuable employer-employee connections and enables firms to bounce back quickly during the recovery stage.

However, the situation in the developing countries is more challenging due to their limited fiscal space, the structure of their economies and labour market arrangements. In many L-LMICs, the informal sector accounts for a large part of the economy. The lockdown measures, travel restrictions and reduction in aggregate demand have created a negative shock on jobs and income, with more than 1.6 billion informal sector workers being affected [96]. To mitigate the burden of income loss, most governments in developing countries implemented or widened their unemployment and social security initiatives. The timing of these payments is of high importance as many low-income households might not have sufficient savings and have limited access to borrowing. Borrowing from social networks (e.g. relatives, friends, colleagues) is also likely to be difficult when the pandemic has created widespread economic disruptions and uncertainties. However, the effectiveness of government assistance programmes would be reduced if the rapid roll-out of payments were not implemented to the eligible recipients. To improve the delivery of social benefits, developing countries have started to simplify administrative procedures and increase technological capacity to collect information online and process payments electronically [96].

Job losses were particularly severe in many developing countries whose economies are less diversified and who have been relying on export-oriented industries, such as hospitality, tourism and light manufacturing. The majority of these jobs attract low wages, and workers in these occupations and industries are highly vulnerable to losing their jobs or being suspended without pay as they are least able to transition to "work from home" arrangements. For example, in Bangladesh, the domestic labour market suffered from severe contraction caused by public health restrictions and a sharp decline in exports, particularly from the garment industry. About 46% of Bangladesh producers reported a large number of their orders had been cancelled during the pandemic, and as a result, more than 1 million garment workers lost their jobs or were temporarily suspended without pay [97].

The situation is also exacerbated as these low wage and informal workers could not rely on unemployment benefits as unemployment protection mechanisms are either non-existent or very limited in the majority of L-LMICs (see Figure 38.2). In the early stages of

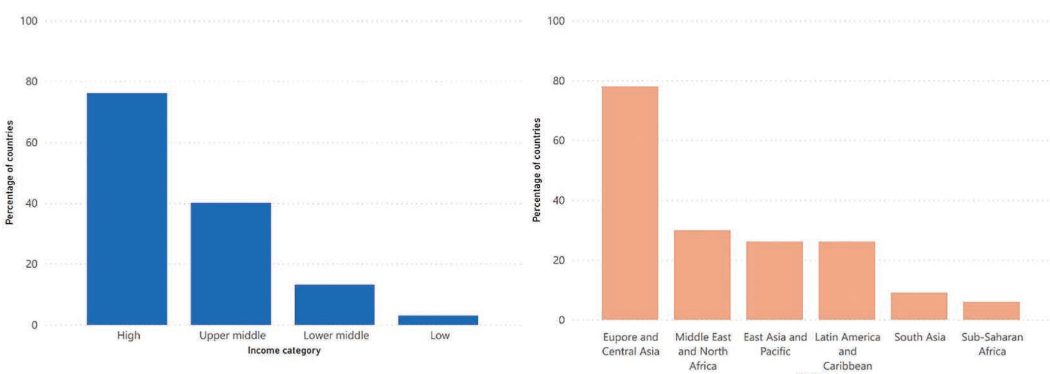

FIGURE 38.2 Availability of unemployment protection by income and region. (World Bank. https://blogs.worldbank.org/developmenttalk/its-time-expand-unemployment-protections.)

the pandemic, it was estimated that the informal workers experienced a drop of 60% in their income [98].

In addition to the heterogeneity in unemployment levels in industries, the impacts of the pandemic on income levels have also been different in rural and urban areas. This is largely attributed to higher human mobility, interconnectedness and population density in urban areas; hence more restrictive containment measures were put in place to mitigate the spread of COVID-19. As a result, for example, in Bangladesh, more than 72% of urban households reported that they lost their main source of income compared to 54% of rural households [99].

38.1.4.3 Migration Flows and Remittances

The economic crisis induced by the COVID-19 pandemic had a significant impact on migration and remittance flows. Lockdowns, travel restrictions and social distancing requirements significantly reduced economic activities in many developed and upper-middle-income countries, which are target destinations for low-waged labour migrants. In addition to the reduction of job opportunities, migrants also face elevated health risks of getting COVID-19 as they often live in suboptimal and overcrowded conditions with no or limited health care in their host countries [100]. Despite a strong public health rationale to extend COVID-19 testing and treatment initiatives to all residents, including migrants, many governments have preferred to prioritize their citizens' given constraints on health systems [101]. This situation was exemplified in the Gulf States with many low-waged migrants restricted to move out of their living compounds and thousands had already been dismissed or furloughed [49]. These migrant workers faced severe financial challenges, as they often do not have regular employment contracts nor can rely on unemployment insurance or social assistance payments.

This is especially challenging for L-LMICs as migrant remittances often account for a large part of their economy and provide an economic lifeline for poor and vulnerable households [102]. Many countries in which remittances account for a large part of foreign exchange revenues might also experience negative macroeconomic implications with respect to inflation, trade and investments. For example, Lesotho and Liberia have very high exposure to foreign exchange, with 86% and 82% of their foreign exchange revenues from international remittances [103]. Furthermore, remittances are important as they can result in poverty reduction in the countries of origin [104,105] and act as an insurance mechanism and a source of investments [106].

Due to the global nature of the COVID-19, with both migrant target destinations and countries of origin being affected, remittances have followed procyclical (rather than countercyclical) behaviour together with the economic downturn in the countries of origin. It is expected that remittances to L-LMICs will drop by $109 billion (around 20% from the 2019 level) in 2020 [102]. This significant reduction in income is reflected in the fall in migrant wages and the drop in the number of jobs available due to the subdued demand for goods and services. While the decline in remittances is expected to be severe in all regions, Europe and Central Asia region and sub-Saharan Africa will be worst affected, with the remittances to drop by 27.5% and 23.1%, respectively [102]. Compared to other regions, migrants from sub-Saharan Africa also experience the highest transfer cost (8.9% of the remitting amount) to send money home [102]. Implementation and promotion of digital and electronic payment systems to drive down the transfer costs have the potential to save significant amounts and increase the disposable income of vulnerable families.

38.1.5 International Collaboration on COVID-19

Many have advocated for extensive collaborative responses to the ongoing pandemic in an attempt to contain its impact and limit further transmission [1,24,56]. The cooperation between international development organizations and national governments has played an important role in addressing health and economic threats by sharing knowledge, developing medical treatments, providing technical expertise and supporting vulnerable countries financially.

Given the limited financial resources of L-LMICs, the provision of official development assistance and emergency financing from international development organizations has played an important countercyclical role aiming to mitigate the health and economic impact of the pandemic. The IMF has made $250 billion available to member countries through multiple lending facilities and debt relief programmes allowing L-LMICs to access concessional borrowing [107]. Similarly, the World Bank Group has planned to provide up to $160 billion in new fast-tracked funding targeting health, economic and social shocks, including $50 billion in grants and low-cost loan facilities for the world's poorest countries [108]. The G20 countries also committed to temporarily suspend debt servicing for the poorest countries [109]. Many other international organizations, including regional development banks, have initiated similar funding and technical assistance programmes to L-L-LMICs. Furthermore, the international development community has advocated for appropriate trade responses in developed and developing countries, which will facilitate the cross-border flow of sensitive goods, such as medical and food supplies [110].

In addition to economic development cooperation, the inter-agency and international collaborations among the scientific community and policy experts have also been extensive during the pandemic. Holistic cooperation within the scientific/academic world and inter-agency collaboration bridged the gap between desks/laboratories and industries (pharmaceuticals), desks/laboratories and politicians, industries (pharmaceuticals) and politicians cannot be overemphasized during this period.

38.2 Conclusion

In this chapter, we have reviewed the literature on approaches to COVID-19 pandemic in L-LMICs. Within the limit of their available resources, L-LMICs took steps to mitigate the challenges posed by the COVID-19 pandemic. It is evident that although the strict restrictions, containment and mitigation efforts put in place to reduce COVID-19 transmission and save lives may have associated economic consequences, especially in L-LMICs [1,111,112]. Prior disease outbreaks in these countries enabled them to prepare infectious disease surveillance protocols that were readily available for deployment during the COVID-19 pandemic. There are similarities and differences in the manner in which the countries responded, leading to the effectiveness or otherwise of similar measures in different countries. For instance, while the lockdown imposed in Mauritius was properly managed and, in combination with other measures, assisted in containing the pandemic in less than 2 months from the time the first cases were declared in the country, such similar measure was not as effective in the other countries leading to a surge in the number of confirmed cases.

The adverse effect of lockdown, such as the accompanying economic and psychosocial issues that challenge the daily livelihood and survival of the majority of the populace, could be a major factor in considering how effective lockdown could be in mitigating infectious disease. International and regional collaboration is essential to mitigate the consequences of the pandemic on a global scale and bounce back quicker on the road to recovery. This is clear from both economic and public health perspectives, as control of COVID-19 is a global public good. In addition to financial and technical support provided to L-LMICs by international development agencies and developed countries, cross-border collaborations and trade cooperation have been crucial in facilitating the flow of essential medical supplies and avoiding food shortages in many L-LMICs. Also worthy of note is that most L-LMICs, as evident from the three countries whose approaches were reviewed in this chapter, adopted multi-sectoral collaborative measures that ensure exchanges of ideas in confronting the virus. Appropriate measures might focus on trade-offs between public health and the economy [25].

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