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Systematic Literature Review

A Scoping Review and Taxonomy of Epidemiological-Macroeconomic Models of COVID-19

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ABSTRACT

Objectives: The COVID-19 pandemic placed significant strain on many health systems and economies. Mitigation policies decreased health impacts but had major macroeconomic impact. This article reviews models combining epidemiological and macroeconomic projections to enable policy makers to consider both macroeconomic and health objectives.

Methods: A scoping review of epidemiological-macroeconomic models of COVID-19 was conducted, covering preprints, working articles, and journal publications. We assessed model methodologies, scope, and application to empirical data.

Results: We found 80 articles modeling both the epidemiological and macroeconomic outcomes of COVID-19. Model scope is often limited to the impact of lockdown on health and total gross domestic product or aggregate consumption and to high-income countries. Just 14% of models assess disparities or poverty. Most models fall under 4 categories: compartmental-utility-maximization models, epidemiological models with stylized macroeconomic projections, epidemiological models linked to computable general equilibrium or input-output models, and epidemiological-economic agent-based models. We propose a taxonomy comparing these approaches to guide future model development.

Conclusions: The epidemiological-macroeconomic models of COVID-19 identified have varying complexity and meet different modeling needs. Priorities for future modeling include increasing developing country applications, assessing disparities and poverty, and estimating of long-run impacts. This may require better integration between epidemiologists and economists.

Keywords: COVID-19, epidemiological-macroeconomic models, scoping review.

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Introduction

The COVID-19 pandemic caused approximately 13 million deaths[1] from 2020 to 2021 and strained many health systems, lowering care quality and availability.[2,3] COVID-19 and consequent policy responses drove approximately $6 trillion loss in world gross domestic product (GDP) in 2020, and fiscal responses to the crisis cost $17 trillion by October 2021.[4,5] Full and partial lockdowns implemented to mitigate COVID-19's health impact have sometimes exacerbated short-term economic losses, even though in the long term some of these may have been economically beneficial. Hence, responding to COVID-19 entails assessing the health and macroeconomic outcomes and possible trade-offs of multiple response scenarios, usually based on evidence from models. Such efforts are not new: epidemiological-macroeconomic models were already developed for pandemic influenza and Ebola,[6-9] and efforts at timely and appropriate communication between stakeholders were made to ensure they were relevant and used to inform policy.[10] For example, the results of epidemiological-macroeconomic modeling were used to advocate for US response to the emergency during senate hearings on Ebola.[11] However, this can be challenging, particularly if trust or understanding of the type of model used has not been built. During the COVID-19 response, formal policy processes in many countries split epidemiological and macroeconomic modeling. In the United Kingdom, epidemiological models are assessed by a pandemic committee (the Scientific Pandemic Infections group on Modelling), whereas macroeconomic modeling is produced by the Treasury,[12,13] with some evidence that epidemiological-macroeconomic models were disregarded out of lack of trust in their reliability.[14] A rapid review of modeling in the United Kingdom further revealed few linked epidemiological and economic outcomes,[15] potentially missing feedback loops between them.

We reviewed the literature to assess the availability and scope of epidemiological-macroeconomic models, describe methods and applications, and make recommendations for future research by economic and health economics modelers/analysts. We hope this work can increase awareness and understanding of epidemiological-macroeconomic modeling, hence helping improve communication and use of such models to inform policy in future pandemics.

Methods

This scoping review uses 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (see Appendix 1 in Supplemental Materials found at https://doi.org/10.1016/j.jval.2023.10.008) and the extension for Scoping Reviews Checklist.[16] Given the rapid evolution in COVID-19 research, it includes preprints/working articles. We searched systematically the National Institutes of Health iSearch COVID-19 portfolio, Econlit, National Bureau of Economic Research, CPER's COVID-19 economics, and C19-economics up to January 14, 2022.

We identified titles/abstracts using COVID-19, modeling, and macroeconomics-related terms (see Appendix 2 in Supplemental Materials found at https://doi.org/10.1016/j.jval.2023.10.008) and then reviewed these to identify macroeconomic models using epidemiological model results (called "linked" models) or integrated alongside epidemiological modeling within 1 single model. Both types are called "epidemiological-macroeconomic models" hereafter.

We then analyzed approaches, scope, policies/interventions assessed, modeling of voluntary measures, outcomes described, disaggregation type, analysis timeframes, locations, and whether researchers compared model results with empirical data (calibration/validation) and included uncertainty in outcomes. We finally discussed the strengths/weaknesses, use cases, and opportunities associated with each method.

See Appendix 2 in Supplemental Materials found at https://doi.org/10.1016/j.jval.2023.10.008 for methodological details and Appendix 3 in Supplemental Materials found at https://doi.org/10.1016/j.jval.2023.10.008 for review protocol.

Results

Study Selection

Figure 1 details the selection process. We included 80 articles (Appendix 4 in Supplemental Materials found at https://doi.org/10.1016/j.jval.2023.10.008 lists all reviewed articles; Appendix 5 in Supplemental Materials found at https://doi.org/10.1016/j.jval.2023.10.008 lists selected articles); 52 were published by June 15, 2023.

Modeling Approaches

Four main modeling approaches emerged during the review. Twenty-six studies (33%) use compartmental epidemiological models integrated with macroeconomic utility maximization ("compartmental-utility-maximization"); 18 models (23%) primarily comprised an epidemiological model, to which stylized macroeconomic projections producing simple estimates of overall GDP impacts were added ("stylized epidemiological-macroeconomic models"). Seven (9%) used computational general equilibrium (CGE) or input-output (I-O) models linked to epidemiological model outputs (hereafter "epi-CGE/I-O models"); 6 (8%) use epidemiological-economic agent-based models (ABMs) ("epi-econ-ABMs"); 4 combine epidemiological CGE/I-O and compartmental-utility-maximization approaches ("mixed" techniques); and the remaining 19 studies (24%) were grouped under "other."

The epidemiological modeling approaches used in each model category are given in the sections below. Briefly, agent- or population-based approaches are generally used. ABMs (including network-based models) simulate the behavior of individual agents (eg, humans, households) depending on their characteristics (eg, age, health). In turn, individuals' status (eg, health) depends on their behavior (eg, infective contact) and past status. Aggregated (eg, COVID prevalence) and disaggregated outcomes emerge from individual agents' behaviors.[17,18] Meanwhile, in population-based models, population-/group-level outcomes are imposed through top-down equations: "well-mixed" population groups ("compartments"), for example, age groups, interact based on rules described through contact matrices. This translates into differential equations that simulate changes in aggregated health outcomes.

Compartmental-utility-maximization models

Compartmental-utility-maximization, often called "SIR-macro" in the literature,[19] is defined as models where a population-based epidemiological element simulates people (or households) moving between compartments representing transmission status (eg, susceptible, infectious, recovered) that is integrated with a macroeconomic model whereby an average household of a given category (eg, wealthier group) optimizes its utility (which depends on work hours/consumption) while respecting household budget constraints. Households may further differ by, for example, job type or wealth. In a pandemic context, labor and consumption can be associated with increased disease risk, and disease decreases household utility (through, eg, decreased consumption), hence shifting households' optimal economic activity level. As the pandemic evolves, utility maximizing households continuously adjust behaviors through voluntary measures. Aggregating model estimates for "average household" archetypes within each category produces country-level aggregates of household labor and consumption The models may also reflect government restrictions (eg, lockdown as a constraint or tax on economic activity) and social transfers and integrate assumptions around investment/production, enabling comparisons between a range of interventions or computation of further macroeconomic indicators. The models minimally require country economic, demographic, and labor data. Some also use mobility data, the share of tele-workable jobs,[20] and contact matrices, as do some of each of the other model types. We chose the "compartmental-utility-maximization" label for these models because the "SIR-macro" label is imprecise on the macroeconomic approach and some models do not use an SIR (susceptible, infected, recovered or removed) structure but SIS (susceptible, infected, susceptible) or SEIR (susceptible, exposed, infected, recovered or removed) approaches.

Stylized epidemiological-macroeconomic models

This category is defined as studies that link any epidemiological model projecting pandemic health consequences over time with an estimate of total GDP impact (by assumption, past observation or expert opinion) without describing intermediate mechanisms. The epidemiological models are mostly (80%) population-based models. Others include an ABM,[21] projections based on geographic/temporal regression,[22] and proportional multistate lifetables.[23,24] Some models assume GDP loss is proportional to the share of population unable to work or to lockdown intensity measured, for example, by the COVID-19 stringency index.[25] Some studies inform projections using experts' opinion[24] or past lockdown data.[26] This group of models did not have a specific preexisting name, so we created the "stylized" label.

Epi-CGE/I-O models

We defined this category by grouping CGE and I-O models linked to epidemiological models.[27-32] The macroeconomic segment of all these models uses a tabular representation of economic flows (I-O matrices for I-O models, social accounting matrices for CGE models) reflecting the relations among economic stakeholders. I-O matrices describe how the inputs/outputs of different industrial sectors relate to the outputs/inputs of other sectors and to final demand. These relations are represented in matrix format, with columns of expenditures in one area (eg, commodities in 1 sector/subsector) related to lines detailing incomes in another area. Social accounting matrices provide a broader representation of the economy as they describe all economic transactions and transfers (including, eg, from the government). To simulate an economy's response to, for example, COVID-related closures, data on responses to change (eg, elasticities) are included. Such models can help model economic interdependencies,[33-36] for example, international or cross-sectoral economic linkages.[37] They can be disaggregated by household type and assess distributional and poverty impacts.[36-38] The macroeconomic element of epi-CGE/I-O models use the outcomes of any epidemiological or individual- or population-based model. For example, the epidemiological model provides disease-related absences and/or healthcare costs that feed into the macroeconomic segment alongside policy-related drivers such as lockdowns. Models in this category tend to focus on medium- and long-term economic changes. CGEs are equilibrium models that do not provide information on the path toward equilibrium, typically computing the impact of economic shocks over one or multiple years.[39] CGE and I-O models require online databases with broad, high-resolution coverage (eg, GTAP[40]) and are often used by the World Bank and International Monetary Fund for developing countries.[39]

Epi-econ-ABMs

We define as "epi-econ-ABMs" models that simulate both health and economic behaviors using agent-based modeling principles. These use agents (eg, individuals, households, firms, governments) with unique, individually distinguishing properties (eg, income, age) that interact following decision-making rules. In self-titled ABMs (also called individual-based models in some disciplines[41]) and multiagent system models,[42] agents' interactions are generally represented within a spatial environment.[43] Meanwhile, in network-based models, agents' interactions are represented over social networks, for example, of friends or colleagues.[44,45] Epi-econ-ABMs[46-51] describe both disease-related and economic interactions of boundedly rationale agents[52] and related outcomes (eg, social interactions, working, shopping, job searching) within an integrated framework. Simulated individual health status and individual, firm, or government income/spending are aggregated in a "bottom-up" approach to produce macrohealth and economic indicators. The models can be computationally intensive and require data on agents' locations, characteristics, and interactions.[18] Epidemiological ABMs that input into a separate economic model were excluded from this category.

Mixed and other models

"Mixed" articles are those mixing the abovementioned techniques to the exclusion of other elements and include 4 articles[53-56] combining compartmental-utility-maximization and CGE/I-O techniques. Other articles are in the "other" category including, for example, dynamic general equilibrium models,[57-59] semi-structural models,[60-62] epidemiological-SIR models combined with search-matching models representing frictions in the labor market,[63,64] and models in which reopening is dynamically driven by both the epidemiological and economic situations and trends.[65]

Scope

COVID-19 interventions/responses

None of the stylized models considers fiscal packages (stimulus packages, unemployment insurance, or social transfers). Compartmental-utility-maximization and mixed models most often represent pandemic-related voluntary behavior changes. One model in 5 simulates multiple disease mitigation interventions (Fig. 2). Policy implementation may face administrative, logistical, and compliance challenges; however, implementation challenges beyond noncompliance to lockdowns were not explicitly modeled.

Model outcomes, disaggregation, and representation of inequalities/disparities

All reviewed models produce both health (eg, cases/deaths) and economic outcomes. Stylized models have limited variety in economic outcomes. Epi-econ-ABMs and labor market models (within the "other" category) most often simulate employment (as opposed to just working hours). Compartmental-utility-maximization models more commonly assess inequalities/disparities in epidemiological and/or economic outcomes (Fig. 3). Finally, the only model that assesses COVID-19's poverty impacts is an epi-CGE model,[29] which also assesses equity and food insecurity; 16% of studies simulate additional outcomes, for example, government deficit, wage changes, or firm default.

Disaggregated models can help simulate inequities in outcomes and/or assess aggregates with greater precision. Some age-structured models ignore younger subpopulations.[66-69] In integrated models (epi-econ-ABMs and compartmental-utility-maximization models), because there is only one model, disaggregation concerns both the economic and epidemiological elements equally, which is not the case for stylized and epi-CGE/I-O models: this can hamper analysis of the pandemic's combined health and economic impacts on specific groups (Table 1).

Timeframe

A minority of articles (14%), mostly epi-econ agent based, "other," and "mixed," discussed the path to economic recovery beyond the next wave and immediate impacts of lockdowns, highlighting the long-run impacts of international linkages through export demand or Official Development Aid,[53,54,57] the impact of government income and spending choices on economic recovery,[50,57] job loss, firm bankruptcy, and firm reopening. None assessed human capital losses due to school closures, despite their long-term productivity/growth impacts.[70]

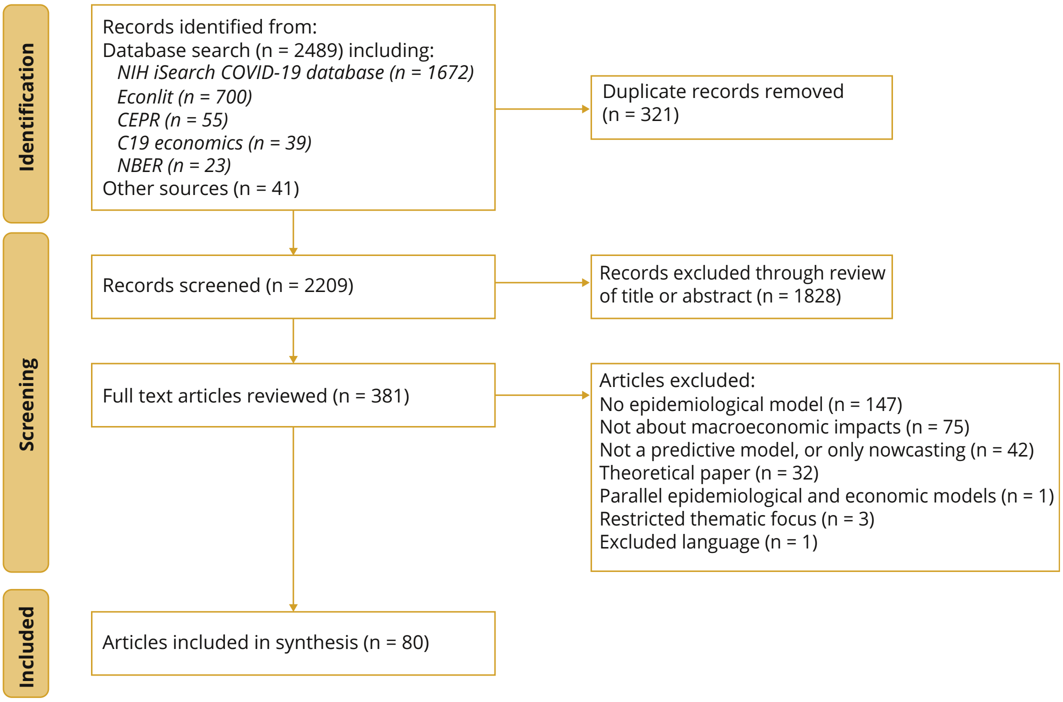
Epidemiological and health impacts of the economic downturn

Integrated models (compartmental-utility-maximization and epi-econ-ABMs) simulate the immediate health impacts of economic considerations through the representation of behaviors in reaction to the risk of disease and economic loss. There are also long-term health effects of macroeconomic losses (eg, on malnutrition or access to healthcare). Four models[23,24,67,71] consider feedback loops from macroeconomic losses (or lockdown policies) to health, 3 of which are "stylized" models, whereas one belongs to the "other" category. They emphasized lockdown-associated mental health and road traffic accident impacts and did not consider how pandemic-driven poverty may increase chronic illness prevalence[72] or delay childhood vaccines.[73,74]

Country of focus

Using the World Bank's country income classification, 85% of studies focus on high-income countries and only 24% on low- and middle-income countries (LMICs), yet approximately half of total GDP impact and 80% of global COVID-19 deaths are estimated to have occurred in LMICs, mostly middle-income countries (70% of total deaths).[1,75] Notably, 43% of epi-CGEs/I-Os, 23% of

Figure 1. Study selection process. PRISMA flowchart of the study selection process.



PRISMA indicates Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

compartmental-utility-maximization models, 17% of epi-econ-ABMs, and 6% of stylized models were applied to LMICs.

Calibration, Validation, and Sensitivity Analysis

Models should normally be calibrated or validated against empirical data and analyze sensitivity to parameter uncertainty.[76-78] This should include data from 2020 onward. Calibration/validation/sensitivity analysis by model category is presented in Table 2. Calibration/validation and sensitivity analyses are more common among later and peer-reviewed articles and were used more extensively for epidemiological than economics modeling. Of 11 articles addressing poverty/disparity impacts, only 3 calibrate/validate them.

Figure 2. COVID-19 responses modeled by model type. Share of studies modeling specific COVID policies (lockdown; testing/tracing, masks, sanitary protocols, treatment and/or vaccines; fiscal packages and social support policies) and COVID-related voluntary behavior change within all models and each model type.

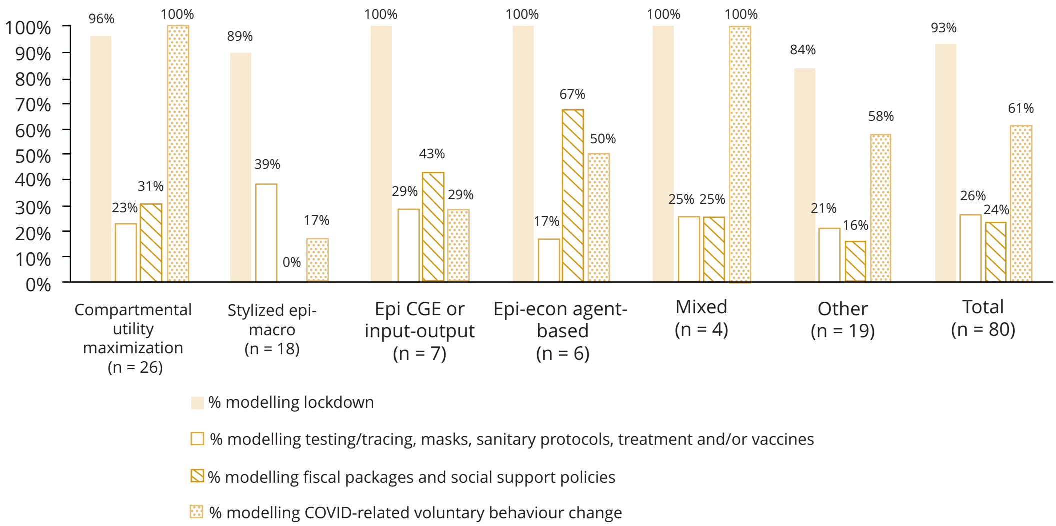


Figure 3. Simulated outcomes by model type. Share of studies simulating changes in labor hours and/or employment (ie, job loss) or disparities in simulated outcomes for different population groups, within all models and each model type.

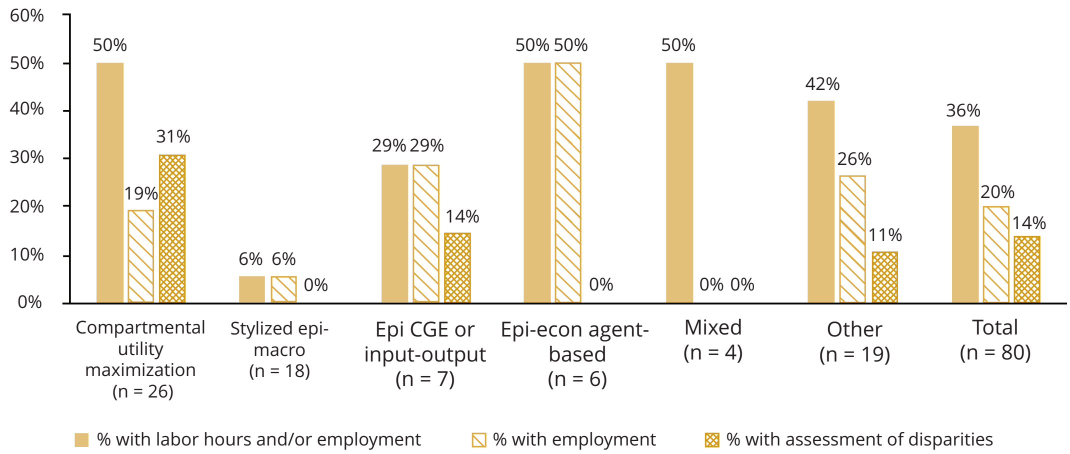


Table 1. Model disaggregation by stratifying variable (percentage of model in each category).

Stratifying variables and levels of disaggregation	Compartmental-utility-maximization	Stylized epidemiological-macroeconomic	Epi-CGE or input-output	Epi-econ-ABMs	Mixed	Other	All models
Age							
Any disaggregation	23	50	71	100	0	63	48
In both epidemiological and economic models	23	0	29	100	0	42	28
Epidemiological and economic models use at least 4 age categories	0	0	14	50	0	21	10
Employment sector or job type							
Any disaggregation	23	11	100	100	100	47	43
In both epidemiological and economic models	23	6	57	100	100	37	35
Epidemiological and economic models use at least 5 sectors	4	0	57	0	50	21	14
Location							
Any disaggregation (including by country)	12	22	43	83*	100	11	26
Any disaggregation (subnational)	8	22	43	83	0	5	19
In both epidemiological and economic models (subnational)	8	11	14	83	0	5	14
Socioeconomic							
Any disaggregation	15	0	14	83	0	16	16
In both epidemiological and economic models	15	0	0	83	0	5	13
No disaggregation of any type	46	33	0	0	0	16	26
Model disaggregated solely by age and/or country	8	33	0	0	0	21	15

Note. All values in %.
epi-CGE indicates epidemiological computational general equilibrium; epi-econ-ABM, epidemiological-economic agent-based model.
*Network-based models in this review were not spatially disaggregated

Table 2. Calibration/validation and sensitivity analysis.

Model category (number of articles)	Share calibrating or validating epidemiological outcomes, %	Share calibrating or validating macroeconomic outcomes, %	Share with sensitivity analysis (in brackets: of both health and macroeconomic outcomes), %
Compartmental-utility-maximization (26)	58	42	50 (19)
Stylized epidemiological-macroeconomic (18)	56	6	72 (21)
Epi-CGE or input-output (7)	71	28	71 (29)
Epi-econ-ABMs (6)	100	17	17 (17)
Mixed methods (4)	25	50	75 (0)
Other (19)	63	32	58 (26)
Total (80)	61	29	58 (21)
Peer-reviewed articles/models (52)	65	29	67 (27)
Gray literature (28)	53	29	39 (11)

epi-CGE indicates epidemiological computational general equilibrium; epi-econ-ABM, epidemiological-economic agent-based model.

Strengths, Limitations, and Opportunities of Modeling Approaches

We identified 4 main approaches to epidemiological-macroeconomic modeling of COVID-19 with different strengths, weaknesses, and uses (see Table 3[2–69,71,79–119]). Understanding these can help modelers identify the best approaches to answer their specific policy questions.

Compartmental-utility-maximization models provide a theoretical foundation for voluntary distancing in response to both economic and health concerns, making them most attractive to simulate such behaviors (Fig. 2). They are often used to model intergroup disparities (Fig. 3) and may integrate groups with different pre-pandemic health status,[79] age,[68,80] comorbidities,[81] contact levels,[81-83] job essentiality/tele-workability,[68,80-84] employment sector,[80,81,83,85] location,[86] and income/wealth.[68,81,83] They commonly assume full rationality and "perfect foresight" of households,[19,80,81,84-98,102,132] approximately one-third[19,83,85,89,91,95,99] represent the economy as producing just final goods, and roughly half represent lockdowns as a tax on production or consumption[19,68,84,86,88-91,96-98,102] instead of directly modeling constraints on agents' behavior. Therefore, efforts to fully validate these models,[68,81,89-91] including measures of disparity,[81] may be particularly important to assess their adequacy to inform decision making.

Stylized models estimate changes in GDP without describing intermediate causal mechanisms or feedback loops. This can expedite construction of simple macroeconomic models attractive to health stakeholders, based on any type of epidemiological model, and providing rough estimates of COVID-19-related policies' short-term impact on overall GDP. These models sometimes focus on the computation of incremental cost-effectiveness ratios or net monetary benefits,[105,106] adding a measure of GDP losses associated with the disease and/or interventions. However, because of the simplicity of their macroeconomic projections, they did not simulate fiscal packages and generally do not disaggregate macroeconomic impacts (Table 1). They often assume GDP change is linear with labor decline or containment level/duration,[22,66,67,107-114,133] but the only article in this category with a calibrated economic model[26] found that, for the United Kingdom's 2020 economy, a quadratic relationship fit data best. Therefore, using empirical country-specific time-series to fit GDP response to lockdown intensity may improve these models.

Epi-CGE/I-O models are well suited to assess complex economic impacts, including cross-sectoral and cross-country interlinkages.[33-37] Often used to model the indirect impact on sectoral output of COVID-related closures in other sectors, they were also used to assess country-level impacts of the 2020-2021 global economic downturn through, for example, changes in export demand or remittances.[29,30] As models that are generally "linked" (6 of 7 models), they can rely on any type of disease model, but few integrate feedbacks from economics to health. They were more often used to model the pandemic's impact in LMICs than other model types, likely supported by the practices and databases developed by institutions such as the World Bank and International Monetary Fund.[39] Finally, the only model in this review estimating the pandemic's poverty impacts[29] is an epi-CGE model. If linked with well-disaggregated epidemiological models showing health risk differentials across population groups, such a model could be well suited to comprehensively represent cumulative health and economic impacts of COVID-19 on individual households and resulting poverty changes.

Epi-econ-ABMs are flexible models that allow for the representation of complex health and economic behaviors from a variety of agents simultaneously. Therefore, they are well suited to represent fiscal packages (Fig. 2) and labor market processes/frictions and their consequences on unemployment (Fig. 3) or economic recovery and feedbacks loops between economics and health. Furthermore, because they use heterogeneous agents, these models represent the most disaggregated approach (Table 1) and could in principle be a good tool to explore policy impacts on inequalities[134] even though the models identified through this review have not, in practice, focused on equity. They can identify how specific neighborhoods (if spatially explicit) and economic sectors or nodes within interaction networks (if network based) are affected by COVID-19, contribute to its spread, or affect the economy under different policy scenarios, therefore helping

Table 3. Model approaches, strengths/limitations, uses, and opportunities.

Model type	n	Technical characteristics	Strengths	Limitations	Use and opportunities
Compartmental-utility-maximization models[19,68,79-104]	26	Integrated epidemiological and economic models Feedback between the economy and health through household maximization of their utility function One or a few groups of households that are considered as well mixed for the purpose of epidemiological modeling and identical and fully rationale for the purpose of economic modeling	Voluntary behaviors and impacts on both health and economic outcomes (including feedback loops), equity impacts	Sometimes simplified representation of the economy and policies, eg, single good, lockdown as a tax on economic activity Typically assumes agents with perfect foresight despite a context of high uncertainty	Voluntary behaviors, representation of stratified populations, and broad inequality impacts Inequality has generally been assessed by contrasting average outcomes across key population groups depending on, eg, age, job contact rates, tele-workability and essentiality, or wealth/income. There may be an opportunity to more systematically calibrate/validate all model outputs, including measures of disparities.
Stylized epidemiological-macroeconomic models[21–24,26,66,67,69,105-115]	18	Linked epidemiological and economic models Dynamic epidemiological model linked to stylized economic assumptions, experts' opinion, and/or previous economic impact Any type of epidemiological model (compartmental or agent based) with any disaggregation may be used. Economic estimates focus on total GDP	Simple way of linking health and economics; provides rough estimates of macroeconomic impacts; can use type of epidemiological model	Lack of disaggregation or modeling of fiscal packages or feedback loops from economics to health A linear formulation (most common formulation) may be an oversimplification.	Overall GDP changes associated with any epidemiological model There should be an opportunity for more systematic calibration/validation of the shape of the response of GDP to lockdown stringency.
Epi-CGE/I-O models[27-32,116,117]	6	Generally (6/7 models) linked epidemiological and economic models. Any type of epidemiological model (compartmental or agent-based) with any disaggregation may be used. Generally comparative-static economic model, comparing economic outcomes at a start and endpoint without description of intermediate states Many sectors, multiple population subgroups	Analysis of the ripple effects of COVID-19 through different sectors, agents, and the market; poverty impacts Can use any type of epidemiological model	Complex models requiring detailed economic data sets Not built to easily reflect feedbacks from the economics to health	Model of detailed COVID-19-related macroeconomic impacts accounting for interlinkages within the economy and including the impact of exogenous changes on the national economy Sector-specific disaggregation in these models is an asset to inform sectoral ministries. CGE models may provide an opportunity, if combined with well-disaggregated epidemiological models, for an in-depth assessment of COVID-19's cumulative health and economic impacts.

continued on next page

Table 3. Continued

Model type	n	Technical characteristics	Strengths	Limitations	Use and opportunities
Epi-econ-ABMs[46-51,118,119]	6	Integrated epidemiological and economic models Epidemiological and economic outcomes emerge from individual-level behaviors of different agents (eg, individuals, firms, banks, the government) interacting within a network and/or spatial structure. Individual behaviors may be specified simply or using utility functions and is boundedly rationale. These models allow for high granularity and flexibility (many actors/ processes/timescales may be represented).	Disaggregation, representation of equity issues, and/or targeted policies Can provide detailed models of specific regions or cities if spatially explicit Can simulate a broad range of policies, behaviors, and economic-health feedbacks	When representing states or countries, may require high computing power or the representation of large areas at a smaller scale for computational tractability	Simulation of various policies, including fiscal packages, and outcomes including employment May be used to model complex behaviors (eg, labor market frictions) that influence the speed of economic recovery Identification of "smart" policies with optimum health and economic outcomes targeting social links (network-based models), sectors, or locations (spatially explicit models) with high disease spread potential and low economic contribution
Mixed[53-56] and other[57-65,71,120-131] models	24	Combined and/or relatively less common techniques	Varied	Varied	Mixed models may provide an opportunity to combine some of the strengths of multiple model techniques, eg, to represent international trade linkages between economies in the context of COVID.[2–54] In the "other" category, epi-labor market models[63,64] can help analyze labor market policies; adapted central bank models[60,61] present an opportunity to bring epidemiological consideration within the tools routinely used for economic policy making; "other models" may also be a good choice to assess the long-term recovery path after the end of the pandemic-related global health emergency.[57]

epi-CGE indicates epidemiological computational general equilibrium; epi-econ-ABM, epidemiological-economic agent-based model; GDP, gross domestic product; I-O, input-output.

identify "smart" policies.[46,49] Finally, because these models can be computationally demanding, many[46,49] have been applied to relatively small geographic regions, often[46,48-50] at a smaller scale.

Some articles mix several model types[53-56] to represent international linkages in the context of COVID-19, which may help combine the strengths of different approaches. However, some simplifications have been made: although an important strength of epi-CGE models is sectoral disaggregation,[55,56] models combining CGE and compartmental-utility-maximization approaches have aggregated sectors into 2 broad categories, suggesting that there might be a trade-off between complexity and tractability when attempting to combine multiple model types.

"Other" approaches can also provide interesting results, depending on the technique used, and can be a better fit than the 4 most common approaches for specific policy questions. For example, labor market models can help assess optimal government labor policies, including intergenerational equity concerns.[63] Furthermore, analyses of long-run recovery were highly represented in "other" and "mixed" models.[53,54,57,61]

Discussion

Areas for Further Development

Epidemiological-macroeconomic models provide unique policy insights: they allow for joint analysis of economic and health impacts of policy choices.[66,69] Good data are key: earlier models, particularly economic components, were less calibrated/validated; in emerging pandemics, data scarcity is common, and economic impact data have lagged behind health data. Ensuring the rapid production and release of economic indicators during pandemics could strengthen epidemiological-macroeconomic modeling.

In integrated models, behavioral feedback loops create impacts that are substantially different from those obtained through epidemiological or macroeconomic models alone.[19,68,98] These models would benefit from closer collaboration between epidemiologists and economists: for example, linking epidemiological and macroeconomic models to assess cumulative health and economic impacts on different groups requires agreement on stratifying features to ensure coherence/relevance from health and economic perspectives. Unfortunately, the epidemiological and economic components of these models often stratify their populations using different criteria (Table 1).

Input from and communication with relevant policy makers and key advising bodies to understand their needs and identify models that may best address them would also be essential to use relevant epidemiological-macroeconomic models in decision making. As shown by the UK experience, confidence in epidemiological-macroeconomic modeling is often limited, potentially driving counterproductive decisions.[14]

In addition, relatively few combined models incorporate vaccination, although the economic implications of vaccination may have been analyzed using other types of models, for example, cost-effectiveness analyses.[135-138] It is also plausible that earlier models did not address vaccines that were not yet available. Other areas deserving greater emphasis are detailed below.

Modeling in LMICs

Expanded coverage of LMICs (currently 24% of studies) requires more than porting techniques from high-income settings.[87,97,98] LMICs have very different age structures and contact patterns, so many models would need to be age disaggregated (53% of all reviewed models and 69% of LMIC models have no age structure) using context-specific contact matrices.[139] LMIC specificities could also be captured by models that account for their comorbidity levels.[98,140,141] Calibration approaches need to account for differences in health outcome data quality and other pertinent data (eg, stratified serology). Models could also consider key economic specificities of LMICs, such as typical individuals being closer to subsistence level and fewer tele-workable and more informal jobs, limiting leeway to socially distance without losing income critical to meet basic needs. This may be modeled by introducing a subsistence consumption level[30,81,87,98] and/or by assuming unskilled workers have no savings,[29] as done in certain reviewed models. Finally, LMIC governments tend to have less fiscal capacity to mitigate pandemic impacts.[57,84] Therefore, identifying fiscal/support measures within the means of LMIC governments[142] is important.

Projecting impacts on disparities and poverty

Another key issue identified in this review is the limited number of models used to analyze impacts on disparities and/or poverty, with few[31,81] validating simulations using real-world data on sectoral or income differences in output, spending, or employment. Inequity stemming from policy implementation challenges is an evidence gap. Differences in acceptability and access to treatment, vaccine supply,[143] and health promotion have largely been ignored despite their importance.[144]

Finally, only one of the identified studies[29] analyzed pandemic impacts on poverty metrics, including labor loss through disease (using figures disaggregated by age and country), sector-specific closures, and exogenous changes in, for example, oil prices and export demand. Combining a well-disaggregated epidemiological model with a similarly disaggregated economic model could help assess the cumulative health and economic impacts of COVID-19 on vulnerable individuals. The impacts of country-level (eg, price changes) and group-level (eg, closure of specific sectors during lockdown) macroeconomic changes on households should be combined with household-specific costs (eg, out-of-pocket spending for COVID-19-related hospitalization). Such a model would give a comprehensive picture of the risks of poverty and/or catastrophic spending that households face. To inform such a model, the World Bank high-frequency COVID-19 surveys,[145] World Health Organization's data on out-of-pocket spending,[146] World Health Organization/World Bank reports on healthcare coverage,[147,148] and country-specific reports on the burden of COVID-19 on households (eg, in the United States[149] or Kerala[150]) may be mobilized.

Long-term health and societal impacts of COVID-19

This review identified few epidemiological-macroeconomic models addressing long-term health and economic impacts. Only some[23,24,67,71] have attempted to integrate the health impacts of the economic crisis even though some information is available in Banks et al.[72] Efforts to assess the speed/shape of economic recovery[48,50,53,54,57,61] in light of changes in the pandemic may require updating. Short horizon models also fail to capture current changes that are correlated with longer-term economic trajectories, for example, educational disruptions, particularly in low-income countries.[70,151] Developing a model that accounts for these impacts may be difficult, but they should be considered during policy decisions.

Finally, there are concerns that COVID-like pandemics may become increasingly common.[152] Successive pandemics may reshape countries' economies, affecting the attractivity of certain professions, return to entrepreneurship in certain sectors (eg, restaurants), or viability of firms of certain sizes. These considerations could potentially be assessed with estimates of frequency, health burden, and pandemic response[153] and associated strain on different business sectors and sizes. For example, business reopening protocols can put a disproportionate strain on small firms in the Chilean context.[120] Such analyses may be complex but critical to anticipate indirect changes to employment and employer demographics.

Limitations of This Review

We excluded 32 "theoretical" models (see Appendix 2 in Supplemental Materials found at https://doi.org/10.1016/j.jval.2023.10.008), but note that, in the early stages of pandemics, economic models that explore relatively "theoretical" scenarios (such as McKibbin and Fernando, 2021[154]) may nevertheless be of high policy value. Among included articles, earlier models, particularly earlier economic models, are less calibrated or validated: in an emerging pandemic, data scarcity is common, and economic impact data have lagged behind health data.

COVID-19 modeling is evolving quickly and relevant work published/preprinted after mid-January 2022 was not included. With the end of the emergency phase of the pandemic, most countries have reduced reliance on lockdowns, whereas many individuals have reduced spontaneous physical distancing measures.[155,156] This may have reduced the drive to use epidemiological-macroeconomic models. Recent areas of concern include the long-term macroeconomic consequences of COVID (eg, inflation, supply chain disruptions, labor market changes) and vaccination/treatment cost-effectiveness. This suggests epidemiological-macroeconomic modeling may have moved toward a greater reliance on epi-CGE/I-O, "stylized," and "other" models.

We did not examine other high impact diseases such as influenza or Ebola and excluded short-term predictions and associated techniques (eg, nowcasting). Models using epidemiological-microeconomic approaches were also missed; hence, our conclusions do not stand for all epidemiological-economic modeling of COVID-19. Finally, good models do not necessarily inform policies, but we did not attempt to review the institutional context within which the models were applied.

Conclusion

This review describes model types, strengths, limitations, and uses in articles combining COVID-19 epidemiological and macroeconomic modeling, hoping to inform future modeling. It highlights the need for better equity and poverty simulations, application to developing countries, and improved data and modeling.

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