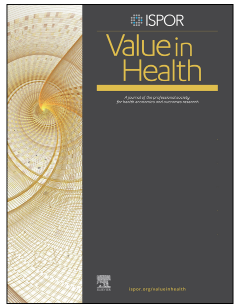

A scoping review & taxonomy of epidemiological-macroeconomic models of COVID-19

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Precis:
Four main epidemiological-macroeconomic COVID modelling techniques are commonly used to inform policymaking. Gaps in simulating equity and poverty and modelling in developing countries remain.

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Highlights section:

- Formal processes in many countries split epidemiological and macroeconomic modelling informing policy responses to shocks such as COVID, potentially missing feedback loops.
- Our scoping review of epidemiological-macroeconomic modelling techniques identified four main approaches: epidemiological models with compartmental-utility-maximization models, which provide a theoretical representation of voluntary behavior change, stylized macroeconomic projections producing simple estimates of overall GDP impacts, epidemiological models linked to computable general equilibrium or input-output models, often used to simulate sector-specific impacts, and epidemiologic-economic individual-based models that have been used to model, among others, labor market friction and the implementation of fiscal packages.
- There are important remaining gaps in terms of equity and poverty simulations, consideration of long-run health and economic trends, and modelling for low- and middle-income country contexts.

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 paper reviews models combining epidemiological and macroeconomic projections to enable policymakers to consider both macroeconomic and health objectives.

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

Results. We found 80 papers modelling 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 four categories: compartmental-utility-maximization models, epidemiological models with stylized macroeconomic projections, epidemiological models linked to computable general equilibrium or input-output models, and epi-econ-ABMs. 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 modelling needs. Priorities for future modelling 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. epidemiological-macroeconomic models; COVID-19; scoping review

1. Introduction

The COVID-19 pandemic caused around 13 million deaths[1] in 2020-21 and strained many health systems, lowering care quality and availability[2,3]. COVID-19 and consequent policy responses drove around $6 trillion loss in world 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 modelling were used to advocate for US response to the emergency during Senate hearings on Ebola[11]. This can however be challenging, particularly if trust/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 modelling. In the UK, epidemiological models are assessed by a pandemic committee (SPI-M), while macroeconomic modelling 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 modelling in the UK 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 modelling, hence helping improve communication and use of such models to inform policy in future pandemics.

2. Methods

This scoping review uses 2020 PRISMA guidelines (see S1) and the extension for Scoping Reviews Checklist[16]. Given the rapid evolution in COVID-19 research, it includes preprints/working papers. We searched systematically the NIH iSearch COVID-19 portfolio, Econlit, NBER, CPER's COVID-19 economics and C19-economics up to 14-Jan-2022.

We identified titles/abstracts using COVID-19, modelling, and macroeconomics-related terms (see S2), then reviewed these to identify macroeconomic models using epidemiological model results (called "linked" models) or integrated alongside epidemiological modelling within one single model. Both types are called "epidemiological-macroeconomic models" hereafter.

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

See S2 for Methodological details are, S3 for review protocol.

3. Results

3.1. Study selection

We included 80 papers (S4 lists all reviewed papers, S5 selected papers), 52 were published by 15-Jun-2023.

Figure 1: Study selection process

3.2. Modelling approaches

Four main modelling 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'); six (8%) use economic-epidemiologic agent-based models ('econ-epi-ABMs'); four combine epidemiological CGE/I-O and compartmental-utility-maximization approaches ('mixed' techniques); and the remaining 19 studies (24%) were grouped under 'other'.

The epidemiological modelling approaches used in each model category are given in the sections below. Briefly, agent- or population-based approaches are generally used. agent-based models (including network-based models) simulate the behavior of individual agents (e.g., humans, households) depending on their characteristics (e.g., age, health). In turn, individuals' status (e.g., health) depends on their behavior (e.g., infective contact) and past status. Aggregate (e.g., 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.

3.2.1. 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 (e.g., Susceptible, Infectious, Recovered) that is integrated with a macroeconomic model whereby an average household of a given category (e.g., wealthier group) optimizes its utility (which depends on work hours/consumption) while respecting household budget constraints. Households may further differ by e.g., job type or wealth. In a pandemic context, labor and consumption can be associated with increased disease risk, and disease decreases household utility (through e.g., 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 (e.g., lockdown as a constraint or tax on economic activity) and social transfers, integrate assumptions around investment/production, enabling comparisons between a range of interventions and/or computation of further macro-economic 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 structure but SIS or SEIR approaches.

3.2.2. 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 agent-based model[21], projections based on geographic/temporal regression[22] and proportional multistate lifetables[23-25]. Some models assume GDP loss is proportional to the share of population unable to work or to lockdown intensity measured e.g., by the COVID-19 stringency index[26]. Some studies inform projections using experts' opinion[24] or past lockdown data[27]. This group of models did not have a specific pre-existing name, so we created the "stylized" label.

3.2.3. Epi-CGE/I-O models

We defined this category by grouping Computational General Equilibrium (CGE) and input-output (I-O) models linked to epidemiological models[28-33]. The macroeconomic segment of all these models uses a tabular representation of economic flows (I-O matrices for I-O models, Social Accounting Matrices (SAMs) for CGE models) reflecting the relations between 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 (e.g., commodities in one sector/subsector) related to lines detailing incomes in another area. SAMs provide a broader representation of the economy as they describe all economic transactions and transfers (including e.g., from the government). To simulate an economy's response to e.g., COVID-related closures, data on responses to change (e.g., elasticities) are included. Such models can help model economic interdependencies[34-37] e.g., international or cross-sectoral economic linkages[38]. They can be disaggregated by household type and assess distributional and poverty impacts[37-39]. The macroeconomic element of epi-CGE/I-O models uses the outcomes of any epidemiological, individual- or population-based model. The epidemiological model provides, for example, 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[40]. CGE and input-output models require online databases with broad, high resolution coverage (e.g., GTAP[41]) and are often used by the World Bank and International Monetary Fund (IMF) for developing countries[40].

3.2.4. Epi-econ-ABMs

We define as "epi-econ-ABMs" models that simulate both health and economic behaviors using agent-based modelling principles. These use agents (e.g., individuals, households, firms, governments) with unique, individually distinguishing properties (e.g., income, age) that interact following decision-making rules. In self-titled agent-based models (also called individual-based models in some disciplines[42]) and multi-agent system models[43], agents' interactions are generally represented within a spatial environment[44]. Meanwhile, in network-based models, agents' interactions are represented over social networks e.g., of friends or colleagues[45,46]. Epi-econ-ABMs[47-52] describe both disease-related and economic interactions of boundedly rationale agents[53] and related outcomes (e.g., 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 macro-health 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.

3.2.5. Mixed and other models

“Mixed” papers are those mixing the above techniques to the exclusion of other elements and include four papers[54-57] combining compartmental-utility-maximization and CGE/I-O techniques. Other papers are in the “Other” category including e.g., dynamic general equilibrium models[58-60], semi-structural models[61-63], epidemiological-SIR models combined with search-matching models representing frictions in the labor market[64,65] and models in which reopening is dynamically driven by both the epidemiological and economic situations and trends[66].

3.3. Scope

3.3.1. 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 five simulates multiple disease mitigation interventions (Figure 2). Policy implementation may face administrative, logistical and compliance challenges, however, implementation challenges beyond non-compliance to lockdowns were not explicitly modelled.

Figure 2: COVID-19 responses modelled by model type

3.3.2. Model outcomes, disaggregation and representation of inequalities/disparities

All reviewed models produce both health (e.g., 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 (Figure 3). Finally, the only model that assesses COVID-19's poverty impacts is an epi-CGE model[30], which also assesses equity and food insecurity. 16% of studies simulate additional outcomes e.g., government deficit, wage changes or firm default.

Figure 3: Simulated outcomes by model type

Disaggregated models can help simulate inequities in outcomes and/or assess aggregates with greater precision. Some age-structured models ignore younger subpopulations[67-70]. 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).

Table 1: Model disaggregation by stratifying variable

3.3.3. Timeframe

A minority (14%) of papers, 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[54,55,58], the impact of government income and spending choices on economic recovery[51,58], job loss, firm bankruptcy and firm reopening. None assessed human capital losses due to school closures, despite their long-term productivity/growth impacts[71].

3.3.4. 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 (e.g., on malnutrition or access to healthcare). Four models[23,24,68,72] consider feedback loops from macroeconomic losses (or lockdown policies) to health, three of which are 'stylized' models, while 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[73] or delay childhood vaccines[74,75].

3.3.5. 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, around 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)[1,76]. 43% of epi-CGEs/I-Os, 23% of compartmental-utility-maximization models, 17% of epi-econ-ABMs and 6% of stylized models were applied to LMICs.

3.4. Calibration, validation and sensitivity analysis

Models should normally be calibrated or validated against empirical data and analyze sensitivity to parameter uncertainty[77-79]. This should include data from 2020 onward. Table 2 summarizes calibration/validation/sensitivity analysis by model category. Calibration/validation and sensitivity analyses are more common among later and peer-reviewed papers, and were used more extensively for epidemiological than economics modelling. Of 11 papers addressing poverty/disparity impacts, only three calibrate/validate them.

Table 2: Calibration/validation and sensitivity analysis

3.5. Strengths, limitations and opportunities of modelling approaches

We identified four main approaches to epidemiological-macroeconomic modelling of COVID-19 with different strengths, weaknesses and uses (see Table 3). Understanding these can help modelers identify the best approach(es) to answer their specific policy question(s).

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 (Figure 2). They are often used to model inter-group disparities (Figure 3) and may integrate groups with different pre-pandemic health status[80], age[69,81], comorbidities[82], contact levels[82-84], job essentiality/tele-workability[69,81-85], employment sector[81,82,84,86], location[87] and income/wealth[69,82,84]. They commonly assume full rationality and ‘perfect foresight’ of households[19,81,82,85-101], approximately one third[19,84,86,90,92,98,102] represent the economy as producing just one/two final goods, and roughly half represent lockdowns as a tax on production or consumption[19,69,85,87,89-92,94,99-101] instead of directly modelling constraints on agents’ behavior. Efforts to fully validate these models[69,82,90-92], including measures of disparity[82], may therefore 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 macro-economic 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[103,104], 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[22,67,68,105-113], but the only paper in this category with a calibrated economic model[27] found that, for UK's 2020 economy, a quadratic relationship fit data best. Using empirical country-specific time-series to fit GDP response to lockdown intensity may therefore improve these models.

Epi-CGE/I-O models are well-suited to assess complex economic impacts, including cross-sectoral and cross-country interlinkages[34-38]. 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 2020/21 global economic downturn through e.g., changes in export demand or remittances[30,31]. As models that are generally "linked" (6/7 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 like the World Bank and IMF[40]. Finally, the only model in this review estimating the pandemic's poverty impacts[30] 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. They are therefore well-suited to represent fiscal packages (Figure 2) and labor market processes/frictions and their consequences on unemployment (Figure 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[114] even though the models identified through this review have not, in practice, focused on equity. They can identify how specific neighborhoods (if spatially explicit), economic sectors or nodes within interaction networks (if network-based) are affected by COVID-19, contribute to its spread, or impact the economy under different policy scenarios, therefore helping identify 'smart' policies[47,50]. Finally, because these models can be computationally demanding, many[47,50] have been applied to relatively small geographic regions, often[47,49-51] at a smaller scale.

Some papers mix several model types[54-57] to represent international linkages in the context of COVID-19, which may help combine the strengths of different approaches. Some simplifications have however been made: while an important strength of epi-CGE models is sectoral disaggregation[56,57], models combining CGE and compartmental-utility-maximization approaches have aggregated sectors into two 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 four most common approaches for specific policy questions. For example, labor market models can help assess optimal government labor policies, including intergenerational equity concerns[64]. Further, analyses of long-run recovery were highly represented in ‘other’ and ‘mixed’ models[54,55,58,62].

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

4. Discussion

4.1. Areas for further development

Epidemiological-macroeconomic models provide unique policy insights: they allow for joint analysis of economic and health impacts of policy choices[67,70]. Good data is key: earlier models, particularly economic components, were less calibrated/validated: in emerging pandemics, data scarcity is common, and economic impact data has lagged behind health data. Ensuring the rapid production and release of economic indicators during pandemics could strengthen epidemiological-macroeconomic modelling.

In integrated models, behavioral feedback loops create impacts that are substantially different from those obtained through epidemiological or macroeconomic models alone[19,69,101]. 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 modelling is often limited, potentially driving counter-productive decisions[14].

In addition, relatively few combined models incorporate vaccination, though the economic implications of vaccination may have been analyzed using other types of models e.g., cost-effectiveness analyses[115-118]. It is also plausible that earlier models did not address vaccines which were not yet available. Other areas deserving greater emphasis are detailed below.

4.1.1. Modelling in LMICs

Expanded coverage of LMICs (currently 24% of studies) requires more than porting techniques from high-income settings[88,100,101]. 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[119]. LMIC specificities could also be captured by models that account for their co-morbidity levels[101,120,121]. Calibration approaches need to account for differences in health outcome data quality, and other pertinent data (e.g., stratified serology). Models could also consider key economic specificities of LMICs, such as typical individuals being closer to subsistence level, fewer tele-workable and more informal jobs, limiting leeway to socially distance without losing income critical to meet basic needs. This may be modelled by introducing a subsistence consumption level[31,82,100,101] and/or by assuming unskilled workers have no savings[30], as done in certain reviewed models. Finally, LMIC governments tend to have less fiscal capacity to mitigate pandemic impacts[58,85]. Identifying fiscal/support measures within the means of LMIC governments[122] is therefore important.

4.1.2. 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[32,82] 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[123], and health promotion have largely been ignored despite their importance[124].

Finally, only one of the identified studies[30] 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 e.g., 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 (e.g., price changes) and group-level (e.g., closure of specific sectors during lockdown) macroeconomic changes on households should be combined with household-specific costs (e.g., 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[125], WHO's data on out-of-pocket spending[126], WHO/World Bank reports on healthcare coverage[127,128], and country-specific reports on the burden of COVID-19 on households (e.g. in the USA[129] or Kerala[130]) may be mobilized.

4.1.3. 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[23,24,68,72] have attempted to integrate the health impacts of the economic crisis even though some information is available in Banks et al.[73]. Efforts to assess the speed/shape of economic recovery[49,51,54,55,58,62] 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 e.g., educational disruptions, particularly in low-income countries[71,131]. 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[132]. Successive pandemics may reshape countries' economies, affecting the attractivity of certain professions, return to entrepreneurship in certain sectors (e.g., restaurants), or viability of firms of certain sizes. These considerations could potentially be assessed with estimates of frequency, health burden, and pandemic response[133] 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[134]. Such analyses may be complex but critical to anticipate indirect changes to employment and employer demographics.

4.2. Limitations of this review

We excluded 32 "theoretical" models (see S2), but note that in the early stages of pandemics, economic models that explore relatively "theoretical" scenarios (such as McKibbin et al., 2021[135]) may nevertheless be of high policy value. Among included papers, earlier models, particularly earlier economic models, are less calibrated or validated: in an emerging pandemic, data scarcity is common, and economic impact data has lagged behind health data.

COVID-19 modelling 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, while many individuals have reduced spontaneous physical distancing measures[136,137]. This may have reduced the drive to use epidemiological-macroeconomic models. Recent areas of concern include the long-term macroeconomic consequences of COVID (e.g., inflation, supply chain disruptions, labor market changes) and vaccination/treatment cost-effectiveness. This suggests epidemiological-macroeconomic modelling may have moved towards 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 (e.g., nowcasting). Models using epidemiological-microeconomic approaches were also missed, hence our conclusions do not stand for all epidemiological-economic modelling 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.

5. Conclusion

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

6. Supporting Information

S1 – Supporting information 1 – PRISMA checklist.

S2 – Supporting information 2 – Queries and definitions used for study identification and characteristic extraction.

S3 – Supporting information 3 – Study protocol.

S4 – Supporting information 4 – List of all identified studies with reasons for inclusion/exclusion.

S5 – Supporting information 5 – Characteristics of included models.

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7. Figures

Figure 1: Study selection process

PRISMA flow chart of the study selection process

Figure 2: COVID-19 responses modelled by model type

Share of studies modelling 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 (i.e., job loss) or disparities in simulated outcomes for different population groups, within all models and each model type.

1. **Tables**

Table 1: Model disaggregation by stratifying variable

	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 & economic models use at least four age categories	0%	0%	14%	50%	0%	21%	**10%**
Employment sector or job type							
Any disaggregation	23%	11%	100%	100%	100%	47%	**43%**

	Compartmental-utility-maximization	Stylized epidemiological-macroeconomic	Epi-CGE or input-output	Epi-econ-ABMs	Mixed	Other	All models
In both epidemiological and economic models	23%	6%	57%	100%	100 %	37%	**35%**
Epidemiological & economic models use at least five 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%**
Socio-economic							

	Compartmental-utility-maximization	Stylized epidemiological-macroeconomic	Epi-CGE or input-output	Epi-econ-ABMs	Mixed	Other	All models
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%**

* Network-based models in this review were not spatially disaggregated.

Table 2: Calibration/validation and sensitivity analysis

Model category (number of papers)	**% calibrating or validating epidemiological outcomes**	**% calibrating or validating macroeconomic outcomes**	**% 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 papers/models (52)	65%	29%	67% (27%)
grey literature (28)	53%	29%	39% (11%)

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

Model type	Nb	Technical characteristics	Strengths	Limitations	Use and opportunities
Compartmental–utility-maximization models[19,69,80-93,95,96,98-102,138-142]	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 modelling, and identical and fully rationale for the purpose of economic modelling.	Voluntary behaviors and impacts on both health and economic outcomes (including feedback loops), equity impacts.	Sometimes simplified representation of the economy and policies e.g., 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, for example, 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.

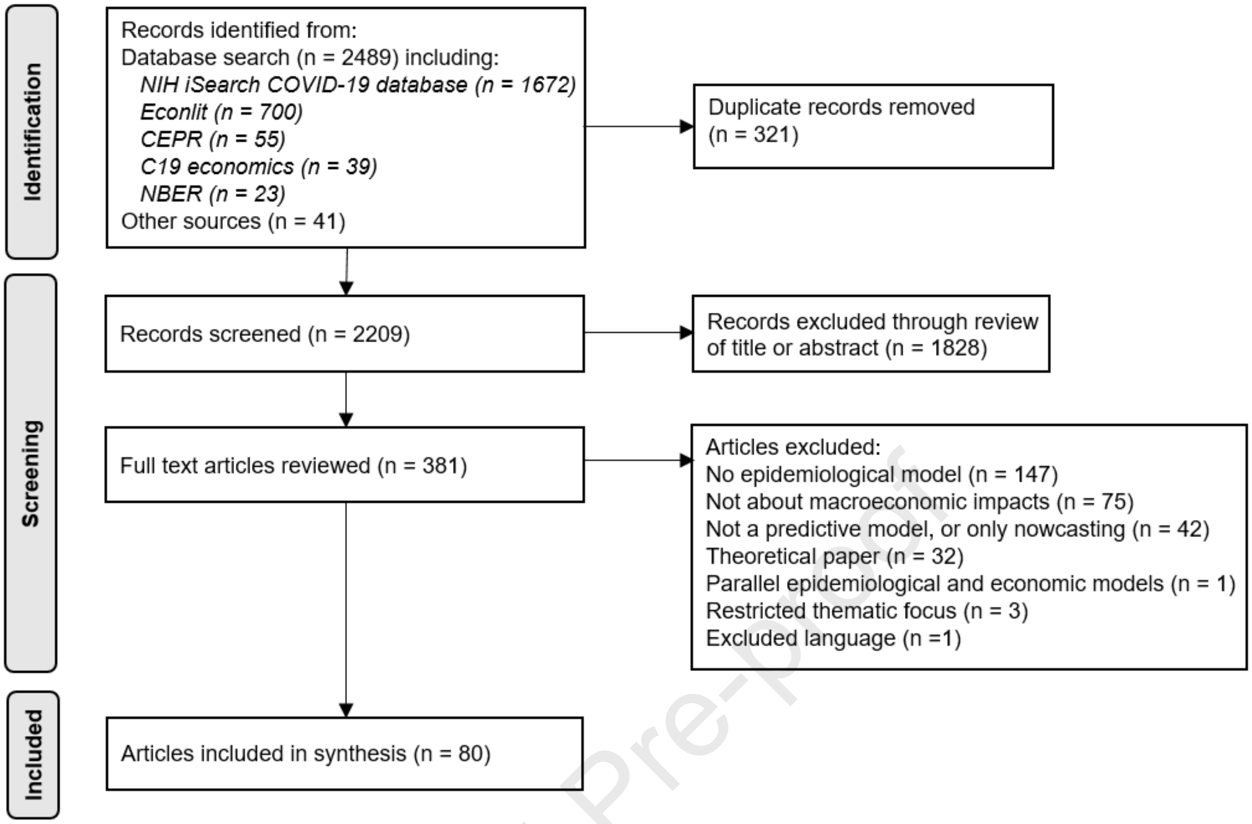
Stylized epidemiological-macroeconomic models[21-25,27,67,68,70,103-106,108-113,143]	18	Linked epidemiological and economic models. Dynamic epidemiological model linked to stylized economic assumptions, experts' opinion and/or prior economic impact. Any type of epidemiological model (compartmental or 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 modelling of fiscal packages or feedback loops from economics to health. A linear formulation (most common formulation) may be an over-simplification.	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[28-33,144,145]	6	Generally (6/7 models) linked epidemiological and economic models.	Analysis of the ripple effects of COVID-19	Complex models requiring detailed economic datasets. Not	Model of detailed COVID-19-related macroeconomic impacts accounting for interlinkages within the economy

		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 end point without description of intermediate states. Many sectors, multiple population subgroups.	through different sectors, agents and the market; poverty impacts. Can use any type of epidemiological model.	built to easily reflect feedbacks from the economics to health.	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.
Epi-econ-ABMs[47-52,146,147]	6	Integrated epidemiological and economic models. Epidemiological and economic outcomes emerge from	Disaggregation, representation of equity issues and/or targeted	When representing states or countries, may require high computing power or the	Simulation of various policies, including fiscal packages, and outcomes including employment. May be used to model complex

		individual-level behaviors of different agents (e.g., individuals, firms, banks, the government etc.) 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).	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.	representation of large areas at a smaller scale for computational tractability.	behaviors (e.g., 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[54-57] and other[58-66,72,134,148-159] 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, for example to represent international trade linkages between economies in the context of COVID[2-55]. In the "Other" category, epi-labor market models[64,65] can help analyze labor market policies; adapted central bank models[61,62] 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[58].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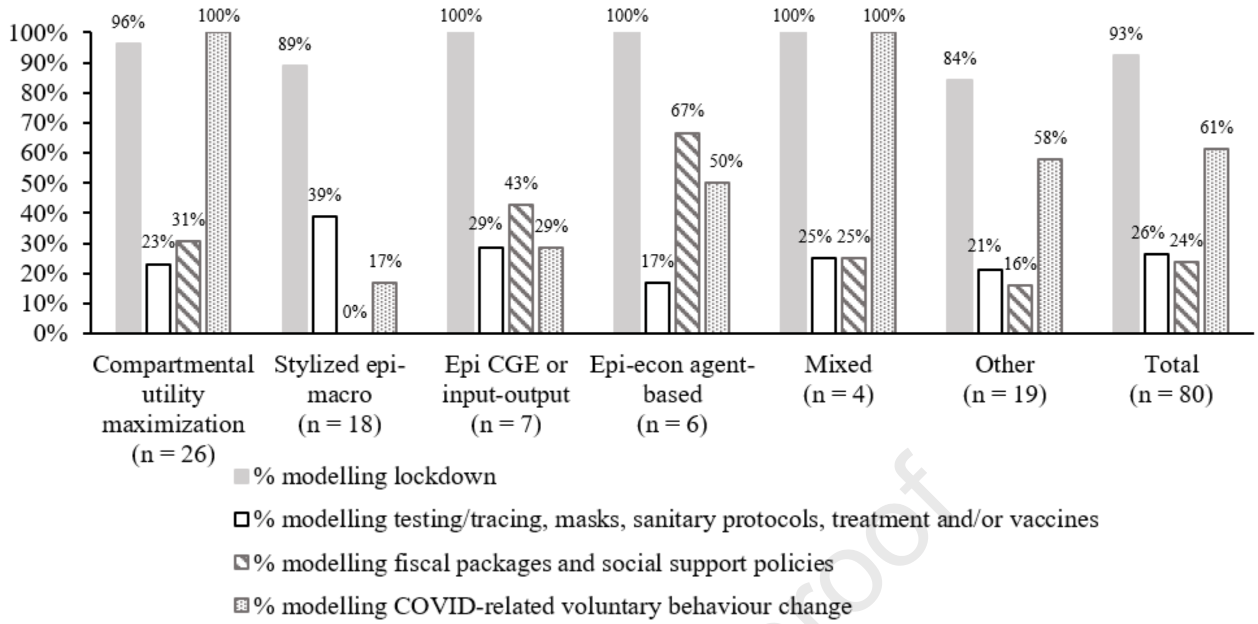
Database search (n = 2489) including:
NIH iSearch COVID-19 database (n = 1672)
Econlit (n = 700)
CEPR (n = 55)
C19 economics (n = 39)
NBER (n = 23)
Other sources (n = 41)
Duplicate records removed (n = 321)
Screening
Records screened (n = 2209)
Records excluded through review of title or abstract (n = 1828)
Full text articles reviewed (n = 381)
Articles excluded:
No epidemiological model (n = 147)
Not about macroeconomic impacts (n = 75)
Not a predictive model, or only nowcasting (n = 42)
Theoretical paper (n = 32)
Parallel epidemiological and economic models (n = 1)
Restricted thematic focus (n = 3)
Excluded language (n =1)
Included
Articles included in synthesis (n = 80)



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Epi CGE or input-output (n = 7)
Epi-econ agent-based (n = 6)
Mixed (n = 4)
Other (n = 19)
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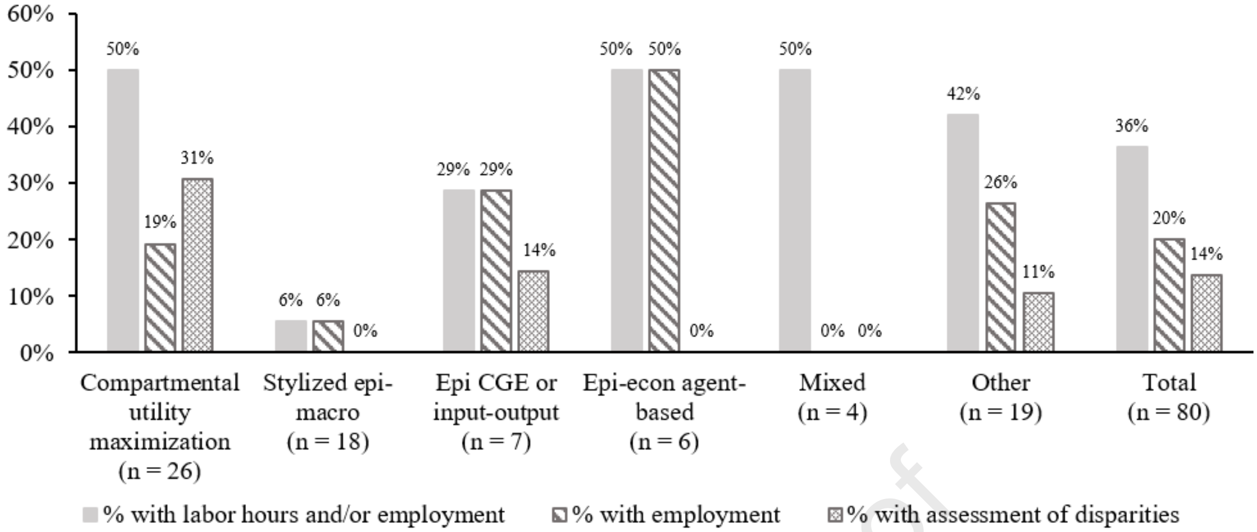
% modelling lockdown
% modelling testing/tracing, masks, sanitary protocols, treatment and/or vaccines
% modelling fiscal packages and social support policies
% modelling COVID-related voluntary behaviour change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Epi-econ agent-based (n = 6)
Mixed (n = 4)
Other (n = 19)
Total (n = 80)
% with labor hours and/or employment
% with employment
% with assessment of disparities