# AI in Combating the COVID-19 Pandemic

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*The SARS-CoV-2 virus, the COVID-19 disease, and the resulting pandemic have reshaped the entire world in an unprecedented manner. Massive efforts have been made by AI communities to combat the pandemic. What roles has AI played in tackling COVID-19? How has AI performed in the battle against COVID-19? Where are the gaps and opportunities? What lessons can we learn to enhance the ability of AI to battle future pandemics? These questions, despite being fundamental, are yet to be answered in full or systematically. They need to be addressed by AI communities as a priority despite the easing of the omicron infectiousness and threat. This article reviews these issues with reflections on global AI research and the literature on tackling COVID-19. It is envisaged that the demand and priority of developing "pandemic AI" will increase over time, with smart global epidemic early warning systems to be developed by a global collaborative AI effort.*

COVID-19 has reshaped the entire world in an unprecedented manner for over two years, and as of yet, there is no clear indication of its disappearance. It has caused about 6 million deaths and over 440 million confirmed infections.[a] However, its future is still uncertain, and any indication on tackling future pandemics requires systematic and in-depth thinking and reflection. In tackling the various uncertainties and challenges caused by the pandemic, AI has played a pivotal role, in particular, in supporting automated, virtualized, distributed, mobile and telemedicine, communicating, community servicing, business innovations, normalizing living and economic activities, and online working, studying, and entertaining.[1–3] AI has been in the epicenter in the fight against the COVID-10 pandemic, from diagnosing and detecting the SARS-CoV-2 virus and identifying COVID-19 symptoms to saving lives and restricting the spread of the pandemic.

In reviewing the roles of AI in fighting the pandemic,[3] several fundamental questions should be answered: How does COVID-19 challenge AI? What roles has AI played in fighting the pandemic? How well has AI performed against COVID-19? How can AI better cope with the challenges? And more broadly, how can AI be better prepared for future pandemic management? In this article, I would like to share my shallow observations on these issues, building on my systematic review of AI against COVID-19, in particular, data-driven COVID-19 modeling[3] and global scientist efforts.[4] The main motivation of this article is to encourage deeper and wider AI attention, thinking, and developments in containing COVID-19, future pandemics, natural and social disasters, and other significant challenges, including those highly improbable or even unimaginable events (so-called "gray rhino" and "black swan" events), and being prepared to intervene in their consequences and impact.

The global research communities have made focused significant progress in understanding, quantifying, and containing the virus, disease, and pandemic. We have conducted a comprehensive literature review of how global scientists responded to tackling COVID-19.[3,4] We collected and analyzed 281,718 formal publications and 24,271 preprints made by global scientists on COVID-19 from Web of Science, Scopus, SSRN, and medical repositories from January 2020 to December 13, 2021.[b] First-authored researchers from 172 countries and regions have committed to constituting this body of knowledge

[a]WHO COVID-19. [Online]. Available: https://covid19.who.int/

[b]The data were extracted from Web of Sciences (JCR 2021), Scopus (CiteScore, SNIP, and SJR in October 2021), WHO, U.S. National Library of Medicine, Google Scholar (H5-index on December 18, 2021), ResearchGate, Guide2research, Crossref, MedRxiv, BioRxiv, and Arxiv.



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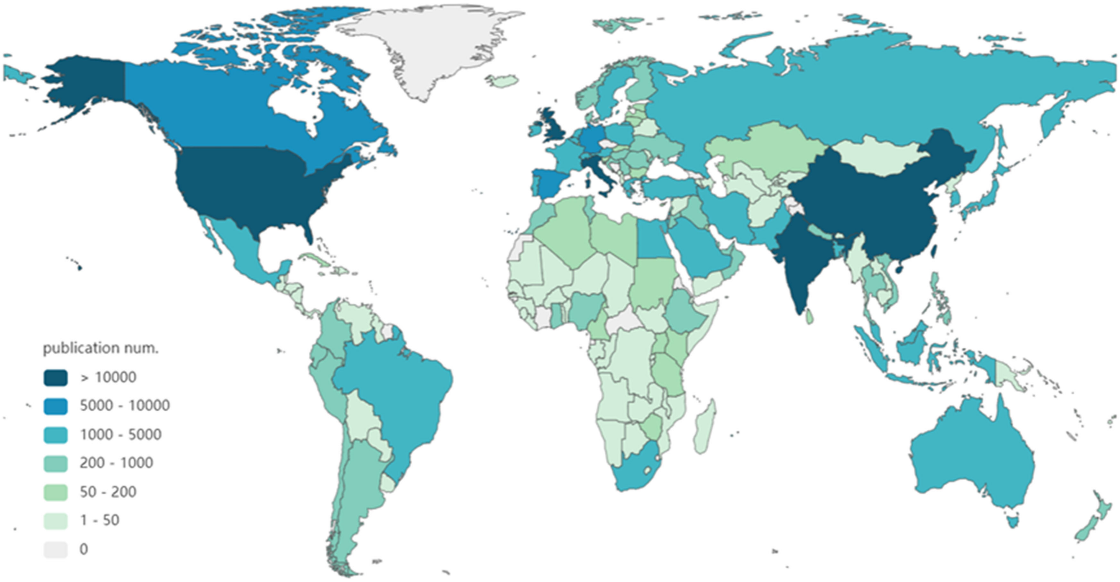


**FIGURE 1.** World map of first-authored publications by 172 countries and regions on COVID-19: USA (46,655 first-authored publications), China (18,601), Italy (14,211), U.K. (14,054), and India (12,840) make the top-5 in terms of their publication number.

on COVID-19, as shown in Figure 1. Of these 305,989 manuscripts, 38,730 are related to AI, with 5095 AI-related publications from computer science, 17,499 from medical science, and 3283 from social science. This comprehensive review and our more specific review on AI for modeling COVID-19[3] disclose various observations and insights about AI in the fight against COVID-19. Here, several highlights illustrate the progress of the scientific and AI communities in tackling COVID-19.

## COVID-19 CHALLENGES FACING AI

The COVID-19 pandemic[c] poses significant technical challenges to AI research and engineering.[3] The challenges emanate from (1) coronavirus complexities, COVID-19 disease complexities, and their related system and data complexities; and (2) the challenges of AI tasks and processes in fighting the virus, disease, and pandemic and their associated data, behaviors, businesses, and processes.

### COVID-19: An Open Complex System

On an individual level, the SARS-CoV-2 virus and its COVID-19 disease are both individual living organisms. They present common and specific biological, virological, and medical characteristics in comparison with other viruses and diseases, such as SARS-CoV and Ebola.[5,d] Both the coronavirus and COVID-19 present general biological system characteristics, including self-organization, interactions, and genetic and genomic evolution. These characteristics facilitate (1) a deep understanding of the COVID-19 features of infectiousness, infection, transmission, mutation, resurgence, and evolution; and (2) tailored designs for viral and disease diagnosis, testing, treatment, and intervention policy making.[6]

At the epidemic and system level, the COVID-19 pandemic is an open complex system with both general and pandemic-specific system complexities.[7] These include the following:

1) *Openness:* both the coronavirus and its disease interact and evolve with its host and hosting environments.
2) *Hierarchy:* the pandemic involves human clusters, states to regions, and their hierarchical social, ethical and environmental contexts.
3) *Self-organization:* the virus and disease evolve with self-organizing mechanisms with the system property of emergence.
4) *Interactions:* the virus and disease interact with each other, with their human or other hosts, and with the environments.

[c]Worldometer. COVID-19 Coronavirus Pandemic. [Online]. Available: https://www.worldometers.info/coronavirus/

[d]WHO. Tracking SARS-CoV-2 variants. [Online]. Available: https://www.who.int/en/activities/tracking-SARS-CoV-2-variants/

5) *Heterogeneity:* heterogeneous hosts, viral generations, and underlying contexts (e.g., intervention approaches, and policies).
6) *Dynamics:* the virus, disease, and their hosts and environments evolve over time, circumstance, and context.

Exploring the coronavirus and COVID-19 from virological, biological, epidemic, medical, systematic, and complexity perspectives may disclose both their individual (specific) and holistic characteristics more comprehensively and structurally. These will deepen the understanding of the underlying mechanisms, causes, dynamics, and emergence of the various observations: high contagiousness, high mutation, high adaption, varying incubation, distinct infectious symptoms, host condition-dependent evolution, and interactions with both nonpharmaceutical and pharmaceutical interventions. A deep understanding will facilitate the COVID-oriented AI agenda.

### Complexities of AI Against COVID-19

AI tasks and systems need to tackle the coronavirus and COVID-19 complexities and the characteristics and complexities of their data, behaviors, processes, and systems individually to comprehensively.[3] The corresponding challenges include the following:

1) Quantifying data complexities, such as representing, modeling, analyzing, learning, and managing the uncertainty, inconsistency, non-IIDness, heterogeneity, and dynamics of COVID-19 case data, patient data, and multisource, multidomain, and multimodal external data.
2) Quantifying and managing virus and disease complexities, such as detecting, recognizing, identifying, analyzing, intervening, and managing viral and clinical samples, medical imaging, viral propagation behaviors, processes, interactions, and evolution with host and environment.
3) Quantifying and managing COVID-19 pandemic complexities, such as modeling, simulating, analyzing, intervening, and managing human, viral, and environmental interactions, nonpharmaceutical and pharmaceutical interventions, mental, social, and economical consequences and impact.
4) Designing intelligent COVID-19 products, applications, and services, such as for supporting and optimizing disease treatment, viral testing, medical diagnosis, epidemic isolation and management, and anti-COVID-19 resource and logistic planning, and optimization systems.

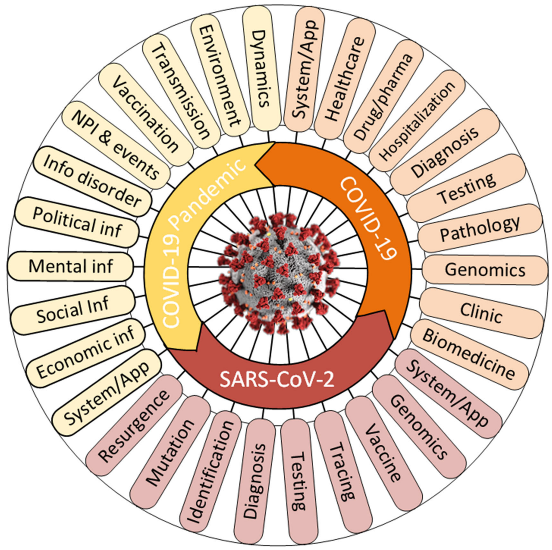


**FIGURE 2.** AI research landscape against COVID-19: major areas in containing the SARS-CoV-2 virus; the COVID-19 disease; and the COVID-19 pandemic.

## WHERE IS AI IN COMBATING COVID-19?

### Major AI Tasks

AI has played a critical role in fighting COVID-19, corresponding to the core, peripheral, and consequent issues in relation to the SARS-CoV-2 virus, the COVID-19 disease, and the COVID-19 pandemic, respectively. Figure 2 summarizes and highlights the core and subsequent areas where AI has played a critical role. The core issues are those directly relevant to the SARS-CoV-2 virus and the COVID-19 disease, which AI directly addresses to understand, identify, quantify, contain, and prevent COVID-19.

The major areas in containing the *SARS-CoV-2 virus* include the following:

1) virus diagnosis and identification;
2) virus mutation analysis;
3) resurgence estimation and prediction;
4) virus biomedical analysis and testing;
5) virus tracing and containment;
6) vaccine development; and
7) systems and applications for processing and containing the virus.

In tackling *the COVID-19 disease*, the major tasks include the following:

1) disease diagnosis;
2) disease pathological processing;
3) disease genomic analysis;

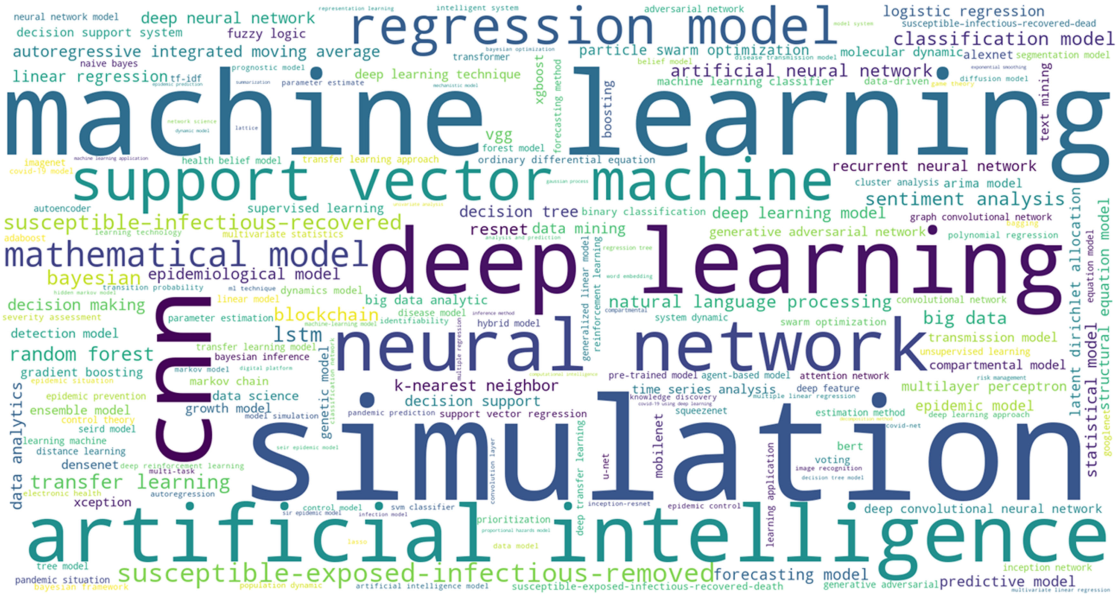


**FIGURE 3.** Word cloud of COVID-19 publications in computer science: top-200 words.

4) disease clinic treatment;
5) disease biomedical processing;
6) disease testing;
7) patient hospitalization;
8) disease pharma and drug development;
9) COVID-19 healthcare; and
10) corresponding health and medical systems and applications.

In fighting *the COVID-19 pandemic*, the major tasks include a fundamental agenda on the following:

1) epidemic transmission,
2) epidemic environment and external factors,
3) epidemic dynamics,
4) nonpharmaceutical interventions and events, and
5) vaccination.

Furthermore, consequent issues, such as

6) information misorder and misinformation,
7) mental and psychological influence,
8) social influence,
9) economic influence,
10) political influence, and
11) corresponding systems and applications, result from and are impacted by the COVID-19 pandemic, where AI has contributed to contain their consequences and impact.

## Global AI Research Effort

Out of the 36,830 AI-related studies in the literature,[4] 17,499 are on AI for medical science, 5089 are from computer science, and 3283 are from social science (SSRN-based). An analysis of these manuscripts using natural language processing reveals the following results. They involve almost all AI techniques and areas, including statistical and mathematical modeling, machine learning, NLP, deep learning, computer vision, data mining, simulation, evolutionary computation, and AI-enabled genomic analysis, system and application development.

Figure 3 shows the top-200 word cloud of 5095 AI-related publications appearing in computer science journals and conferences. The visualization highlights the frequency of the words: simulation, machine learning, artificial intelligence, various shallow (e.g., support vector machine), and deep learning (e.g., CNN) methods, regression models, and mathematical models, including susceptible–infectious-removed (SIR) models. The statistics also show that research on shallow analytical and learning methods and deep neural networks constitutes the majority of the research in the field of computer science.

In contrast, Figure 4 shows the top-200 word cloud from the 17,499 AI-related publications in medical science. The analysis highlights the AI techniques widely applied in COVID-19 medical manuscripts. Conventional mathematical methods overwhelmingly dominate AI applications, including linear and nonlinear regression models, univariate and multivariate statistics, statistical models, such as Bayesian models, and differential equation-based SIR models. Interestingly, while machine learning and artificial intelligence rank

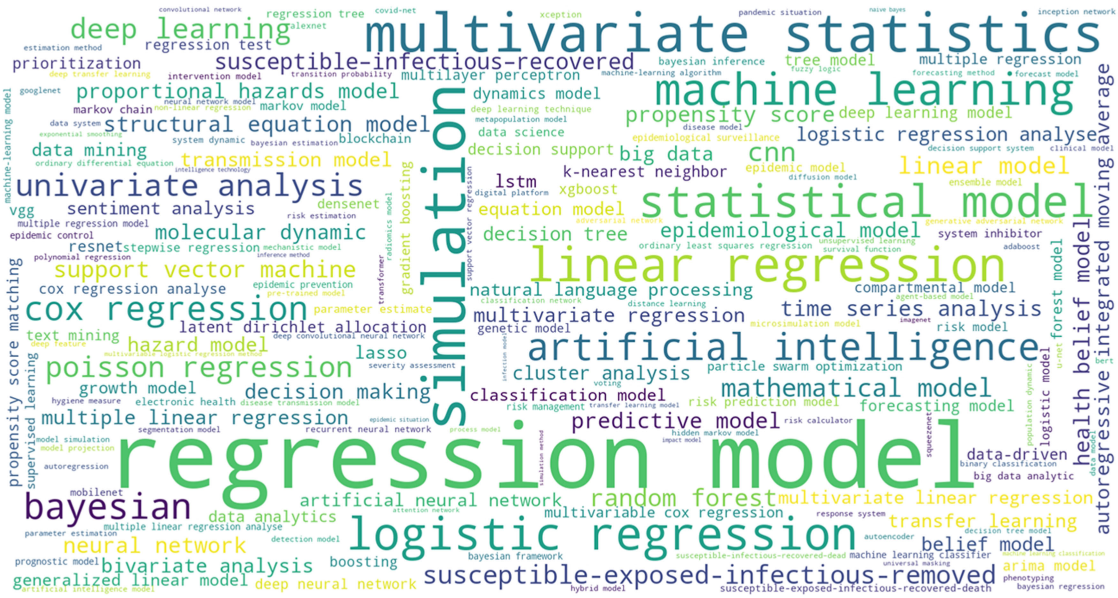


**FIGURE 4.** Word cloud of COVID-19 publications in medical science: top-200 words.

in the top-10, deep neural networks were not a large focus in the medical literature, in comparison with the overwhelming focus on shallow and classic analytical mathematical and statistical methods, in particular, various regression models.

## HOW HAS AI PERFORMED AGAINST COVID-19?

AI techniques have substantially contributed to the understanding, quantification, identification, diagnosis, and treatment of the virus and disease; vaccine and drug development; data, text, and image analysis and learning; clinical, pathological, and genomic analysis and processing; intervention and management; unprecedented influence and impact; and the information disorder and misinformation of the SARS-CoV-2 virus, the COVID-19 disease, and their pandemic. Various works[3] have reported or compared the performance of specific AI techniques in tackling the SARS-COV-2 virus, the COVID-19 disease, and the pandemic. Typical examples are the rapid COVID-19 diagnosis on X-ray and other medical imaging resources,[8,9] the prediction of COVID-19 cases, spread and resurgence,[10] the discovery of antibodies for drug development,[11] the impact estimation of NPIs,[10,12] policies,[13] and human mobility[14] on the COVID-19 spread and death, the influence analysis of public health actions on controlling the virus mutation,[15] the misinformation impact on COVID-19-related knowledge circulation and vaccination intention,[16] and analyzing the mental and socioeconomic impact of COVID-19.[17]

Figure 5 illustrates the number of monthly publications on major COVID-19 problems in the period from January 2020 to December 13, 2021. The major issues are COVID-19 mental health, mortality prediction, lockdown, anxiety, vaccine, public health, X-ray, depression, spread prediction, and risk factors. The intensive interest in case and transmission prediction in the middle stage has been substantially reduced, replaced by an increasing studies on vaccines and mental health.

However, the commitment from each country is very biased and imbalanced in the researched problems and techniques.[4] Figure 6 shows the number of first-authored publications of the top-10 countries on top-10 business problems using top-10 focused methods. Their primary technical interests are in regression, SIR models, and classic and deep machine learning.

A further exploration of the publication quality shows a significant division between countries. Figure 7 shows the paper-averaged publication quality of G20 countries in terms of the five publication impact metrics: H5-index, Impact Factor, CiteScore, SNIP, and SJR. The top-5 countries per the paper-averaged sum of these five factors are the U.K. (90.298), Germany (89.333), France (88.418), USA (86.423), and China (85.655).

## GAPS AND OPPORTUNITIES

### AI Research Pros and Cons

AI has made significant contributions to containing COVID-19,[18] showing the following features:

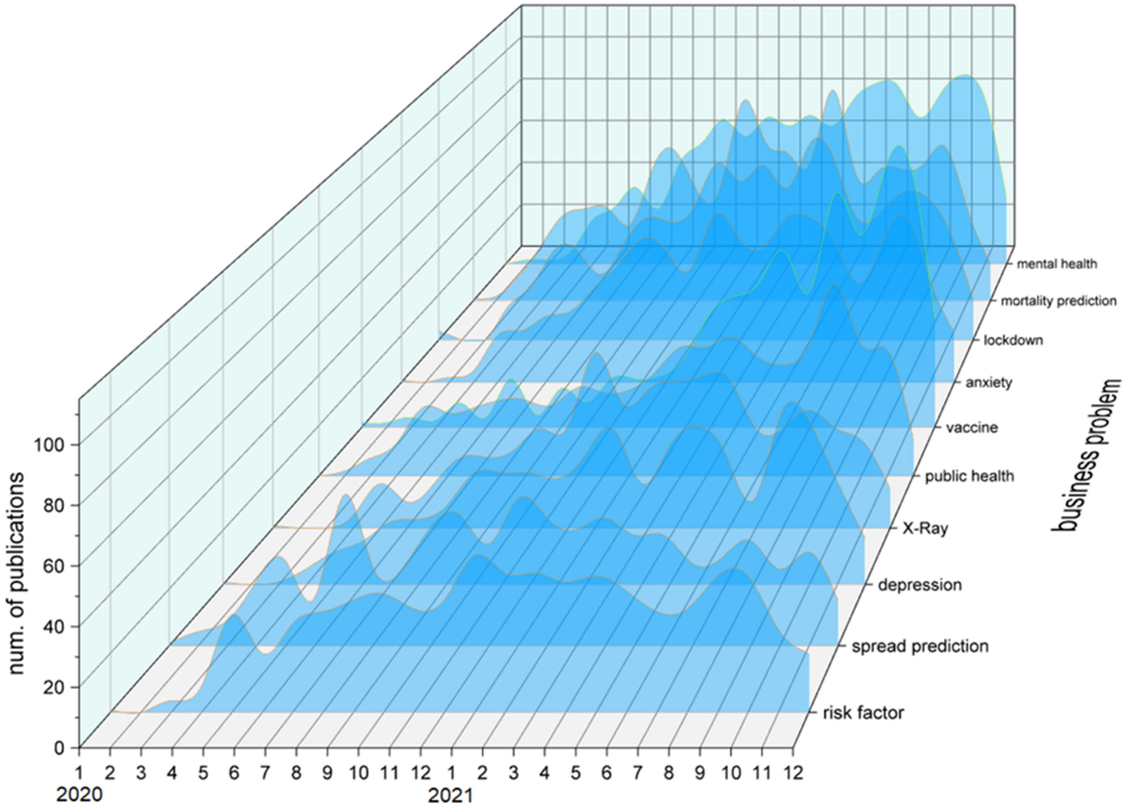


**FIGURE 5.** Monthly publication distributions addressing top-10 COVID-19 problems: mental health, mortality prediction, lockdown, anxiety, vaccine, public health, X-ray, depression, spread prediction, and risk factors.

1) the coverage and intensity of addressing major business problems are very comprehensive, as shown in Figures 2 and 5;
2) the research broadly involves both conventional and modern AI techniques, as shown in Figure 3;
3) the number of publications and their regional coverage and quality are enormous and fast paced, as shown in Figure 1; and
4) AI has been widely applied to address COVID-19 challenges and business objectives by not only computer science but also other disciplines, in particular, medical science and social science.

However, the existing research also discloses some major disadvantages, pitfalls,[19] and gaps. First, the research has been overwhelmed by simple applications of AI techniques. This appears in not only the medical and social science literature but also computer science publications. Second, very limited research has been devoted to developing original and significant AI techniques to tackle COVID-19. This may have driven the imperative early-stage need to understand the emerging COVID pandemic without paying much attention to its intrinsic and intricate characteristics and challenges. Third, the application of AI techniques in developing anticoronavirus drugs and vaccines has made limited progress in areas, such as discovering SARS-CoV-2-specific genomic and molecular structures and mutations. This shows the immaturity of AI communities and the challenges they face in being able to rapidly and effectively tackle emergent disasters and exceptions like the COVID-19 pandemic. Furthermore, the research on COVID-19-oriented intelligent systems, devices, and applications, e.g., for mobile tracing, contactless and unmanned rapid diagnosis and testing, rapid and scalable genomic or clinical diagnosis, and in-body treatment nanorobots, is very limited. Finally, cross-disciplinary AI research on COVID-19 is very limited. This may result in a simple application of AI in medical and social science publications and a shallow understanding and evaluation of AI innovations made by computer scientists.

## Opportunities for AI Against COVID-19

The SARS-CoV-2 virus, the COVID-19 disease, and their pandemic have incorporated some unique and

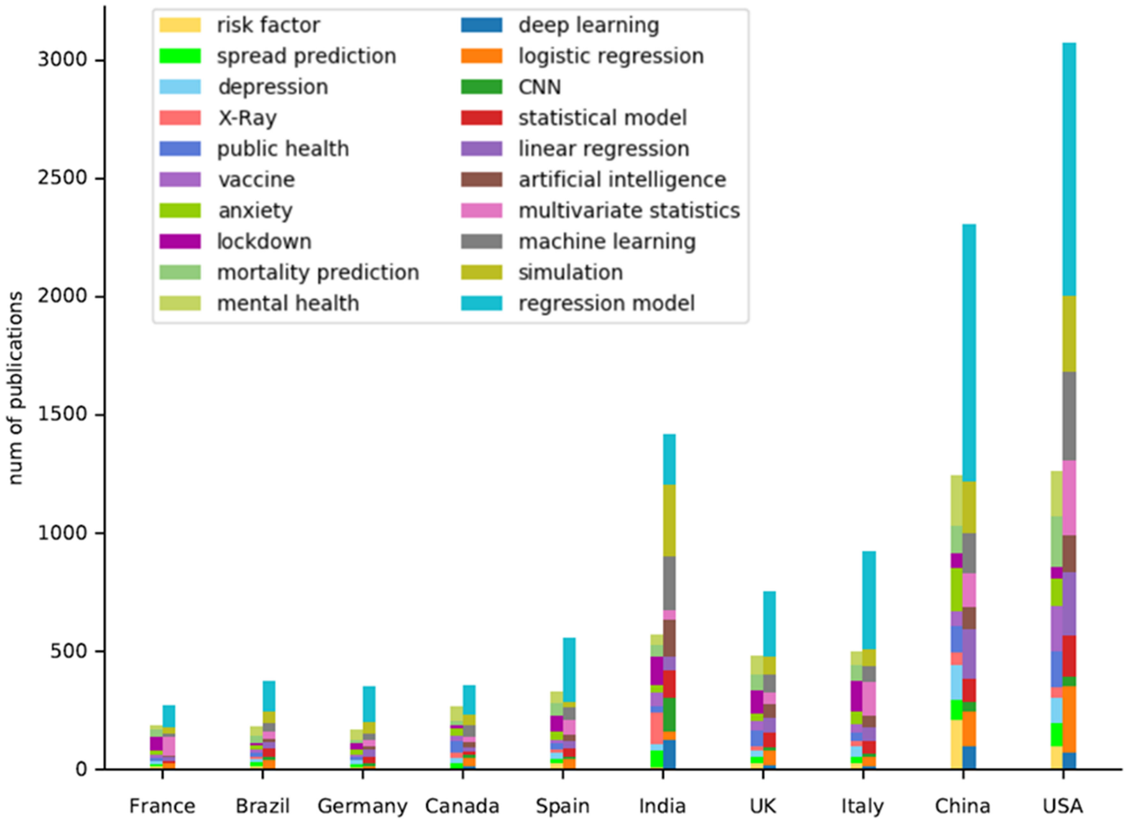


**FIGURE 6.** Top-10 countries to address top-10 COVID-19 problems using top-10 AI techniques.

significant new complexities in the virus, disease, pandemic, and their corresponding data, containment processes, behaviors, and systems. Examples are the high adaption and mutation of the virus and its mysterious transmission, the asymptomatic but infectious stage of the disease, the rapid inflammation and infection of multiple organs, and the complex interactions between the virus, vaccine, and drugs. They significantly challenge the existing body of knowledge on epidemic description, intervention, prevention, and prediction.

One rarely studied area is to *model the complex multiparty interactions* between the virus infectiousness and mutation, strong or soft NPIs, vaccination efficacy, and the case and spread movement.[20] This is challenging as it has to precisely represent the respective factors and then quantify their interactions and influence on each other. Such research is expected to inform intervention policy formation and adjustment over the COVID-19 evolution and resurgence.

Our understanding of the virus is still limited. *COVID-19 quantification and virology* are challenging. The corresponding AI models have to estimate various viral and interactive complexities. Examples include representing and modeling the viral genomic structures, molecular structures and interactions, viral mutation and adaption mechanisms, viral interactions with the environment, host cell binding and entry, viral interactions with host target cells, the viral replication, assembly, loading, maturation and release, the infectiousness duration and factors, and the influence of vaccine and drugs on the virus evolution. These may be complemented by coronavirus sample-based pathogenic, viral, and molecular analyses to enrich the SARS-CoV-2 virology and pathogenesis.

*AI for COVID-19 treatment and prevention* is another important topic. Common practices in relation to medical imaging analysis, respiratory signal analysis, and clinical test sample analysis are insufficient due to the lack of discriminating factors. Further work is required to jointly analyze multimodal data, such as X-ray images, breathing patterns, blood test results, and body health conditions. Since the virus may favor some organs for target attack, developing nanorobots to identify and destroy coronavirus in the human body, and enabling retroviral gene therapies and macrorobots is thus essential for viral environmental inspection and treatment.

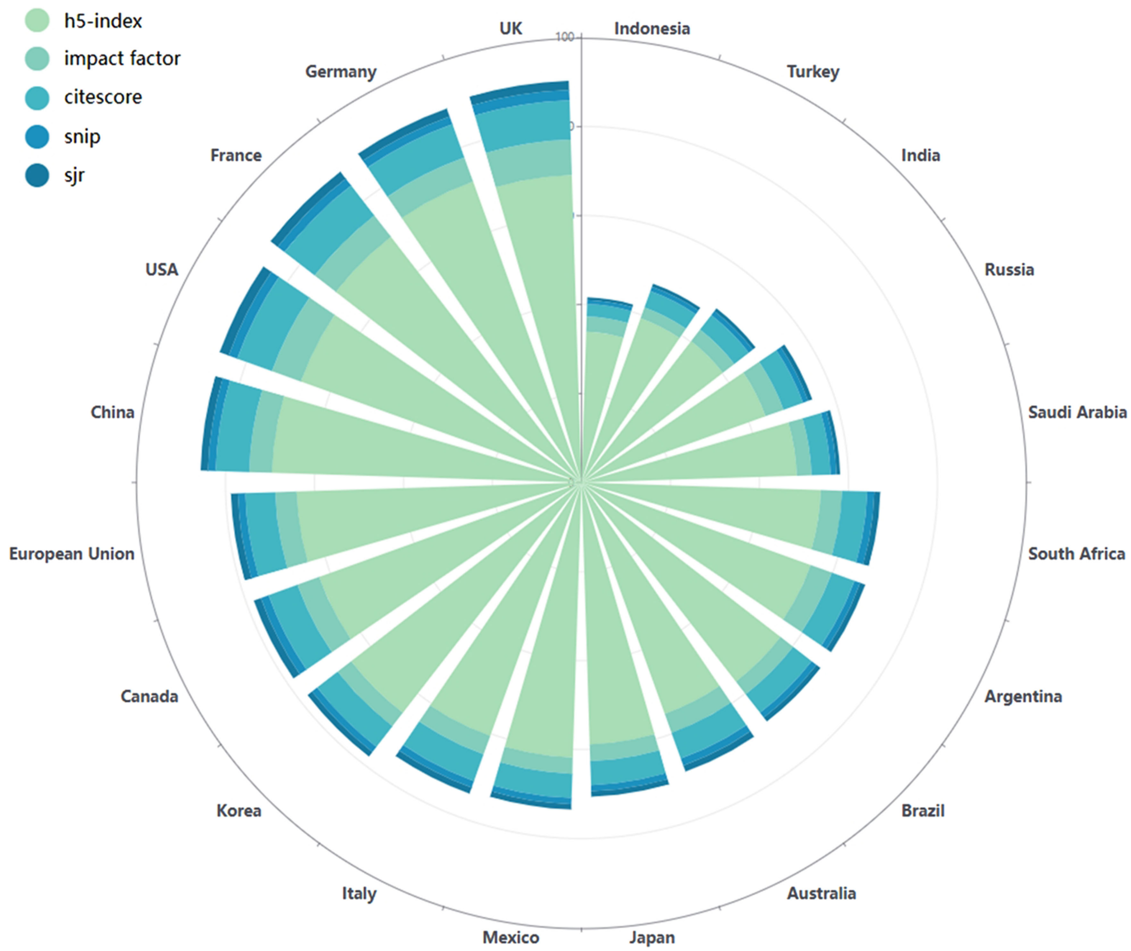


**FIGURE 7.** Paper-averaged COVID-19 publication quality of G20 countries in terms of five quality factors: H5-index, impact factor, CiteScore, SNIP, and SJR; metrics are averaged per publications.

Furthermore, *AI for vaccine and drug development* is playing an increasingly critical role in fighting COVID-19. More AI research, in particular, data-driven AI, may discover new candidate drugs and vaccines, e.g., assisting in pathobiological analysis, pattern matching between gene targets and vaccine or drug candidates, analyzing the SARS-CoV-2 molecular mechanisms, characterizing the COVID-19 interactions with human cells and immune systems, and predicting immunogenic peptides and epitopes.

Finally, *the influence and consequence of COVID-19 on mental, social, economic, geopolitical, and global aspects* are unprecedented and even may be perpetual. More research is required to quantify, estimate, evaluate, and predict the consequences on the regional and global economy, transport, logistics, material resourcing and planning, manufacturing and supply chain, and trade. The same tasks also apply to quantifying the psychological impact on children, home schooling and officing, family violence, and mental challenges, including depression and suicide. In addition, the research on modeling and evaluating the significant changes and their impacts on intellectual, cultural, geopolitical, societal, and environmental aspects caused by COVID-19 is restricted. The relevant research is expected to provide evidence on or insights into COVID-19 consequences and to estimate and mitigate their impact.

## "PANDEMIC AI" FOR FUTURE MANAGEMENT

The review of AI for combating COVID-19 discloses important experience, indications, and lessons for managing future epidemics and pandemics. These include the various aspects discussed in the aforementioned sections. In addition, a critical agenda for AI-enabled future pandemic management is to enforce global (between countries and regions) and interdisciplinary (between AI and epidemic communities) collaborations. Pandemic management involves many critical strategies, including preparation, early warning, prevention, policy formation, intervention, and consequence mitigation. Such pandemic management is much more challenging than ordinary enterprise, multinational, or state-level management. Centralized planning, management, resourcing, operations, and communications may not be applicable. In the following, I expand on the aforementioned coverage of specific AI techniques and tasks to a few other perspectives by focusing on global pandemic collaborations and data-driven smart pandemic management. These form a view of and need for developing "epidemic AI" or "pandemic AI."

## AI for Future Pandemic Preparation

There are many strategies to enforce the early preparation and warning for future epidemics or pandemics. These include fundamental work on AI-enabled epidemic and pandemic education and consulting services, e.g., by developing mobile Apps, knowledge portals, professional websites, online chatbots, and community question-answering services. Developing pandemic preparation protocols and policies is another important agendas. AI-enabled protocols and policies for containing epidemics and pandemics may be categorized for public health and hygiene management, general practices by professional bodies, and preparation agenda and strategies for policy makers. AI can collect and evaluate the relevant protocols and historical experience, analyze reflections and feedback, and recommend attentive areas and findings. AI can also enable efficient and personalized communications to categorized or disenfranchised communities for timely preparation. I envisage increasing professional and commercial services may emerge to address these tasks and supply the corresponding products and applications by new advances in Web 3.0 and 5G.

## AI for Future Pandemic Prevention

One useful and essential task is to collect data about past epidemics and pandemics, and analyze, categorize, summarize, and evaluate previous practices, lessons, reflections, and feedback. Rapid similarity analysis can then be undertaken when a new unknown virus emerges somewhere in the world using AI techniques, with the results recommended to policy makers for warning and prevention action-taking. When new cases are identified, immediate actions are activated to correctly record viral bursts, collect viral samples and patient's clinical data, share the testing and diagnostic results, and report and update case and transmission data, etc. in a timely manner. Furthermore, pathogenic, clinical, biomedical, and data-driven analyses (e.g., on the relevant images, videos, or texts) can be activated for diagnosis, similarity analysis, pattern matching, and drug and vaccine candidate matching, etc.

## AI for Global Pandemic Collaboration

Developing *global epidemic early warning systems* may be an important lesson learned from tackling the COVID-19 pandemic and a priority for international organizations, including the WHO and the United Nations. In such global pandemic early warning systems, global protocols, and policies for pandemic preparation and management are enforced; capabilities for early warning are imparted; and data matching, updating, and communications with member countries and regions are enabled. AI can play a fundamental role in automatically collecting, processing, and analyzing the relevant transactional, event-based, textual, imagery, and medical data from public resources; AI can enable global data logging and matching programs (e.g., through collaborations between each country's centers for disease control and prevention) and empower data and knowledge benchmarking, sharing, and transparency. AI techniques can then deeply analyze and predict the epidemic timing, probability, severity, location, and consequences in a burst region and compare them with past examples and experience for better preparation, prevention, and intervention. Early warning messages can be classified and broadcasted to those subscribed countries and organizations for further investigation, validation, and action-taking.

## AI for Benchmarking Pandemic Management

Another critical lesson learned from the COVID-19 pandemic is the significant imbalance, bias, deviation, and uncertainty of viral and pandemic management policies, standards, capabilities, and practices. Global organizations, including the WHO should advise and evaluate the benchmarking and policy formation in each country or region in tackling global pandemics and extreme events. While this may be highly challenging due to practical differences and imbalances in many aspects across countries and regions, AI has the ability to mitigate these discrepancies. One critical task is to develop benchmarkable, conditional, and personalized pandemic preparation, diagnosis, detection, intervention, and management protocols and guidelines, categorized and classified for uncertain, undeveloped, developing, and developed scenarios. Another is to enforce, evaluate, and optimize pandemic practices and policies when such data are collected and shared to global pandemic early warning systems. AI can identify their gaps, conduct contrast analysis between countries and regions, discover insights and observations for a specific country or region, and recommend optional personalized strategies and next-best actions.

### AI for Ethical Pandemic Management

It is commonly seen that different policies and practices are often adopted by various countries and regions in tackling COVID-19-like pandemics. Ethical pandemic management identifies and evaluates unsafe, unfair, biased, privacy-violated, antihumanity, and unaccountable policies, behaviors, and practices; detects and prevents under or overactions, such as in disenfranchised communities, undermedical services, or over quarantine; and identifies and mitigates unethical policies and behaviors and their negative impact on human rights, and humanity. Ethical pandemic management also refers to the focus on humanity rather than political goals and the care balance between directly and indirectly affected individuals and groups. Unethical practices may be related to biased healthcare, NPIs, vaccinations, medical treatments, containment, monitoring, surveillance, and human rights concerns.[2] Ethical AI can also enable more explainable, transparent, accountable, fair, and just viral, medical, societal, and political protocols and practices.

There are many other areas and issues to address in forming the body of knowledge of pandemic AI and the readiness of AI for future epidemic and pandemic. These include but are not limited to viral analytics, medical analytics, vaccine and drug developments, intelligent viral testing robots, public healthcare servicing robots and chatbots, nanorobots for viral and medical identification and treatments, and intelligent systems and applications for various and personalized community servicing and communications.

## CONCLUDING REMARKS

The COVID-19 pandemic has brought about incomparable challenges and consequences to the world and AI. Despite the significant progress made in AI in relation to combating COVID-19, the related work is shallow, superficial, and observational. Being prepared in terms of developing AI readiness and competencies for future pandemic management involves many challenges and opportunities, including developing epidemic-specific AI, and AI-enabled global pandemic research, development, and early warning systems. Epidemic AI developments will also benefit other exceptional and extreme event management, for those so-called "gray rhino" and "black swan" events. With AI-enabled benchmarks and better practices for addressing global biased and imbalanced practices and marginalized and vulnerable groups, it is also hoped that AI can improve the ethical, human right-oriented, and differential impacts that may be caused by COVID-19-like pandemics and improper policies and practices.

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## REFERENCES

1. OECD, *OECD Policy Responses to Coronavirus (COVID-19): Using Artificial Intelligence to Help Combat COVID-19*, Apr. 23, 2020. [Online]. Available: https://www.oecd.org/coronavirus/policy-responses/using-artificial-intelligence-to-help-combat-covid-19-ae4c5c21/
2. AAAS, "Artificial intelligence and COVID-19: Applications and impact assessment," American Association for the Advancement of Science, Washington, DC, USA, Tech. Rep., May 2021. [Online]. Available: https://www.aaas.org/sites/default/files/2021-05/AIandCOVID19_2021_FINAL.pdf
3. L. Cao and Q. Liu, "COVID-19 modeling: A review," 2021, *arXiv:2104.12556*.
4. L. Cao and W. Hou, "How have global scientists responded to tackling COVID-19?," UTS, Tech. Rep., 2022. [Online]. Available: https://datasciences.org/covid19-modeling/
5. WHO, "Transmission of SARS-CoV-2: Implications for infection prevention precautions," *Sci. Brief*, Jul. 2020. [Online]. Available: https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions
6. O. Vandenberg *et al.*, "Considerations for diagnostic COVID-19 tests," *Nature Rev. Microbiol.*, vol. 19, pp. 171–183, 2021.
7. L. Cao, *Metasynthetic Computing and Engineering of Complex Systems*. London, U.K.: Springer, 2015.
8. V. Priesemann *et al.*, "An action plan for pan-European defence against new SARS-CoV-2 variants," *Lancet*, vol. 397, no. 10273, pp. 469–470, 2021.
9. D. Mendels *et al.*, "Using artificial intelligence to improve COVID-19 rapid diagnostic test result interpretation," *Proc. Nat. Acad. Sci.*, vol. 118, no. 12, 2021, Art. no. e2019893118.

10. J. Dehning *et al.*, "Inferring change points in the spread of COVID-19 reveals the effectiveness of interventions," *Science*, vol. 369, no. 6500, 2020, Art. no. eabb9789.
11. R. Magar, P. Yadav, and A. Farimani, "Potential neutralizing antibodies discovered for novel corona virus using machine learning," *Sci. Rep.*, vol. 11, 2021, Art. no. 5261.
12. S. Flaxman *et al.*, "Estimating the effects of non-pharmaceutical interventions on COVID-19 in Europe," *Nature*, vol. 584, pp. 257–261, 2020.
13. M. Hamilton *et al.*, "An analysis of the impact of policies and political affiliation on racial disparities in COVID-19 infections and deaths in the USA," *Int. J. Data Sci. Anal.*, vol. 13, pp. 63–76, 2022.
14. B. Du *et al.*, "Modelling the epidemic dynamics of COVID-19 with consideration of human mobility," *Int. J. Data Sci. Anal.*, vol. 12, pp. 369–382, 2021.
15. N. Grubaugh *et al.*, "Public health actions to control new SARS-CoV-2 variants," *Cell*, vol. 184, no. 5, pp. 1127–1132, 2021.
16. M. Vlasceanu and A. Coman, "The impact of information sources on COVID-19 knowledge accumulation and vaccination intention," *Int. J. Data Sci. Anal.*, pp. 1–12, 2022, doi: 10.1007/s41060-021-00307-8.
17. World Bank, "The global economic outlook during the COVID-19 pandemic: A changed world," 2020. [Online]. Available: https://www.worldbank.org/en/news/feature/2020/06/08/the-global-economic-outlook-during-the-covid-19-pandemic-a-changed-world
18. N. Plohl and B. Musil, "Modeling compliance with COVID-19 prevention guidelines: The critical role of trust in science," *Psychol., Health Med.*, vol. 26, no. 1, pp. 1–12, 2021.
19. M. Roberts *et al.*, "Common pitfalls and recommendations for using machine learning to detect and prognosticate for COVID-19 using chest radiographs and CT scans," *Nature Mach. Intell.*, vol. 3, pp. 199–217, 2021.
20. L. Cao and Q. Liu, "How control and relaxation interventions with or without vaccination influence the resurgences of COVID-19 under different virus mutations," *medRxiv*, 2021, doi:10.1101/2021.08.31.21262897.


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