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The medical and societal impact of big data analytics and artificial intelligence applications in combating pandemics: A review focused on Covid-19

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ABSTRACT

With Covid-19 impacting communities in different ways, research has increasingly turned to big data analytics (BDA) and artificial intelligence (AI) tools to track and monitor the virus's spread and its effect on humanity and the global economy. The purpose of this study is to conduct an in-depth literature review to identify how BDA and AI were involved in the management of Covid-19 (while considering diversity, equity, and inclusion (DEI)). The rigorous search resulted in a portfolio of 607 articles, retrieved from the Web of Science database, where content analysis has been conducted. This study identifies the BDA and AI applications developed to deal with the initial Covid-19 outbreak and the containment of the pandemic, along with their benefits for the social good. Moreover, this study reveals the DEI challenges related to these applications, ways to mitigate the concerns, and how to develop viable techniques to deal with similar crises in the future. The article pool recognized the high presence of machine learning (ML) and the role of mobile technology, social media and telemedicine in the use of BDA and AI during Covid-19. This study offers a collective insight into many of the key issues and underlying complexities affecting public health and society from Covid-19, and the solutions offered from information systems and technological perspectives.

1. Introduction

Pandemics are a worldwide challenge, mainly for healthcare but also for other industries. Coronavirus (Covid-19) is an infectious disease that was first reported December 2019 in Wuhan, China, and has since spread all over the world with varying speed and intensity (World Health Organization, 2020). The prevalence of this global pandemic has emphasized the need to investigate health disturbances and prepare response strategies more quickly than the pace of the infectious disease (Atkinson et al., 2020).

The introduction of big data analytics (BDA) in healthcare makes it possible to study the effects of the crisis, facilitate pandemic strategies, and discover vaccines and treatments (Lv et al., 2021). BDA refers to the techniques, technologies, systems, practices, methodologies, and applications for analysing the vast amount of data to understand organizations and society better (Galetsi et al., 2019). BDA techniques include forecasting, optimization, simulation, and others that assist in decision-making (Doumpou and Zopounidis, 2016). One of the most

emerging analytic techniques in healthcare is machine learning (ML), which automates the execution of rules through algorithms with many successful artificial intelligence (AI) applications in the healthcare sector (Davenport and Kalakota, 2019; Galetsi et al., 2020). AI with its ML algorithms makes BDA simpler by automating and enhancing data preparation, data visualization, predictive modelling, and other complex analytical tasks. AI's algorithms use big datasets to train themselves to perform a specific task, such as identifying a lesion in a radiographic image (Kulkarni et al., 2020b) and therefore make raw data meaningful for decision-making purposes.

Covid-19 applications can use BDA to deal with increasingly large amounts of data. Over time, availability of larger data help refining algorithms for applications and increase their output accuracy. This was not feasible a few decades ago because of data storage and computing power limitations. Nowadays, we can handle any data sizes with cloud servers and the current computing power. For these reasons, ML/AI applications development has gained prominence. The advancement of cloud computing has given rise to instant data retrieval from servers

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around the world. Decision support-systems are being built with access to large repositories of data residing in cloud servers linked to various data sources stemming from individuals or organizations. Consequently, IT professionals constantly develop new infrastructure and new applications with big data capabilities to help stakeholders making informed decisions (Wang et al., 2018).

Specifically, during Covid-19, the proliferation of diverse big datasets (e.g., data from public records, social media and sensor data from smartphones), was a critical driver of empirically based problem-solving. Therefore, available digital technologies and big data on Covid-19 facilitated researchers, practitioners and policymakers in developing numerous BDA/AI Covid-19 applications in short time hoping to successfully direct strategies and responses to the pandemic and its unforeseen ‘black swan’ events (Sheng et al., 2020).

Nonetheless, developing these applications requires huge investments, by organizations and the government, in human and technological resources, and capital. This can result in diverting resources from other pressing needs for the betterment of the society. Additionally, the extent of using new information technologies for gathering and analyzing big data is profoundly influenced by the country’s ability to acquire, absorb, and use new innovations for social good (Mehraeen et al., 2020). Most of these AI-driven tools are reinforced and practiced in high-income countries (Naseem et al., 2020). Less developed countries, due to capital shortage, lack of technological expertise and poor infrastructure may face barriers in implementing such applications, which impedes effective management and control of the pandemic. Some examples include challenges in identifying Covid-19 cases, rapidly re-organizing limited hospital resources for the infected and regular patients and understanding population behaviour against the restriction measures (Ozsahin et al., 2020; Belciug et al., 2020; Imran et al., 2020).

The World Health Organization (WHO) has envisioned securing the health and well-being of people around the world with the concept of “Health For All” (HFA/2000). Because of this, healthcare organizations worldwide have shown a growing responsibility to improve diversity, equity, and inclusion (DEI) efforts to better serve patients and their families. This planned effort is attempted by understanding peoples’ backgrounds including culture, gender, religious beliefs, and socioeconomic status (diversity); by ensuring populations effectively benefit from best practices in treatment (equity); and by providing high-quality care and treatment experience for all social groups (inclusion) (Piggott and Cariaga-Lo, 2019). However, despite the growth in public policy research and government interest in fostering socio-economic determinants and equity in health policies, “unhealthy” public policies are still implemented among certain segments of the population (Embrett and Randall, 2014). As an example, public hospitals in Saudi Arabia require male guardian permission to allow an adult woman to be admitted or receive care of any kind, even an urgent medical procedure (Beckerle, 2016). In the case of Covid-19, the literature shows that different political beliefs, ideologies, and attitudes create a split in societal perceptions on public health issues such as vaccination and medical protocols (Ward et al., 2020).

An aspect that should not be overlooked about effective implementation of Covid-19 BDA applications based on DEI principles is lack of common understanding of such principles in different parts of the world. This impedes the adoption of a global mindset for a common DEI approach. Initiatives must be localized to avoid the appearance of not relevant or not culturally tailored diversity mandates (Goodman, 2013). In the implementation of any localised strategy; local laws, regulations, and societal norms need to be acknowledged and the systems and processes established must suit the way things get done locally (Goodman, 2013). The current focus of DEI is based on North American social and political context (Majmudar and Kymal, 2020), which takes away the attention from the rest of the world where DEI might be of greater importance but with a different focus.

A search in the international literature for reviews related to BDA, AI, and Covid-19 revealed a lack of articles that analyse both the medical

and social impact of BDA/AI applications for managing the pandemic. There are few informative papers that profile research in BDA discussing various aspects of modern technology used to tackle Covid-19, including medical image processing, disease tracking and prediction outcomes, computational biology, and medicines (Jia et al., 2020). There is also a number of opinion papers on similar issues (Dwivedi et al., 2020; Kulkarni et al., 2020a; Sheng et al., 2020); reviews and profiling papers relevant to a specific BDA method, such as AI (Pham et al., 2020; Chiroma et al., 2020) or to a certain aspect of Covid-19 diagnosis, such as chest X-rays and CT scan imaging analysis (Ozsahin et al., 2020) or reviews and overviews of mHealth (Islam et al., 2020), telemedicine (Battineni et al., 2020) and social media analysis (Alhumoud, 2020). However, none of these investigate the medical and social aspects of the use of BDA and AI for Covid-19.

Therefore, this study explores the usefulness of BDA for tackling Covid-19 under a social and medical approach. It especially examines AI methods and new applications of big data analysis, their positive or negative effects on society and the pandemic and what more can be done. Through a DEI lens, this research examines whether the developed BDA and AI for Covid-19 applications are available to all individuals and communities. Specifically, it examines capacity requirements, for full participation of community in the provided medical services created by these advances (equity). Further, it looks at how to cater to the most disadvantaged to be able to use the provided information and technologies (inclusion) by capturing and supporting diversity based on individuals’ and societies’ demographic characteristics, religion, culture, and so forth.

Overall, the study addresses the following research questions.

RQ1. What are the applications of BDA and AI for Covid-19 management?

RQ2. What are the values of these applications from a medical and societal/DEI perspective?

RQ3. What are the societal/DEI challenges created by these applications?

RQ4. How can future research help mitigate these societal/DEI challenges and help create new applications that can bring additional solutions in combating pandemics and other large-scale health issues and crises?

The main contribution of this research is to identify the significant applications that analyse big data in response to Covid-19 and discuss their direct and long-term benefits to healthcare and the society along with their limitations and challenges under the lens of DEI. This research also identifies to develop additional responsible BDA applications for similar cases. Identifying and recognizing the positive and negative effects of rapid advances in technology can assist policymakers, scientists, and technology developers to avoid malfunctions and provide diverse and equitable healthcare to all population segments.

2. Research methodology

We followed the key principles of the PRISMA methodology to conduct the literature review. The methodology includes three stages to synthesize the themes of this research: 1) input, 2) processing and 3) output.

The first stage, input, involves the identification of relevant articles in the Web of Science® (WoS), a database containing quality impact factor journals. Screening the literature revealed that important tools in battling the pandemic are artificial intelligence (AI) and machine learning (ML) analysis methods, and the broad use of smartphones and social media since the last outbreak (Bansal et al., 2020; Rao and Vazquez, 2020). Therefore, the search strategy for relevant articles concentrated on a list of keywords. The list includes general terms providing a wide dataset of BDA methods that scientists use to design and apply methods against Covid-19. It also includes terms that ensure

we do not miss articles that use specific, popular BDA techniques, as identified from an initial literature screening. Our keyword list allowed us to maximize the number of articles in our dataset. The detailed search strategy is provided below. Studies published online in 2020 (including early publications of 2021) were retrieved from the WoS a year after the first appearance of Covid-19. The keywords “Big Data”, “Big Data Analytic”, “Artificial Intelligence”, “Machine Learning” and “Mobile app” were combined with the keywords “Pandemic”, “Epidemic”, “Coronavirus”, “Covid-19” and “SARS-Cov-2” on a one-to-one basis. Only journal research papers and review studies that were written in English and relevant to Covid-19 and BDA were included in the dataset. We included only articles and reviews to capture the full information of a study, which is usually better presented in a published journal article. The initial keyword search retrieved 985 records, but from an abstract scan, only 607 papers were finally included in our dataset after applying the inclusion-exclusion criteria. Content analysis of these papers was conducted January–July 2021.

The second stage of the research process focuses on grouping and classifying the papers into selected topics by capturing the relevant texts with the use of the NVivo software after full-text review. The categories and their sub-categories, which act as the guide to the dataset content analysis, were inspired by recent literature in the health BDA field (Galetsi and Katsaliaki, 2020). After reviewing all 607 papers we established 15 sets of BDA/AI Covid-19 applications based on their contents and intentions. We assigned these papers into the 15 identified sets of applications and then allocated these sets into two topics based on their targeted entities: 1) public healthcare and 2) individuals and community. Within the pool of articles, we have identified around 30 papers that relate to DEI, Covid-19 and BDA/AI together, and we used them to drive our discussion of identifying the social challenges for each set of applications.

We applied text retrieval methods to capture specific information from the papers. The relevant section that explained its link to a sub-dimension was recognized and coded by the NVivo software.

The third stage of the methodology, output, presents the results of the classification process. First, a profile of the dataset’s content is presented (e.g., publishing journals, institutions, data types used) and the highlights of citation, co-citation analysis from the use of VosViewer software. Because the collected sample of the published work is large, it can be characterized as representative and therefore a presentation of some proportional results of this dataset could shed some light on the research conducted thus far in this area. Secondly, the content analysis of the data pool answers to the main research questions by providing an overview of the developed BDA/AI applications for Covid-19 and an understanding of their impact, challenges, and future directions. The tables in the appendix include article frequencies per set of applications and indicative research examples. Fig. 1 outlines the research methodology strategy.

3. Dataset profiling

This section presents an overview of our dataset demographics, including country of origin and authors’ affiliation, publishing journals, subject areas, most cited and co-cited papers and authors. We provide statistics on generic paper classification, Covid-19 research in various disciplinary fields, BDA capabilities and techniques, and sources of data. We also identify various stakeholders of the BDA/AI applications.

The dataset includes publications from 61 countries. USA is first with 175 published articles (counting the number of authors affiliated with that country), followed by China (114) and India (80). Overall, the 607 papers are published in 290 different journals, with IEEE Access and the Journal of Medical Internet Research having the highest number of publications. The four most popular journals have a short publishing history (launched after 2000). Most papers belong to the subject area of “Computer Science & Information Systems” followed by “Medical Informatics.” Harvard University stands at the top with 31 articles, followed by the University of California (20). These universities excel in many fields of science and are ranked in the top 10 universities

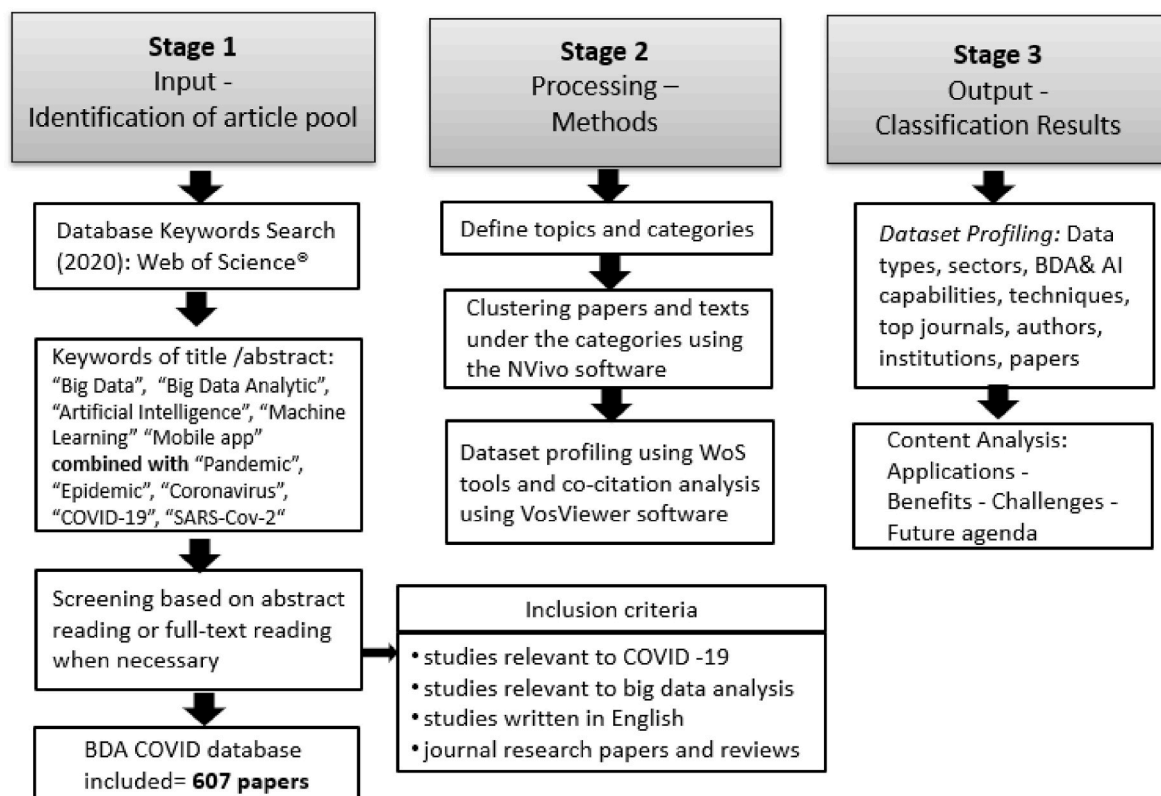


Fig. 1. Research methodology approach.

worldwide (Times Higher Education: World University Rankings, 2010–2019). The most cited paper (Wang et al., 2020) out of the 607 papers (all published in 2020), is published in JAMA with 659 citations in WoS (as of Feb 16, 2022). The paper is about Taiwan's government response to Covid-19, making Taiwan an example of how a society can use infrastructure and BDA to respond quickly to a crisis and protect the interests of its citizens. All papers have many co-authors (>7), indicating the importance of group work for achieving quick academic output. The most frequently co-cited papers amongst our 607 papers are the first publications using data from patients in Wuhan, China's hospitals (Huang et al., 2020; Wang et al., 2020; Chen et al., 2020). Professor Duong (Radiology department, Montefiore Medical Center-Albert Einstein College of Medicine, NY, USA) and Dr Haifang Li (Radiology department, Renaissance Medicine School, Stony Brook University, NY, USA) are the researchers with the highest number of publications and are also the most co-cited authors. It is notable that the majority of the most publishing authors are junior researchers from China, where the pandemic began.

The dataset comprised a range of paper types. Most of them were experimental papers (65.0%), followed by reviews (16.0%), opinion papers (9.2%), case studies (8.2%) and surveys (3.3%). In the fields that were investigated with the aid of BDA techniques, most papers were about public health (61%), followed by human behaviour (10.5%), social science (9.2%), business (7.7%), pharmacology (5.1%), environment (2.6%), tourism (2%), and other. Many papers were classified under more than one field. The developed methods utilized the evaluation: BDA capability by 36.7%, the prediction capability (29.5%), monitoring (23.4%), reporting (12.5%) and data mining (8.3%). The BDA techniques employed in mitigating the effects of the pandemic were usually AI methods, such as ML (Ardabili et al., 2020), deep-learning (Abdel-Basset et al., 2020), neural network analysis (Shrivastav and Jha, 2021), natural language processing (Leelavathy and Nithya, 2020) and incorporation of cloud computing (Ndiaye et al., 2020). For more information on these techniques, readers can refer to the references.

In the investigated applications, the data used came from a variety of sources. From the sample of 607 papers, more than 55% mention the analysis of clinical patient data, such as EHR and medical images retrieved in most cases from healthcare centres. Another 21% of studies analyse patient behaviour data which are collected from wearable sensors and social sites. The studies also manipulate pharmaceutical data (6.5%), including drug therapeutic mechanisms retrieved from chemical laboratories of hospitals, research organizations and pharmaceuticals companies, and finally administrative and cost data (5%) mostly financial and operational in nature, retrieved from healthcare centres, health insurance and other commercial companies.

Although many stakeholders were identified in the examined studies, the final beneficiaries of BDA Covid-19 research were mostly the society and the patients as they were offered diagnosis and ways to tackle their disease. Other stakeholders were IT specialists who, with their valuable contribution, designed the desired systems, physicians and health professionals who were provided with tools that helped them understand the disease, and policymakers who receive information from these applications about the current and future progress of the pandemic for taking appropriate measures.

4. Results: applications and impact

This classification attempts to map the knowledge in the field and explains BDA and AI impact in tackling Covid-19. Therefore, in this section we offer a list of significant BDA/AI applications that were developed to deal with the pandemic. Tables A1, A2 and A3 in the appendix present the main set of applications based on their target-group: public healthcare, individuals and the community. Each table reports for each set of applications the indicative BDA/AI technique/method, the immediate healthcare benefit and enduring societal benefits derived from such techniques and methods, and their associated challenges

facied by society The last column in these tables reports the frequency of the research studies associated with each set of applications (N), and the second column provides an indicative reference for each application category (Key Ref). This indicative reference is selected either based on popularity (number of citations) or ease of understanding its current use.

4.1. BDA/AI applications for public healthcare

According to Table A1 (appendix), nine different types of models/applications that refer to public health and medicine were identified in the literature. The majority of BDA models were developed by using AI on clinical datasets for evaluation and prediction to make medical treatments more efficient.

In particular, the first category of applications focuses on the identification of Covid-19 positive patients. Some of the 185 papers focus on detecting SARS-CoV-2 from chest CT scan images (Ardakani et al., 2020) or from chest x-ray images (Brunese et al., 2020). Novel AI models using chest images from coronavirus patients (initially retrieved from collaborating Chinese medical centres) were developed by researchers in university medical schools and biomedical engineering centres specialized in image processing and cardio-thoracic imaging. This chest imaging data trained the ML algorithms to identify whether the patient is covid positive. Such AI models/toolkits can easily be deployed worldwide to other hospitals' radiology departments, either online or integrated into their systems. Because these models are highly sensitive and can diagnose unclear cases, they can provide a second opinion to radiologists and physicians.

This pool of papers also focuses on detecting SARS-CoV-2 from blood tests, like real-time polymerase chain reaction (RT-PCR) tests that detect the presence of the virus by amplifying the virus' genetic material until it can be detected by scientists in a microbiologist lab, and also from a nasal swab or saliva rapid antigen tests (Brinati et al., 2020) that are now self-administered too. The latter tests work by detecting specific proteins-antigens, on the surface of SARS-CoV-2 particles by a convolutional neural network which classifies microscopy images of single intact particles of different viruses (Dey et al., 2020). Physicists and biomedical scientists have worked with clinical collaborators to make this discovery possible. The rapid antigen tests are now provided by pharmacists and can be done by individuals at home.

All methods (CT, x-ray, blood tests) seem to bring results that are quite accurate, though not of the same accuracy. This is important when considering countries with different levels of medical technological resources. These Covid-19 detection methods are fast, widely available and do not impose substantial cost. Even the chest imaging AI models can be implemented in any radiology department providing the opportunity to also be implemented in deprived areas via telecommunication analysing the images remotely (Ardakani et al., 2020). These applications can gain society's trust because they can provide accurate results creating the sense of a widely available and accessible system that is not influenced by personal or human bias (Nouri, 2021). The majority of developed countries appear to embrace technological advances by providing social status rewards to innovation and holding more patents for inventions including patents related to Covid-19 (Frey et al., 2020). However, certain cultures may be more skeptical towards technological advances, which deprives them of participating in the testing of new diagnostic tools and therapies (Drissi et al., 2020). In a cyclic way, this skepticism may lead to exclusion of these societies because of their absence from the development phase which may also create reservations for the use of such Covid-19 detection models.

In the second category, we identified systems that predict and monitor whether Covid-19 will spread in the population, forecasting the progress of the outbreak and the relevant policy decision scenarios such as "no action," "lockdown," and "new medicines" (Alanazi et al., 2020; Allam et al., 2020). Another study in this area proposes a "bioinspired metaheuristic" model, which simulates how Covid-19 spreads and infects healthy people from the primary infected individual (patient zero)

using data such as reinfection probability, spreading rate, social distancing measures and traveling rate to simulate Covid-19 activity as accurately as possible (Martínez-Álvarez et al., 2020). Another novel application is a drone model, equipped with a thermal vision camera to detect human body temperature in order to monitor the spread of the disease in the population (Manigandan et al., 2020). We also observed the use of ML algorithms to identify possible Covid-19 cases more quickly using phone and web surveys (Rao and Vazquez, 2020). Sentiment data such as spatio-temporal data detecting human mobility have been used by researchers in various fields (e.g., computer scientists, statisticians, and epidemiologists) in order to capture population movement patterns and trajectories (Abdallah et al., 2020). The necessary data are collected by smartphones and transmitted for further mapping analysis e.g., call detail records (CDR) data from mobile network base stations and from a wide range of surveillance technologies, such as facial recognition and thermal cameras, biometric wearables, smart helmets, drones, smartphone GPS, QR codes, and Bluetooth functions (Kitchin, 2020). Specifically, GPS aids in crowd mapping for tracking the spread of Covid-19. The Bluetooth smartphone function detects other devices retained for a certain time within a specific range of distance and notifies the smartphones that have been sufficiently in contact with the infected individual's device, assuming that the infected individual has reported the infection to the app. The QR codes scanning method with the physical temperature testing equipment or thermal imaging cameras track through the smartphone app the individuals' movement on public transport (Li and Guo, 2020). Such use of GPS, QR codes and Bluetooth tracking data have been implemented by governments of several countries, such as Australia and Singapore, through the use of a centralized governmental mobile app, to trace whether infected patients are staying at home as part of quarantine measures or have come in contact with infected individuals (Li and Guo, 2020). Based on the predictions of these novel models, policymakers make decisions about population movement restriction measures. The variety of these applications provide outcomes based on the real situation, helping governments issue lockdown policies only in specific places, instead for the whole country, to balance the human rights of free movement against the health risks. However, pursuing such applications comes with challenges such as personal rights violation because restriction measures such as quarantines, canceling mass gatherings, isolation may conflict with ethical and religious principles. Moreover, tracing and tracking the movement of infected people (like they do in Singapore) also violates people's privacy, so people might not comply with these measures (Nguyen et al., 2020). Furthermore, these prediction models use real-time, regional data, which assumes that data collection takes place locally and repeatedly, but not all regions or even countries have the technological and financial resources or the expertise to develop prediction models for continuous Covid-19 monitoring.

The third category of applications refers to models predicting mortality risk. Some of the models forecast the mortality rate in specific countries (An et al., 2020). Many studies focus on defining the right parameters for predicting mortality from Covid-19. These parameters are gathered from healthcare settings and include the number of positive Covid-19 cases per day in the population, hospitalized Covid-19 patients, respiratory rate, arterial oxygen partial pressure, chest x-ray images (Assaf et al., 2020) and more. There are also novel applications that can predict the risk of patients with other chronic diseases, such as cardiovascular diseases (Brown et al., 2020) or glaucoma (Bommakanti et al., 2020). In this category, we also identified ML models using the Covid-19 patients' geographical, travel, health and demographic data to predict the severity of the cases and the possible outcomes (recovery or death) in nationwide cohorts (Iwendi et al., 2020). In these studies, researchers and medical professionals across the world have used population demographic and clinical data from national healthcare centres and laboratories to provide safe results at the national level (Budd et al., 2020). In the same category, there are also mobile applications and wearable sensors for analyzing and reporting the status of health, fitness

and recovery or risk probability of Covid-19 patients by identifying pain levels and variations in heart-rate (Josephine et al., 2020). Using the predictive national mortality rates and other demographic indicators such as education, migrants background, religion and employment, policymakers can closely monitor the populations and communities most affected and avoid health inequities (Tai et al., 2021). However, because socioeconomically disadvantaged people from low income and education levels face barriers to obtaining, processing, and understanding basic health information and following instructions, they may not be able to participate in national level studies and health interventions (Stormacq et al., 2020), such as the studies that require mobile apps and wearable sensors for their analysis. As a result, social minorities may be under-represented in such population observations and therefore may not obtain the appropriate treatment when needed (Kirby, 2020). Studies have shown that widely used algorithms to identify high-risk patients were significantly biased against race groups, revealing systemic inequalities that led to poor access to care for such groups (Röösli et al., 2021).

The fourth category is optimizing Covid-19 patient management in healthcare centres. The articles in our review discuss several applications, such as systems that outline the route of Covid-19 patients in the intensive care unit (ICU) considering the queueing parameters, while optimizing necessary resources such as beds and associated hospital costs (Belciug et al., 2020). This category also includes the development of the CPAS, the Covid-19 ML-based hospital capacity planning and analysis system in the UK. This system was deployed in coordination with NHS Digital (Qian et al., 2021). In this category we also find studies that use ML modelling to predict the length of Covid-19 patients' hospital stays based on clinical data (Kasilingam et al., 2021). In all these applications, medical staff and administration within hospitals and among hospital networks have used various data to facilitate the management of COVID-19 patients: hospital admissions, bed occupancy and electronic health records (EHR) from the hospital information systems (HIS), drug prescriptions from the e-prescription system, and medical images from the cloud-based medical image sharing systems of healthcare centres (Bae et al., 2020). Improved patient management in emergency departments decreases delays in treatment for all patients and increases social distancing and safety in healthcare centres. It is true though that not all healthcare systems worldwide can support these efforts of fast re-arrangement of resources or appropriate resources' acquisition (e.g., extra ICU beds) to react to urgent situations. Therefore, this might lead to better treatment of civilians in high-income countries compared to developing countries, creating social inequalities (Alamo et al., 2020). Moreover, heavy reliance on AI models for optimal allocation of limited resources for tackling Covid-19, such as ventilators, ICU beds, lead to delicate decisions that may provide a false sense of objectivity and equity while diverting scarce resources from regular healthcare services (Laudanski et al., 2020).

In the fifth category, we included models that intend to create warning systems for society by using data from several sources to look for Covid-19 pre-symptoms. We also found ML models that combine disease estimates from digital traces, such as official health reports, Covid-19-related internet searches, and news media activity to forecast Covid-19 activity in certain areas in real-time (Liu et al., 2020). Also, there are digital approaches such as contact tracing apps to manage population mobility and to provide the public with dynamic and credible updates on the Covid-19 pandemic (Nakamoto et al., 2020). Patient behaviour data are gathered from mobile apps, such as from GPS and from beacons or QR codes that may reveal the spatial location of the users. Based on these data, the models reveal congested population areas so that health policymakers and governments can release restriction warnings (Simmhan et al., 2020). Similarly, in this category we also include studies using electronic wearable devices for immediate sensing of Covid-19 clinical symptoms, such as fast heart rate (Pépin and Bruno, 2020). However, ethical concerns have been raised about the broad use of contact tracing technology and therefore app developers are

prompted to build more trustworthy platforms for collaborative use of raw individual-level data which will ensure that private information is not used against certain social groups (Chatfield and Schroeder, 2020). Documentation, validation and explainability of these platforms is a first step regarding the transparent use of such intellectual property (Luen-go-Oroz et al., 2020). Transparency is necessary to understand intended predictions, target populations, hidden biases, class imbalance problems including the ability to generalize emerging technologies across hospital settings and populations (Rösli et al., 2021).

In the sixth category of applications, we identified models that focus on drug repurposing and investigational therapies such as IDentif.AI (Abdulla et al., 2020), an AI-based platform, which can interrogate a 12-drug candidate therapy set, representing around half a million drug combinations against the SARS-CoV-2 virus collected from a patient sample. Such platforms identify drug interactions and optimize infectious disease combination therapy that inhibits lung cell infection with clinically relevant dosages (Abdulla et al., 2020). Another application is an AI-based approach that integrates known information about the functional interaction of proteins with experimental and patient data available in public repositories, with a focus on clinical translation. Simultaneously, a web server uses an alternative method to corroborate the drug combination (Artigas et al., 2020). Overall, these applications, developed by bioinformatics researchers and medical laboratory staff, use pharmaceutical data translated in drug regimens and doses. By testing them and comparing clinical outcomes from laboratories, such as cell density, allow physicians and drug manufacturers to mix or create certain drug substances for (to-be) infected patients to face the virus (Abdulla et al., 2020). These platforms accelerate the process of identifying Covid-19 treatment, ensuring populations benefit from best practices and enhancing the value of equity when such drug combinations are easily available in all countries' healthcare settings. However, if drug patents, manufacturers, and expensive or scarce substances are involved, then equity is usually lost, and exclusion plays out especially for low-income people in developed countries and the population in developing countries. Moreover, there are different opinions and ethical considerations about whether specific clinical trials due to the urgent situation have correctly followed the existing medical protocols in terms of recommended processes and time allowed for realizing side-effects (Agoro, 2020). Furthermore, in most cases, the clinical trials are held in developed countries and the patient sample may not be appropriately diversified. Until recently, the majority of such samples consisted of young white men (Murthy et al., 2004). Clinical research should ensure diversity and inclusion by creating mechanisms that better engage with underrepresented communities and include patient samples from diversified race, ethnicity, age, and sex. A high-quality dataset must be collected at first in order to mitigate bias in the data being fed into the AI application (European Union Agency for Fundamental Rights, 2019).

In the seventh category, we identified studies about applications for detecting probability of false negative or false positive Covid-19 cases. These applications use ML approaches to identify the top performing analysis methods and determine the accuracy of SARS-CoV-2 detection in nasal swab samples of rapid antigen tests (Nachtigall et al., 2020). In addition, they determine the accuracy of frameworks that collect real-time symptoms data from Covid-19 cases (such as fever, cough, shortness of breath) from biosensors and wearable devices and physicians monitoring suspected cases using cloud infrastructure and propose algorithms avoiding false positive or negative results (Otoom et al., 2020). Best practices in medicine, and more accurate disease diagnoses are considered social goods for all populations. However, the complex nature of AI solutions may also lead to biased output because of the unpredictable or unexpected occurrences in the internal data analysis process that inform about false alarms and emergent measures in society (Sipior, 2020). Due to possible bias, these systems denote their accuracy percentage for their prediction, however, this percentage might also be miscalculated (e.g., rapid test results accuracy). It is known that actuarial risk algorithms in the US health insurance industry affect millions

of patients and may exhibit significant racial and other biases at a given risk score. Specifically, in cases of false test results, the algorithms may result in decisions causing unequal access to care as health systems rely on such prediction algorithms to classify patients with complex health needs (Obermeyer et al., 2019).

In the eighth category, we find ML algorithms that are used as vaccinology tools to investigate the entire SARS-CoV-2 proteome, which is crucial to viral adherence and host invasion, in order to induce high protective antigenicity (Ong et al., 2020; Zame et al., 2020). Pharmaceutical data such as proteomes, proteins genomics, etc. are analyzed by such applications in pharmaceutical companies and laboratories to introduce vaccines to the populations (Ong et al., 2020). These applications lead to faster invention and introduction of vaccines which can offer protection to large populations and especially to groups of people most at risk. Nevertheless, because AI/ML algorithms are often developed on non-representative samples and evaluated based on narrow metrics, algorithmic bias and disparity may exist (Zou and Schiebinger, 2021). Moreover, the Covid-19 immunity ethics has started a big debate among societies (Allam et al., 2020) about the criteria applied for the acquisition of these vaccines from drug manufacturers (usually the main criterion is based on monetary values meaning that rich nations are the first to get them) and the distribution rules within a nation's population as for the prioritization of the groups of people who are first vaccinated (Chagla and Pai, 2021).

The last category includes bioinformatic models that attempt to understand the nucleotide sequences of diseases, analyzing the viral genome sequences using approaches such as data stream, digital signal processing, and ML techniques (Batra et al., 2020). The methods invented to analyse the DNA sequences of virus are the beginning of analysis of many other diseases by geneticists. These methods lead to a better understanding of the viruses and other diseases' behaviour, and eventually to the discovery of better therapies and treatments. A major social concern is the extended use of automated applications to manipulate genetic data which are stored in electronic databases without clear rules for their management, who uses them and for what purpose (Capps et al., 2019).

4.2. BDA/AI applications for individual and community

Continuing with the next set of applications pioneered during the Covid-19 pandemic that are targeted to individuals or communities, we come across models that report populations' mental health impacted from Covid-19. An example of this is the design of a sophisticated AI chatbot, on a smartphone application, that can diagnose and recommend immediate measures to psychologically distressed patients who have been exposed to the virus (Battineni et al., 2020). Such an application is especially useful for people living in remote areas. Other applications combine ML methods and AI using data collected from Twitter—about the healthcare environment, emotional support, business economy, social change, and psychological stress—to analyse reactions and sentiments of citizens from different cultures and to advise on subsequent actions taken by different countries (Imran et al., 2020). Another indicative study developed a digital platform to detect the needs and pressing situations of frontline healthcare workers through a self-assessment test and provide support resources for their well-being (Mira et al., 2020). Data sources of these applications are mainly people behaviour data retrieved from questionnaires, social media networks and platforms, or mobile applications. The analysis of these data by the IT specialists provides information to psychologists, physicians, and policymakers in order to detect new mental health statuses and other needs in certain segments of the population (e.g. children with prolonged home confinement due to school closures and social distancing) and offer support. Inclusion and protection of vulnerable social groups (such as the children, domestic violence victims, unemployed, healthcare workers, people with mental health disorders, and the elderly) is attempted by customizing these applications to cater for the

forementioned subpopulations (Balcombe and De-Leo, 2020). However, data gathered from social media platforms spark data privacy concerns, especially when it involves sharing confidential healthcare information. Moreover, the inability of many elderly and disabled people to use technology, such as mobile apps through which these innovations are offered, may finally exclude them (Sufian et al., 2020). Therefore, the developed applications might not reach the populations most in need of support.

The second set of applications under this category includes chatbots through mobile apps invented to track and directly communicate individuals' vital signs to a registered doctor to be factored into a treatment decision (Ros and Neuwirth, 2020). This category also includes the design of mobile apps such as "Check Your Mask," which validates the correct way to wear a protection mask by taking a selfie and suggests improvements to limit the spread of Covid-19 and protect people from infection through personalized measures (Hammoudi et al., 2020). Moreover, it includes mobile-friendly applications and sensors that incorporate algorithms that consider epidemiological factors like fever, breath sounds and other symptoms to help patients decide when to seek medical care (Heo et al., 2020). This kind of tool provides immediate healthcare to people who have difficulty moving, such as the elderly or disabled, making it possible to be included in medical treatment. However, as said before, these groups of people may not own or be acquainted with the use of such technology. Moreover, this more automated diagnosis process may affect the doctor-patient relationship and undermine doctors' diagnostic authority in the long-term (Lupton and Jutel, 2015).

The third set of applications uses ML-based frameworks to measure the spread and tension of misinformation to verify the credibility of data from social media (Al-Rakhami and Al-Amri, 2020). Attempts such as CovidSens, a social sensing-based risk alert system, analyses social data to infer the state of Covid-19 propagation, keep the general public informed about the spread of Covid-19, and identify risk-prone areas by predicting future propagation patterns (Rashid and Wang, 2021). These models are mainly created by computer scientists who run sentiment analysis on data of a certain time period gathered from social sites and platforms (e.g., tweets). Therefore, the results identify and track untrusted sources of Covid-19 information that derive from certain religious or political groups, and measure the "traffic" that this information has created by the number of followers, likes, etc. This knowledge is valuable to cyber fraud policymakers for protecting societies from disorientation and conspiracy theories. However, not distinguishing between intentional and unintentional spread of false information probably driven by different ideologies may result in unethical criticism of opinions of certain social groups (Brennen et al., 2021).

The fourth set of applications is relevant to lockdown measures introduced by several governments, which affect personal life and the global economy. Flexible modelling frameworks have been developed that use available epidemiological data to show the results of lockdown measures in slowing down the disease transmission in specific countries (Aguiar et al., 2020). To locate problems and mitigate consequences, ML classification models and complex algorithm models evaluate the effectiveness of lockdown regulations by investigating whether a correlation exists between lockdown procedures and infection rate (Al Zobbi et al., 2020). Epidemiological data and healthcare information systems data (such as ICU admissions) used in these applications are provided by healthcare centres and are continually collected (Aguiar et al., 2020). Another approach uses ML models fed by meteorological and urban data to quantify the health implications of the reduced air pollution in the presence and absence of the lockdown measures (Saravanan, 2020). The information about the positive or negative outcomes from a lockdown policy in society and in the environment is valuable feedback for the policymakers to better protect certain regions and communities. However, the results of these metrics could encourage authorities to continue strict measures, increasing individuals' psychological problems and creating social frustration by limiting social

interaction (Ardabili et al., 2020). Extended lockdown policies may lead to society division and social confrontation and conflict.

The fifth set of applications is models for investigating different communities' reactions to the same news about the Covid-19 outbreak. An indicative study investigated reactions by analyzing the text of readers' comments on news of lockdown measures and social distancing norms across India, such as masks in public spaces and on transportation (Debnath and Bardhan, 2020). Other applications used the same method to compare different populations and countries (Imran et al., 2020). In these applications, computer scientists, usually from IT consulting companies or universities, use data mining techniques to retrieve user comments from social media and press articles when a new policy regarding Covid-19 is released. Then, they apply text analytics and sentiment analysis techniques to capture public opinion. The results are discussed with policymakers, psychologists, and communication specialists to evaluate the impact of the policy. In case of massive public reaction, policymakers will either drop the policy, or based on the reported arguments, will attempt to persuade the public to abide by the regulation. The benefit of this type of application is the ability to recognize different social groups' reactions and inform policymakers for improved healthcare policies. On the contrary, there are issues to ascertain credibility hidden behind anonymity (e.g. internet trolls) that is intended mostly to manipulate public opinions and therefore it is important that the affected parties should verify the sources of such information (Al-Rakhami and Al-Amri, 2020).

Lastly, we observe frameworks and models, developed by computer scientists and pedagogists, which use AI and educational data analysis tools in learning management systems. Such systems help teachers generate better learning methodologies for online classes and use data mining algorithms in educational databases to identify students' knowledge deficiencies. AI techniques learn from users' interactions by analyzing students' data (e.g., times of microphone-camera on/off, speaking time, chatting time, online quiz scores-performance), and a virtual assistant can be developed to manage the information of each student and offer automatic and personalized monitoring for improving communication and students' learning quality at home (Lv et al., 2021; Villegas-Ch et al., 2020). These efforts lead to a better and more effectively learning experience for socially distanced individuals. However, this effort may exclude people in poverty, who cannot afford the digital infrastructure for distance learning (Budd et al., 2020).

5. Challenges and future agenda

This section reports the findings of concerns as stated by researchers in their studies included in the dataset and their suggestions for overcoming them. BDA and AI provided fast and efficient solutions to face the outbreak but also created numerous challenges. The previous section presented evidence that scientific efforts to find technological solutions to limit the effects of the pandemic effected society positively and negatively, especially in terms of DEI.

Table A3 (appendix) summarizes six main categories of concerns, the main approaches that these studies propose for mitigating them, an indicative reference from our dataset, and the number of studies that refer to each concern.

The most recognized challenge, appearing in 154 papers, concerns the ethical issues of privacy, the use of personal data to limit the pandemic spread, and the need for security to protect data from being overused by technology. Digital technologies could be abused by benign users, malicious attackers, public authorities, and other powerful players in social media, compromising integrity and confidentiality and creating financial loss and social upsets (Wang et al., 2020). For example, genetic information and viruses' DNA sequences are included in electronic databases without being regulated for their management and maintenance, who is allowed to use their information and for what purpose. It is fundamental to create ethical frameworks for bioinformatics and new paradigms to safeguard and oversee data collection and

storage (Capps et al., 2019).

Researchers call for collective efforts from multiple parties, including governments, health agencies, practitioners, service providers and users, with the common objective to build security and privacy defense lines that cover both technical and social aspects. Researchers highlight the need for strong legislative protection, such as the General Data Protection Regulation (GDPR), the e-Privacy Directive, and the European Charter of Human Rights to safeguard the right to privacy and data protection (Gasser et al., 2020). They also advocate for even more specific protocols, such as the Pan-European Privacy-Preserving Proximity Tracing (PEPP-PT) for development of apps that monitor the spread of the disease and alert people if they have come into contact with a Covid-19 positive case. Despite these guidelines and laws, the consensus amongst the technical community is that some of these frameworks are too academic for practical development (Li and Guo, 2020). The right direction is to develop apps with decentralized architecture, wherein the personal data is enclosed and controlled by individuals on personal devices, instead of the centralized architecture in which personal data collected through the app is controlled by government authority, which is currently the case of most such apps (Li and Guo, 2020). Even though health data governing, and new legislative proposals increasingly focus on privacy by limiting or controlling access to health-related data, implementation of more inclusive strategies is necessary for protecting such data. These strategies must go beyond a pure privacy focus and extend to preventing or penalizing uses that could harm individuals (McGraw and Mandl, 2021).

Another possible challenge of BDA/AI applications is the biased outputs that may result from hastily monitoring the pandemic to offer solutions—the fast collection of not so “clean” data and circumventing some validation model checks. AI systems are built on learning from data, and if the data is skewed, it can have major consequences. Therefore, outcomes from analytics systems may be biased and perform poorly (Kiener, 2020). The teams developing AI Covid-19 applications in organizations may not be diverse enough to build inclusive applications that reflect the diversity of the general population (Nouri, 2021). If these AI Covid-19 applications are not appropriate because of the aforementioned reasons, then it is a case of wasted scarce resources which could have been used for more pressing societal needs.

In the previous section, we argued that AI solutions are essential in reflecting the changed circumstances of life imposed by Covid-19; however, because of the complexity, the degree of confidence in AI results or datasets must always be examined (Sipior, 2020). Since biases may exist in all BDA phases - from how the model is designed, developed and deployed to the quality, integrity and representativeness of the underlying data sources - developers must consider (or be required by national or global authority directives) addressing these biases, and physicians should recommend policies while considering the biases of parameters due to the need for fast solutions (Sipior, 2020).

In the case of an international emergency, the dissemination of factual and timely information is a crucial part of the collective response. Research of previous epidemics show that social media has been effective in presenting the public with both factual and false information (O'Brien et al., 2020). As observed, 90% of Internet users seek online health information as one of the first tasks after experiencing a health concern, so this pandemic exposed societal concerns about online misinformation that can exacerbate the pandemic (Choudrie et al., 2021). For instance, newsfeed algorithms may amplify misinformation and existing approaches are difficult to scale manipulation and bias in human consumption of information or exacerbate polarization among populations with different political or religious perceptions (Bhadani et al., 2022).

For this reason, scientists insist that new methods for testing credibility be developed. They also insist that reputable organizations, such as government bodies and health agencies (e.g., World Health Organization) open links to society and establish a presence on social media as an integral part of their communication strategy with frequent updates

and reports in the national and international levels, so that populations can rely on them for credible information (Naeem et al., 2021).

Additionally, the content analysis of our article pool revealed social inequalities. For example, less developed countries have been excluded from health solutions because modern digital health works well in developed countries that have a fully equipped health system using AI and various mobile-based applications (Kaushik et al., 2020). For this reason, scientists raise concerns about social inequalities due to the unavailability of digital tools and services. They also point out the absence of regulatory authorities avoiding malpractices and, therefore, the need for an appropriate body to consider solutions for patients' data ownership and acceptance of digital health. This goal is to minimize inequity and inequality, and also to raise money to build appropriate smart infrastructure worldwide as the spread of the pandemic does not follow country boundaries (Ndiaye et al., 2020).

There are also concerns about the so-called “immunity ethics” and the societal consequences of Covid-19 immunity passports and the obligation to get vaccinated. Vaccines are particularly urgent because globalization and immigration play a major role in the spread of Covid-19. The control of vaccination through new cutting-edge technologies also creates challenges (O'Brien et al., 2020). Many legal issues ensue about whether immunity counts as a beneficial act for the individual and society or whether these immunity passports incentivize discrimination (Allam et al., 2020). Since a person infected with or vaccinated against Covid-19 can still get the infection again and spread it, there are doubts about whether immunity is achieved. Countries using immunity passports should consider the societal consequences of this decision as it might lead to division in society and raise conflict with uncertain medical evidence to support the logic behind the measure. Immunity passports would impose an artificial restriction on who can resume social and economic activities which might perversely incentivize individuals to seek out infection, especially economically deprived people who cannot afford a period of workforce exclusion (Phelan, 2020). Therefore, governments should be as inclusive as possible in offering access to activities to all people who can safely prove they are Covid-19 negative (e.g., through test, vaccination, or natural immunity) (Drury et al., 2021).

Lastly, three studies emphasized the inequalities in various regions of education and training on how to apply BDA/AI solutions to combat the pandemic. These studies informed policymakers about the risks of certain regions not following best practices. These inequalities may exist in training healthcare workforce in BDA and in how to use the new applications to benefit their population. The global nature of the pandemic requires global solutions, but there is also a need to adapt in certain areas because of their characteristics, such as in pastoral areas, refugee camps or conflict zones to consider different socioeconomic, or cultural and structural variables (Luengo-Oroz et al., 2020). Therefore, policymakers should consider worldwide education strategies in BDA in terms of each country's workforce (Paudel, 2021).

An analysis of our dataset also reveals a future agenda of BDA/AI opportunities that offer solutions to Covid-19 or other crises.

This pandemic experience has shown societies that future living will need to be adaptable. Digital technology can provide opportunities to respond to many future societal challenges and scientists should create future smart ecosystems for collecting, analysing, and sharing real-time information and performance benchmarks to be used by health service providers and policymakers (Marston et al., 2020). New ML and soft computing models should be invented to predict outbreaks and the complex variations in their behaviour across nations by providing benchmarks (Ardabili et al., 2020). Moreover, biobanks should be integrated into healthcare systems, which can preserve the biological material and host prospective cohorts and material related to clinical trials so that research infrastructure can offer access to materials for future medical crises (Holub et al., 2020).

Future applications must also focus on more complex frameworks that can instantly analyse high volumes of emerging clinical trials on

therapies, such as those for Covid-19. Also, these new applications, combined with emerging disciplines such as bioinformatics and cheminformatics, should target structure-based drug designs, network-based methods for prediction of drug-target interactions, and work with AI, ML and Phage techniques to provide alternative routes for discovering patent drugs (Omolo et al., 2020).

Also, social media can further be exploited to offer novel insights. Since Covid-19 revealed that people can experience symptoms for many weeks as well as post-covid symptoms that may change over-time, data about patient experiences could be used to develop rapid assessments of large numbers of social media conversations to monitor public health (Picone et al., 2020).

6. Discussion

Our study reviewed the publications on the Covid-19 pandemic that use BDA and AI algorithms. After providing a dataset profiling of relevant papers, we focused on the applications developed for public health and for the individuals/community, and we examined their impact on society and medicine. This review sheds light on the many benefits of BDA/AI Covid-19 applications and also on their challenges and limitations, especially in terms of DEI. From the literature review, future research prospects include ways to overcome some of these challenges and work towards developing more applications to combat Covid-19 and other crises.

The most frequently used methods relevant to BDA are AI algorithms, specifically ML and deep learning. Researchers mainly from computers and medical informatics disciplines have developed the relevant applications that cover BDA capabilities, such as evaluation, prediction and monitoring. A lot of studies cite the first publications about the pandemic demographics from Wuhan, where Covid-19 started.

Based on the results of our dataset, we identified numerous BDA applications for Covid-19 with novel ML algorithms focused on public health evaluation and prediction models for identifying Covid-19 positive patients, mapping the spread of the disease in the community (Allam et al., 2020), forecasting the severity classification of Covid-19 hospitalized patients and estimating Covid-19 patient admission and in-hospital mortality (Abdulla et al., 2020). These applications have aided decision-making for local or national lockdowns and other measures. This study also identified applications developed for individuals, including mobile applications (mHealth) that use behaviour data to support people facing psychological distress from social distancing, unemployment or overwork (Battineni et al., 2020). Applications also applied text analytics in social media platforms to monitor public opinions about Covid-19 and associated restriction policies (Debnath and Bardhan, 2020), and the sources of misinformation (Brennen et al., 2021) which inform policymakers.

Without underestimating the benefits of these applications on the general population, it is important to stress the concerns that are raised. These concerns are related to equity and exclusions of certain population segments, usually the poorest ones, from participation in and using these new applications and their byproducts (e.g., more healthcare resources allocated to Covid-19 patients; and reducing infection with appropriate local policies, vaccines and new drugs), mainly due to lack of technological infrastructure, financial resources and research expertise (Kirby, 2020; Stormacq et al., 2020).

Moreover, the relevant literature showed that the top challenges of using BDA during the pandemic are: “data privacy,” “bias of output” and “spread of false information”. The use of high volumes of personal data for public-health surveillance raises legal concerns about security and privacy, and interventions have allowed consensual adoption or have made the option of public consent for specific purposes explicit, which highlights the need for public trust and engagement (Budd et al., 2020). Furthermore, there is a lot of discussion on the use of ‘black box’ AI in medicine and the systematic bias between AI’s implicit assumptions and

an individual patient’s background situation (Kiener, 2020). Therefore, physicians must be alert when incorporating patients’ data and interpreting outcomes.

Taking this a step further, it is possible that public authorities and other powerful players may abuse the technologies at the expense of privacy and human rights. Therefore, while the health emergency was depicted as a positive force driving the development and adoption of new digital technologies at scale and speed, their uninhibited implementation in some areas raise legal, ethical and privacy concerns intensifying risks for disadvantaged communities (Hantrais et al., 2021).

Moreover, the development of m-RNA technology and fast vaccine production at a low cost is another benefit for public health. However, many countries’ low vaccination percentages of certain minorities such as migrants, the disabled and people with low income have raised a lot of discussion about their inclusion in the vaccine programs and targeted campaigns (Njoku et al., 2021). A great debate has also started about some countries’ decisions to use compulsion rather than persuasion for their immunization programs and the possibility such decisions do more harm to the well-being of free people than good (Pennings and Symons, 2021). This is also relevant to the discussion of immunity passports which will allow individuals to return to their daily activities but raise immunity ethics concerns regarding pros and cons for the society.

Overall, Covid-19, as a threat to world-wide well-being, has led to vast research into BDA for Covid-19 and the rapid “commercialization” of research. The need for urgent solutions has led researchers to shorten their models’ validation processes to produce fast treatment outcomes. It is hopeful, however, that this need has brought information disclosure related to research about vaccines and drugs formulas that prevent/treat the virus. However, pharmaceutical patents have restricted access to generic supplier companies to develop the vaccine (Siegel and Guerrero, 2021).

The articles also identify the future direction of these applications, describing experimental models and systems that explain human-machine interactions and promote approaches for better data management in unpredictable situations (Iandolo et al., 2020); digital technology that create smart ecosystems to respond to possible health crisis by mitigating diversity, equity and inclusion challenges (Marston et al., 2020); and prediction models of outbreaks that incorporate variations in the behaviour across nations and biobanks (Holub et al., 2020).

It is a great opportunity to learn from the pandemic and its accelerated technology advancements attained in a short time. We can learn how to use related BDA/AI technologies to deal with similar humanitarian disasters in the future. There is also a great need to address the unintended consequences of Covid-19 with BDA/AI technologies.

For example, the models for optimizing Covid-19 patient management in healthcare centres (Table A1-group 4) that focus on appropriate hospital resources allocation can also be used to deal with the reallocation of healthcare delivery resources (e.g., physicians, beds, surgical theatres). These models can address the unintended consequences of Covid-19 such as the prolonged postponement of elective surgeries and treatments which have surmounted during the pandemic making people’s general health deteriorate.

In addition, this pandemic has created many other economic and societal challenges due to social isolation and increased unemployment. These challenges include the increase in mental health cases among children and adult population, addiction to internet usage, agoraphobia, and poverty. Therefore, improving and increasing use of models for mitigating populations’ mental health impact from Covid-19 (Table A2-group 1) is very important to be able to identify psychological distress and addictions and provide these people healthcare resources to fight the problems. Such applications can be improved and used through a mobile app which will monitor patients by scheduled questions related to their health and a chatbot that can provide appropriate responses, through text classification and trained ML algorithms. In combination with behavioral data received by the smartphone (such as phone activity, step counter, sleep, and heart-rate monitor) and video-call

capabilities, a doctor can monitor and manage the patients and intervene with telemedicine when necessary.

The same applies to models for providing personalized telehealth (Table A2-group 2) as this may become the new reality of health services not only for teleconsultation but also for more healthcare tasks, such as measuring vital signs using a mobile app. The increasing use of such models can enhance patient management with patient support systems for automated messages, such as appointment reminders/bookings, clinical results release, and drug prescriptions through an authentication process. Such telehealth options will provide more efficient service and give access to more people, especially all vulnerable people or those leaving in rural areas.

Additionally, with small adaptations in the collected data and in the spread patterns, models for predicting the spread of Covid-19 in the community (Table A1-group 2) can be used for other diseases in the future and for different regions. Models measuring the spread and tension of misinformation for Covid-19 (Table A2-group 2) can be used for other situations of breaking news to flag misinformation.

Models such as those for the immediate identification of Covid-19 positive cases from CT chest images (Table A1-group 1) can be used for more purposes and be functional in mobile apps. For example, image recognition capabilities, such as Google lens, can be embedded in a mobile app and a trained algorithm can perform image matching and automatic differential diagnoses [e.g. for skin cancer (Zakhem et al., 2018) or drug effectiveness from a petri-dish image (Agarwal et al., 2019)].

Another BDA/AI health application for enhancing doctors' experience could retrieve similar patients EHRs by matching a patient's disease, and the doctor can evaluate possible disease progress, survival analysis, causal inference, etc. (Schuler et al., 2018).

These new health applications could shape the future of healthcare and improve society's well-being. However, before such apps are released in the market, many issues must be resolved related to data governance and equity for their availability to all segments of world population.

7. Conclusions

This article illustrates how the pandemic accelerated the adoption of digital technologies such as new applications for diagnosis, e-health online therapies, online working, learning and social interconnectedness. Along with the benefits came new challenges demanding government interventions to prevent harm and social exclusion associated with technological development that did not necessarily result in social progress (Hantrais et al., 2020).

Commercializing science and AI algorithms into useable applications in day-to-day healthcare could bring certain benefits to society, medicine and business, and ethical practices could reduce the negative impact on society. The first step to minimize the risk and provide safe healthcare to humanity is recognizing and identifying the possible effects of using innovative technology when technology becomes the basic road of survival in case of a sudden attack, such as the recent pandemic.

BDA applications created opportunities to identify who is getting sick and dying and who is in danger of being affected, helping governments to take social distancing measures and public health agencies to direct money and resources to the populations most in need (Lopez and Neely, 2021) (e.g., by creating more Covid-19 hospitals and ICUs). On the other hand, numerous scholars, doctors, and policy experts have argued different health inequalities including developing nations with limited health resources, minorities with limited access to healthcare settings and vaccination programs and restriction policies that people find hard to follow due to lack of resources, religious perceptions and ideologies concerning the suppression of human rights.

Detailed guidelines and regulations are needed when developing such applications to ensure technology transparency and data privacy and protection. Moreover, healthcare professions and other segments of

the workforce require training in BDA/AI techniques for better comprehension, use and correct interpretation of the results. Global policymakers should provide necessary resources to introduce the BDA/AI applications equally in the healthcare systems of all countries to equip them with appropriate tools to combat future challenges and to cater to public health and society's well-being. Moreover, they should transfer the generated knowledge of which policies have worked well and which have not for all segments of society in terms of exploiting the new technology for informed decision-making.

This pandemic has introduced new policies and ideologies, raising awareness of the need to create a more caring society (Lopez and Neely, 2021). At the same time, as societies have learned to function remotely during the pandemic, advanced mHealth apps will become very relevant in the near future for accomplishing many health tasks such as diagnosis and health monitoring faster and from everywhere (Galetsi et al., 2021), making healthcare accessible to wider populations. The development of responsible technology must be the target of all health applications, which will help society solve the major problems that affect the well-being of human populations and come closer to the broader mythology of tech-fixes for social problems (Holzmeyer, 2021).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.socscimed.2022.114973>.

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