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Review

Data-Driven Analytics Leveraging Artificial Intelligence in the Era of COVID-19: An Insightful Review of Recent Developments

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Abstract: This paper presents the role of artificial intelligence (AI) and other latest technologies that were employed to fight the recent pandemic (i.e., novel coronavirus disease-2019 (COVID-19)). These technologies assisted the early detection/diagnosis, trends analysis, intervention planning, healthcare burden forecasting, comorbidity analysis, and mitigation and control, to name a few. The key-enablers of these technologies was data that was obtained from heterogeneous sources (i.e., social networks (SN), internet of (medical) things (IoT/IoMT), cellular networks, transport usage, epidemiological investigations, and other digital/sensing platforms). To this end, we provide an insightful overview of the role of data-driven analytics leveraging AI in the era of COVID-19. Specifically, we discuss major services that AI can provide in the context of COVID-19 pandemic based on six grounds, (i) AI role in seven different epidemic containment strategies (a.k.a non-pharmaceutical interventions (NPIs)), (ii) AI role in data life cycle phases employed to control pandemic via digital solutions, (iii) AI role in performing analytics on heterogeneous types of data stemming from the COVID-19 pandemic, (iv) AI role in the healthcare sector in the context of COVID-19 pandemic, (v) general-purpose applications of AI in COVID-19 era, and (vi) AI role in drug design and repurposing (e.g., iteratively aligning protein spikes and applying three/four-fold symmetry to yield a low-resolution candidate template) against COVID-19. Further, we discuss the challenges involved in applying AI to the available data and privacy issues that can arise from personal data transitioning into cyberspace. We also provide a concise overview of other latest technologies that were increasingly applied to limit the spread of the ongoing pandemic. Finally, we discuss the avenues of future research in the respective area. This insightful review aims to highlight existing AI-based technological developments and future research dynamics in this area.

Keywords: artificial intelligence; COVID-19; data-driven analytics; privacy; epidemic; epidemiological investigations; epidemic containment strategies; healthcare; data lifecycle

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1. Introduction

The recent pandemic of novel coronavirus disease 2019 (COVID-19) has changed our lives into a new normal where free-mobility, social gatherings at a large scale, and traveling seem impossible for the next couple of years. The COVID-19 has forced the closure of many cities and borders for a prolonged period of time. Furthermore, changes in the business/work hours and operating procedures of most organizations have completely changed. One of the biggest religious gatherings of the world at Mecca was cancelled or scaled down due to the pandemic last year [1]. Specifically, the whole world is going through an unanticipated and extraordinary challenge of COVID-19 [2]. Although there is a bright hope in terms of vaccine to end this pandemic, its distribution to underprivileged countries is a main challenge. Furthermore, rehabilitation of the healthcare system to pay ample attention to other existing diseases is also one of the main challenges in the near future [3]. In the absence of potential vaccine, one of the main technologies that played a critical role in combating the pandemic is artificial intelligence (AI) [4]. It can help in curbing the disease spread through contact tracing, social distancing, quarantine monitoring, trends analysis, symptoms reporting and analysis, symptoms clustering, symptoms severity estimation, disease spread modeling, and alerting. We explain these services in detail in Section 3. A generic overview of application areas where AI has already demonstrated its effectiveness are shown in Figure 1. This study demonstrates AI applications in the context of the COVID-19 pandemic.

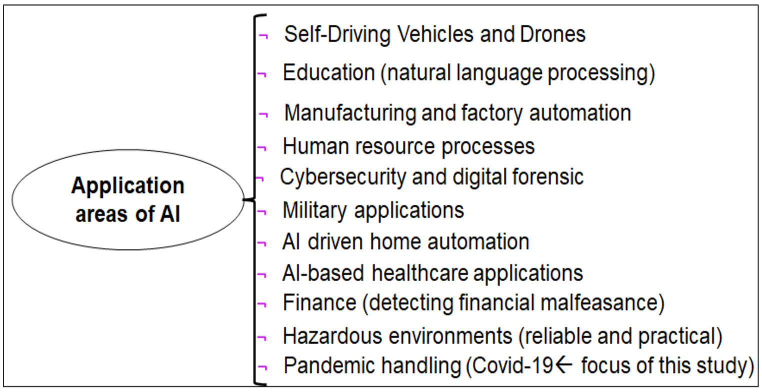

Figure 1. Overview of application areas of AI (Ref. [5]).

The impact and efficacy of AI techniques and models have been reported by many countries in curbing the disease spread. AI models have helped to identify the transmission routes of this disease and helped in mitigating the disease [6]. Further, the adoption of AI aided in recovering the economies from the low-levels with improved policies [7]. The adoption level of AI in each country was different. We present the latest finding about AI use with real-data until November, 2020 [8] and synthetic data from November, 2020 onward in the top ten countries across the globe in Figure 2.

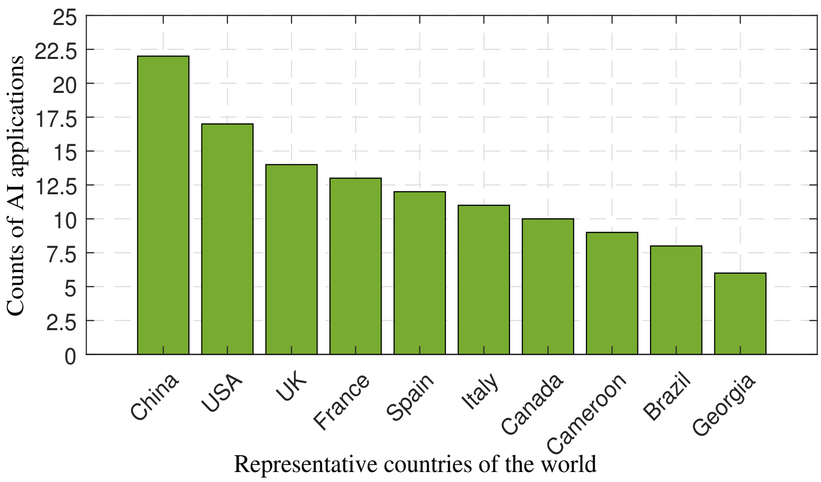

Figure 2. Histogram of data about the use of AI techniques in ten countries (Ref. [8]).

From the results provided in Figure 2, it can be seen that the adoption of AI was higher in China, and this is the first country that curbed the pandemic spread quickly [9,10]. Besides the higher use of AI during this pandemic, the adoption of technical mechanisms (e.g., automated decision support systems, AI-driven diagnosis, and mobile doctors etc.) in the healthcare sector are relatively higher in China compared to other countries [11,12]. Therefore, AI-powered healthcare systems as well as other rigorous measures helped China to contain the spread of COVID-19 quickly. Furthermore, in those countries that adopted AI techniques at a smaller scale, the pandemic forced the closure of many facilities and activities [13]. Although AI played a vital role in this pandemic, many barriers were there in the adoption of AI, such as privacy and data manipulation, etc. In Figure 2, we chosen a sample of ten representative countries based on the origin of the pandemic, severity of disease, higher daily cases tally, digitization in the healthcare sector, and/or COVID-19 variants reported. In some countries (i.e., India, Pakistan, and Bangladesh), the covid cases were relatively higher, but adoption of the digital mechanisms in all these countries is significantly lower. That is why we did not include those countries in the analysis.

There are several studies that have covered this topic, especially AI role in the ongoing COVID-19 pandemic [14–18]. However, these studies have covered only general services of AI in COVID-19 context, and the main emphasis of most studies was on digital surveillance (or contact tracing). Furthermore, the data-driven analytics on actual data and AI essence from multiple perspectives have not been covered in prior studies. To cover these deficiencies, this study provides insightful coverage of the state-of-the-art studies that have devised ways to fight with COVID-19 pandemic leveraging AI. The main contributions of this article in the field of AI-based data-driven analytics in the COVID-era are summarized as follows.

- It covers the role of AI in COVID-19-era in six distinct regards such as epidemic containment strategies (ECS), epidemic data life cycle (EDLC), epidemic handling with heterogeneous sources data (EHHSD), healthcare-specific AI (HCSAI) services, general epidemic AI services (GEAIS), and drug design and repurposing (DDAR) against COVID-19 that have not been covered in the recent literature.
- It discusses the challenges involved in applying AI on the available epidemic data that is not in desirable form until present due to several problems (e.g., diverse formats, legislation, heterogeneous sources, and privacy concerns etc.).
- It elaborates the privacy issues that arise due to the person-specific data movement in cyberspace amid the ongoing pandemic.
- It provides a concise overview of the latest technologies other than AI that contributed in the fight against the recent pandemic through their innovative features.
- It discusses many state-of-the-art studies that have applied AI techniques in the ongoing COVID-19 pandemic for beneficence (i.e., greater good to save lives).
- It provides many state-of-the-art studies that have demonstrated the role of IoT based on heterogeneous data stemming from the ongoing pandemic to lower its effects.
- It discusses the synergy of AI with other emerging technologies in order to lower the effects of COVID-19 on the general public and economies.
- It provides the avenues of future research in the respective area keeping the latest technologies in loop.

The rest of this paper is organized as follows. Section 2 describes the prior research status and compare presented work results with related work. Section 3 provides the role of AI in fighting against COVID-19 through unique services in six different aspects. Section 4 discusses the challenges involved in applying AI on the COVID-19 data that is not in perfect until present. Section 5 summarizes the work, discusses emerging technologies role, AI synergy with other techniques, IoT-based developments in COVID-19 context, and provides promising future research directions. Finally, this article is concluded in Section 6.

2. Prior Research Status

In this section, we concisely present the contribution of previous studies, and compare proposed work results with related work. From the start of this deadly pandemic, AI has played a vital role in tackling it from a non-pharmaceutical interventions (NPI) point of view across the globe. The unique applications of the AI have paved the way to manage the resources well, and lowering the mortality rates through precise forecasting [19–21]. With the help of precise forecasting, extra care can be provided to the vulnerable people having underlying diseases, and treatment can be done on the regular basis [22,23]. Consequently, mortality rates and ICU admission can be prevented in most cases [24]. Arora et al. [25] discussed the potential applicability of AI in the development of early warning systems and accurate and timely forecasting about cases/mortality leveraging social media data. The study suggested that AI can be used in different aspects pertaining to COVID-19, but various issues like unavailability of the large datasets, ethical concerns, security and privacy, and computing resources remain challenging. Huang et al. [26] provided comprehensive coverage of the AI in terms of clinical applications. For example, authors discussed the diagnosis of the COVID-19 via images, ultrasounds, chest scans, X-rays, lab indicators, electronic medical records, and lab indicators. Authors discussed AI role as experienced physicians for diagnosing COVID-19 robustly and accurately. We present the approach of Huang et al. [26] that was proposed in order to perform diagnosis of leveraging AI based on medical characteristics in Figure 3.

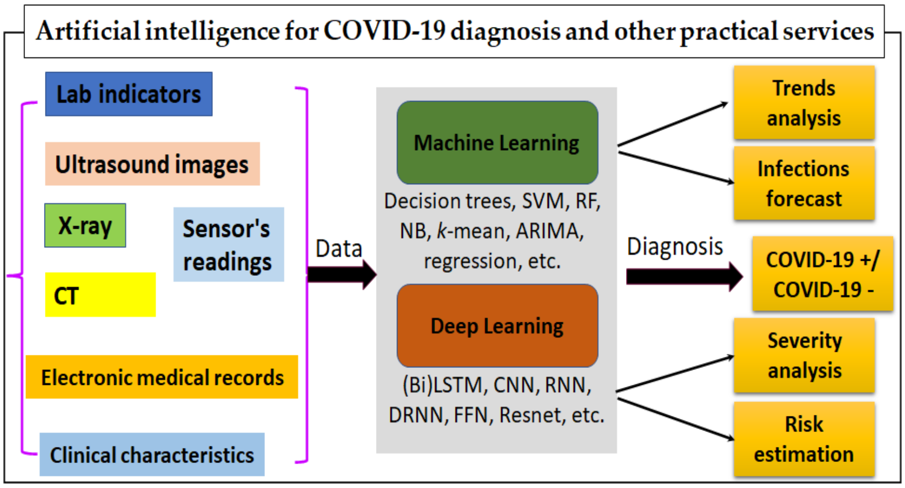

Figure 3. A flowchart of the AI methods employed for COVID-19 diagnosis and other relevant services: ML and DL were mainly applied in the medical characteristic to diagnosis the COVID-19 infection (Partially adapted from Huang et al. [26]).

Motta et al. [27] discussed the AI role from COVID-19 diagnosis and spread control point of views. The authors stressed the need of AI-powered decision systems to fight with the infectious diseases. Cave et al. [28] emphasized the need of using AI ethically while fighting with the COVID-19. Authors discussed four pillars of the biomedical ethics in order to get true benefits from the AI during crisis. The four pillars are (I) Beneficence, (II) Non-maleficence, (III) Autonomy, and (IV) justice. These pillars are an integral part of the healthcare settings in order to truly benefit from AI applications.

- Beneficence: It means that AI use should be beneficent (i.e., save lives) in managing the ongoing pandemic.
- Non-maleficence: It means the objective function of AI systems should be defined carefully in order to avoid unintended harms while managing the pandemic. For example, imposing strict self-isolation on elderly people may lead to mental issues.
- Autonomy: It means that people should be autonomous while controlling and endorsing the technologies including AI during the pandemic. For example, diagnostic support systems employed by healthcare workers in a pandemic should provide enough information about the uncertainty surrounding, and assumptions behind, a recommendation, so that it can be included into their professional judgment.
- Justice: It means that when AI systems are devised for a response to a COVID-19-like pandemic, difficult trade-offs between values could be incorporated. For example, decision about whether to employ centralized or decentralized app approach for data collection in order to manage pandemic should be based on justifiable grounds (e.g., involvement of diverse communities/stakeholders in decisions).

Leslie et al. [29] discussed the dark sides of the AI in terms of health inequity. Authors suggest that in order to reduce the inequalities, a collaboration between different stakeholders is paramount. An important perspective regarding the use of untested AI algorithms/methods in COVID-19 context is presented by the authors [30]. Authors suggested that in order to fully affirm the role of AI in saviour of the pandemic or future pandemics, we need to test the solutions with proofs. Chang et al. [31] concisely discussed the role of the AI from different perspectives including diagnosis to therapy. Authors discussed the role of the AI in three aspects such as epidemiology (predictions mainly), diagnosis, and therapy. According to the study findings, mismatch between epidemiology and data science need to be resolved in order to take advantage of the AI approaches for future endeavors. Vaishya et al. [32] analyzed the literature, and discussed the seven most significant AI applications (as shown in Figure 4) for the COVID-19 pandemic. Authors suggested that AI can play a dominant role in decision making and treatment consistency through robust algorithms. We fully agree with the contributions and significance of all studies cited above in the context of COVID-19 pandemic.

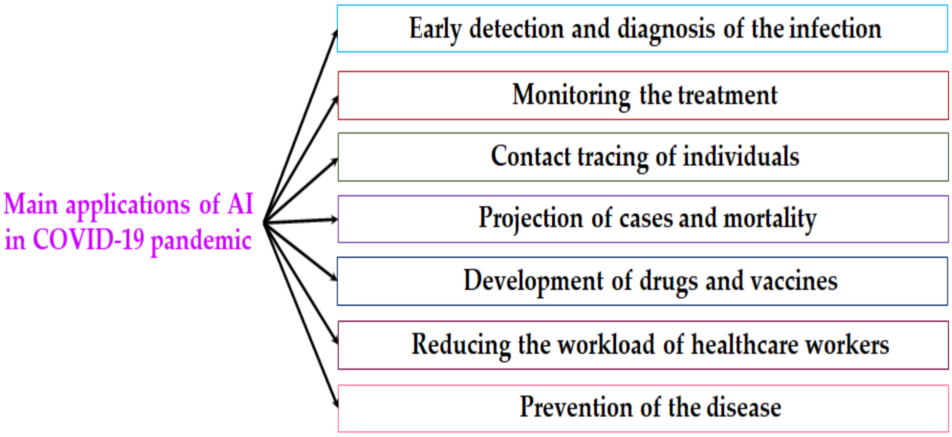

Figure 4. Overview of seven innovative AI applications in the context of COVID-19 (Adapted from Vaishya et al. [32]).

The advantages and significance of the proposed work compared to the prior studies are summarized as follows. (i) it provides insights about huge variety of data that is essential to fight with the COVID-19 leveraging AI from different perspectives, (ii) it discuss AI role in data life cycle and containment strategies that is not covered by any of the previous studies from broader perspective, (iii) it discusses substantial number of challenges comprehensively that hinder the applicability of AI methods in the ongoing pandemic, (iv) it provides the coverage of AI applications from multiple perspectives rather than one/two aspects, (v) it discusses the role of other emerging technologies with whom AI can be converged to serve the mankind in an effective way compared to the recent past, and (vi) it highlights actual AI applications based on the real-world data originating from the COVID-19 diagnosis or clinical practices.

3. Role of Data-Driven Analytics Leveraging AI in the Era of Covid-19

This section concisely presents the role of the data-driven analytics leveraging AI in the era of COVID-19. We categorize the coverage of AI applications/services in six regards such as epidemic containment strategies (ECS) that are in place as NPIs, epidemic data life cycle (EDLC) (aka data collection, storage, pre-processing, analysis, use, distribution, archival, and secure disposal) that is adopted in healthcare sector to fight with the infectious diseases, epidemic handling with heterogeneous sources data (EHHSD) as relying on a data from few sources is insufficient to fight with COVID-19, healthcare-specific AI services (HCSAIS) that can reduce the burden of healthcare workers, general epidemic AI services (GEAIS), and AI role in drug design and repurposing against COVID-19. These services are unique and emphasize the effectiveness of AI in COVID-19 era. Our aim is to highlight the significance of AI in COVID-19 context through relevant data and services. We identify data that relate with COVID-19 through analysis of the COVID-19 characteristics, and corresponding data. For example, SN tweets and comments that use the word COVID or related aspects such as quarantine, social distance, amid pandemic, and spread etc. are classified as COVID-19 data. In addition, some applications are specifically designed to collect and process data that relate with COVID-19. In some cases, data is collected in a proactive manner, and it can relate with COVID-19 when he/she tested positive. Furthermore, we mainly discuss the additional data collected to fight the COVID-19 that varies from site to site as shown in Figure 9. Apart from these services in six regards, AI has been widely used in analyzing the vaccine distributions and other clinical aspects concerning COID-19. We describe each perspective and AI services in each perspective as follows.

3.1. Perspective 1: Epidemic Containment Strategies and AI Role

From the beginning of the pandemic, each country of the world introduced certain strategies to contain the spread of COVID-19, including strict lockdown, cities and school closures, remote telehealth, closure of bars and clubs, and work from home, etc. Apart from these general containment strategies, many digital solutions based on the latest technologies for exposed people identification, close contact analysis, and compliance monitoring with the disease guidelines were also developed. We call such solutions epidemic containment strategies (ECS), and provide different AI-supported services in each ECS. We present the role of AI in seven different ECS that were extensively used in COVID-19 in Figure 5. Based on the extensive review of published studies, we found that AI remained a critical component of every ECS developed to contain the spread of COVID-19 [33–37]. Apart from the services cited in Figure 5, AI can play a vital role in alerting people stay away from the virus contaminated places pro-actively. In addition, it can be used to identify the focus group to whom COVID-19 can affect more due to underlying diseases. Hence, the role of AI in each ECS is vital and essential. Data reported in Figure 5 can be gathered from multitude of sources. For example, surveillance data can be employed for the contact tracing purposes [38]. We present an example of surveillance data based contact tracing example in Figure 6.

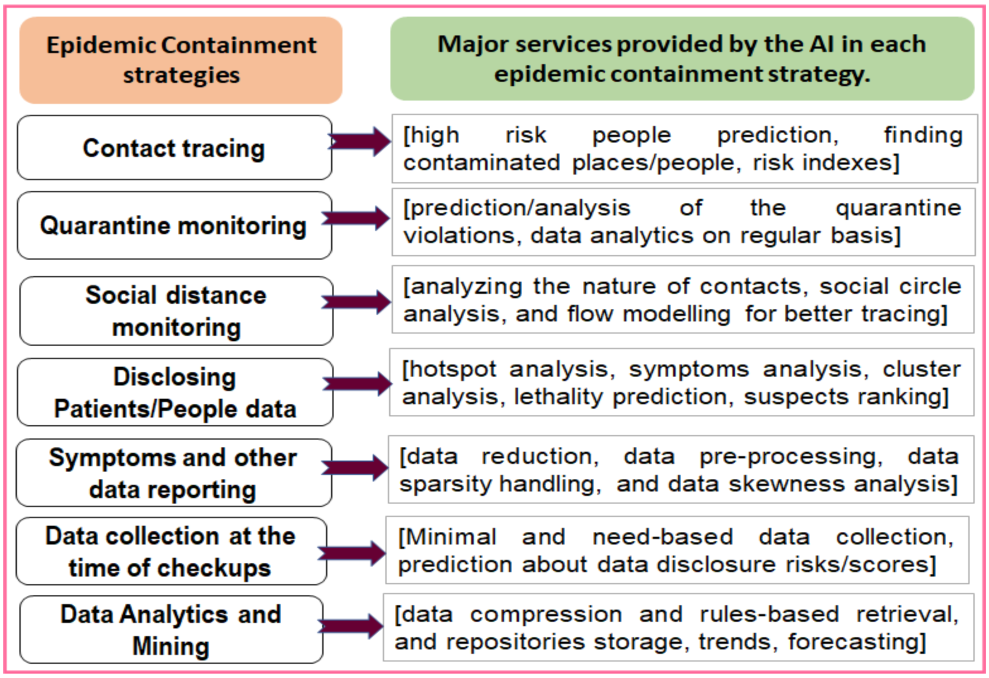

Figure 5. Overview of AI-supported services in ECS in the context of COVID-19 pandemic.

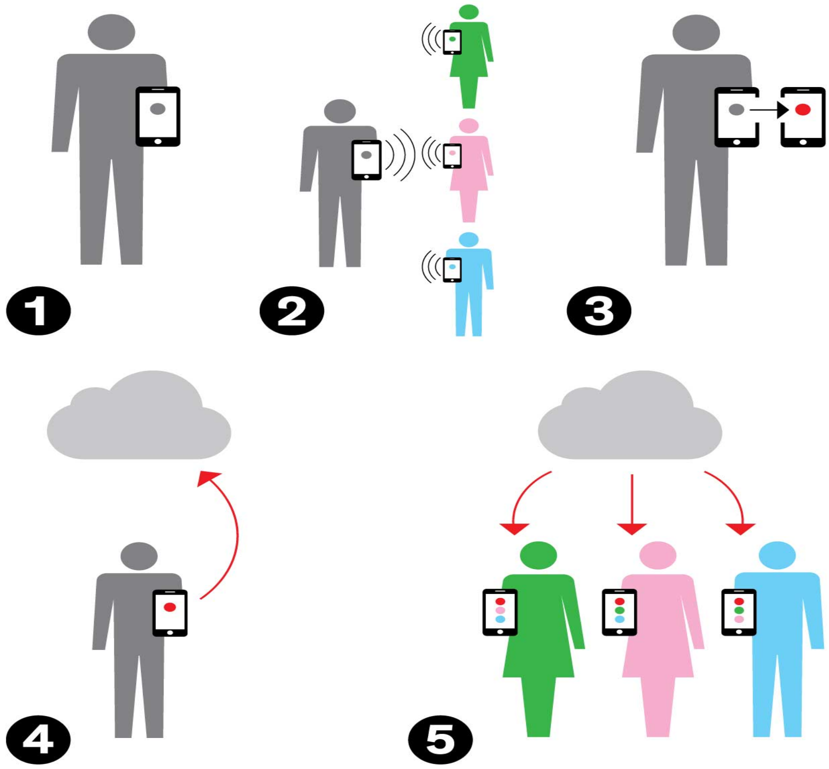

Figure 6. Example of surveillance data based contact tracing for COVID-19 suspects finding. (1) Person A goes to work, bringing a Bluetooth-enabled cell phone with a digital key, which is used to communicate with other cell phones. (2) Person A comes in close contact with persons B, C, and D; all their cell phones exchange key codes with each other. (3) Person A later learns he is infected with COVID-19 and enters his updated status in the app. (4) By agreeing to share his recent status with the database, A instructs the app to send the data to the cloud service. (5) Meanwhile, B's, C's, and D's phones are regularly synchronising the cloud database to check the status of their users' close contacts. When B, C, and D discover that person A has reported himself infected, they all know they should get tested for the COVID-19 (Adapted from Hsu et al. [39]).

The mobile devices generated big data that can be used to monitor the people under quarantine [40]. In addition, GPS data can also be gathered for quarantine monitoring purposes [41]. In South Korea, health authorities usually call people on their cell-phone randomly, and such calls data can be used for the quarantine monitoring. The data to monitor social distance can be collected through Bluetooth technologies, video sequences, smart camera, and IoT platforms [42–45]. Data about the exposed/infected people can be gathered from the relevant clinics/diagnostic-centers. It can be shared with different entities to find the contacts of infected people [46]. COVID-19 symptoms and other related data can be gathered with the help of the wearable sensors, ambient tools, and smart phone technology [47,48]. Personal data at the time of the check-ups can be collected via automated/traditional forms. Subsequently, this data is used to rank the areas based on COVID-19 prevalence etc. Finally, CT and X-ray images data [49], ultrasound imaging data [50], text data [51], social media data [52], biomedical data [53], and big data [54] can be used during analytics. Apart from the data sources mentioned above for each ECS, data can be collected from heterogeneous sources for each category. For instance, analytics can be performed on data collected from variety of sources such as smart watches, sensors, mobile technology, CCTV cameras, GPS locations, Bluetooth devices, and smart write bands, to name a few. In Figure 5, the risk indexes are the quantitative values that denote the risk of being infected with COVID-19 based on gender, age, health status, city of residence, and knowledge of vaccine/treatment. This value is highly useful to evaluate infection risk accurately and taking preventive measures accordingly. AI can be used to rank the most influential indicators, and predicting the index accurately. The parameters used in each AI model can be different. For example, if random forest is employed then parameters can be number of trees, variables required for tree split, sampling scheme, trees' complexity, and model type, etc. The choice of parameters and their values highly depends on the AI model chosen for the desired task.

3.2. Perspective 2: Epidemic Data Life Cycle and AI Role

In South Korea, if a person tests positive for COVID-19, then his/her contact details are collected to find the exposed people [55]. Different entities (i.e., police, mobile carriers, and credit card companies, etc.) collect contact data and process it in accordance with the specified procedures. This mechanism usually follows a lifecycle such as data collection, storage, pre-processing, analytics, use, archival, and deletion. We call this whole process an epidemic data life cycle (EDLC). We describe the role of AI in the EDLC in Figure 7.

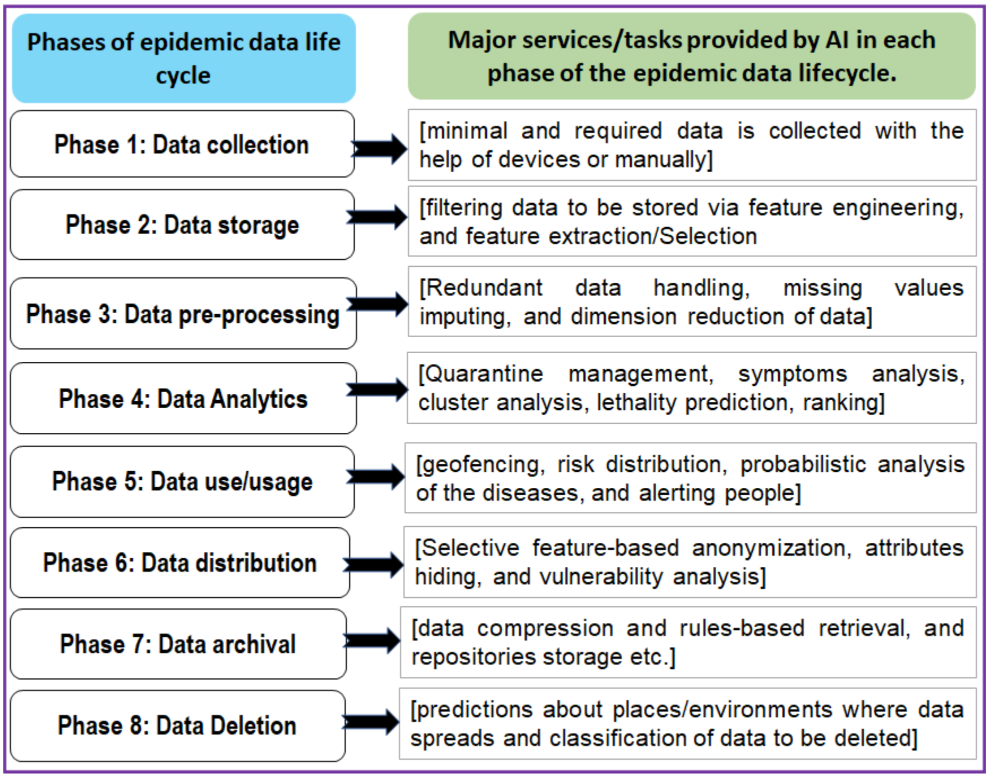

Figure 7. Overview of AI-supported services in EDLC in the COVID-19 context.

AI can enable real-time decision making based on the collected data through EDLC. Since EDLC is essential to curb the spread of COVID-19, different AI mechanisms can be used at each phase of the EDLC. Although AI contributes significantly in all phases of the EDLC, geo-fencing of a certain area to contain the spread of COVID is one of the most useful applications. In geo-fencing, people of certain areas are put under home quarantine, and later they are monitored whether they are within the geo-fenced area or not using AI [56,57]. The example of a geo-fenced area (also referred as hotspot) with a dotted line is shown in Figure 8.

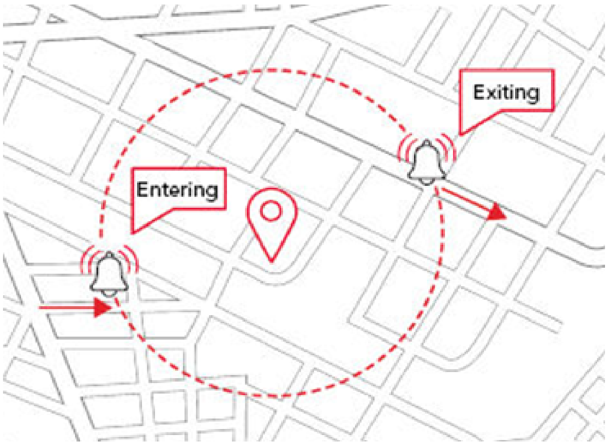

Figure 8. Example of the geo-fenced area.

In South Korea, health authorities usually keep track of the geo-fenced zones/areas and people living in respective areas through real-time location data processing via smart phone application. Furthermore, wrist bands were also used to monitor the quarantine violations in the geo-fenced areas. Data reported in Figure 7 can be collected from the infected individuals by either interviewing them or using the devices (i.e., cell phones) owned by them. Furthermore, every country has implemented various epidemic handling systems in the form of platforms, mobile apps, and integrated frameworks for supporting the EDLC. For example, South Korea has implemented an epidemic investigation support system (EISS) in which data from multiple companies (e.g., credit card, mobile carrier, and pharmacies etc.) is fed into it [58]. The EISS has an ability to collect and share the data with relevant and authorized entities. Similarly, Singapore Government asked their citizens to install a mobile app through which social interactions were recorded and processed with proper consents. Furthermore, data in EDLC can also be collected from the IoT devices and digital tools such as CCTV. The CCTV data have played a vital role in finding the COVID-19 suspects in South Korea. For example, when a sporadic cluster emerged at a gay club, then CCTV data has played a vital role to identify the people who may have been come into contact with infected people leveraging multiple CCTVs footage. We invite interested readers to gain more insight about type and nature of data processed in EDLC in previous studies [59,60]. In [59], authors discussed the consequences of COVID-19 on different people based on their working environments. In [60], authors discussed the importance of big data technologies in processing large scale data. Most of the AI models can handle the missing values present in a data. Furthermore, a simple and popular approach to address missing values related issues is data imputation. It employs statistical methods in order to estimate a value for a column from those values that are present, then replaces all missing values in the column with the calculated statistic. Furthermore, many AI models predict the missing values based on the original data statistics, and determine the missing values.

3.3. Perspective 3: Epidemic Handling with Heterogeneous Sources Data and AI Role

Due to the nature of this pandemic, reliance on single data source, for example, relying solely on individual memory to figure out the contacts he/she has made in the past fourteen days or using popular SN data only to find vulnerable regions [25], etc.) has proven unsatisfactory in many countries across the globe. For example, in South Korea, manual epidemiological investigation (i.e., interviewing confirm patients about their travel information, facilities visits, and persons to whom they met etc.) has failed badly (in addition, it can slow down the containment of virus due to reliance on someone's memory and inaccuracies), and in addition to manual investigation, heterogeneous sources data collection and analysis helped to keep daily cases at a manageable level [61,62]. By using data acquired from different sources such as cellular network, credit card, surveillance cameras, and facilities-visits logs to find the exposed people is called epidemic handling with heterogeneous sources data. Based on the extensive analysis of literature and technical developments [58,63], we classify the countries based on amount of heterogeneous sources data used to handle COVID-19 in four different categories in Figure 9. From Figure 9, it can be observed that South Korea used a huge amount and variety of data. Consequently, South Korea has better control on the ongoing pandemic without strict lock-down. In contrast, France has used less data, but the use of some apps was mandatory, therefore, heterogeneity in data was high. Middle eastern countries have primarily focused on monitoring people compliance rather than huge data collection. In Pakistan, the adoption of digital mechanisms in healthcare industry is relatively low, which is why only required data (e.g., voluntary reporting) was collected and processed during the ongoing pandemic. The heterogeneity in collected data in middle eastern countries and Pakistan are average and low, respectively.

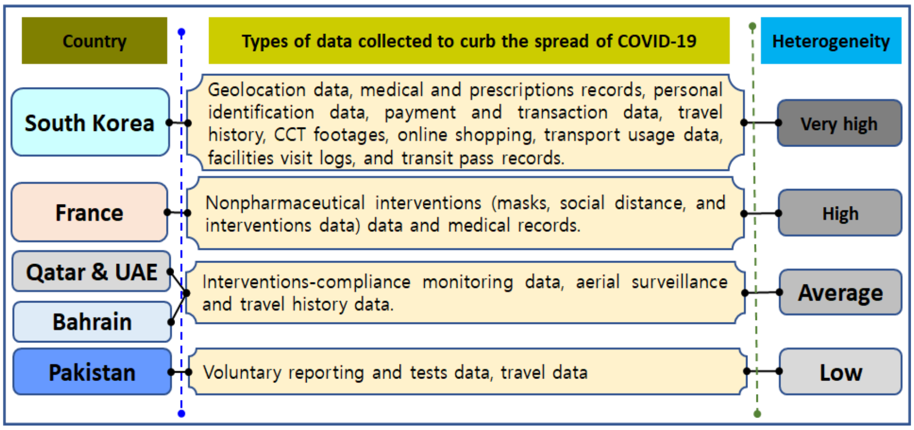

Figure 9. Overview of heterogeneous data collected in different countries of the world.

The different data types listed in Figure 9 can be collected through combination of the digital and manual methods. For example, geolocation data can be collected using GPS sensors or Bluetooth devices. In South Korea, geolocation data of the confirmed patients was collected through mobile carriers. Symptoms and quarantine monitoring related data can be collected using low-cost sensors and/or calling people at random times and acquiring location in real time. Personal data can be collected through forms and websites, etc. Facility visit data can be obtained from logs maintained by each organization on daily basis, and historical diseases data can be obtained from hospital databases and mobile-phone based surveys. Furthermore, travel data can be obtained from the travel agencies or airport staff. Recently, unmanned aerial vehicles have also been deployed to monitor people's compliance with the government guidelines. In addition, data is mostly collected prior to taking COVID test in South Korea. Furthermore, interviews and surveys are promising tools to acquire data. In some countries, cough sound, breathing patterns, blood samples, and temperature reading were taken through integrated platforms and sensors. Furthermore, to assess the spread, weather agencies and meteorologists also contributed to data collection. SN data have also paved the ways for generating symptoms taxonomy, and identification of new and related symptoms to COVID-19. Plenty of data collection methods have been comprehensively discussed by Hensen et al. [64]. We demonstrate the analytics to be performed on the heterogeneous data sources using AI in Figure 10. The analytics results can be extremely useful to keep the cases at a manageable level in order to lower the healthcare burden. Using data-driven analytics from different context can alleviate the pandemic's crisis.

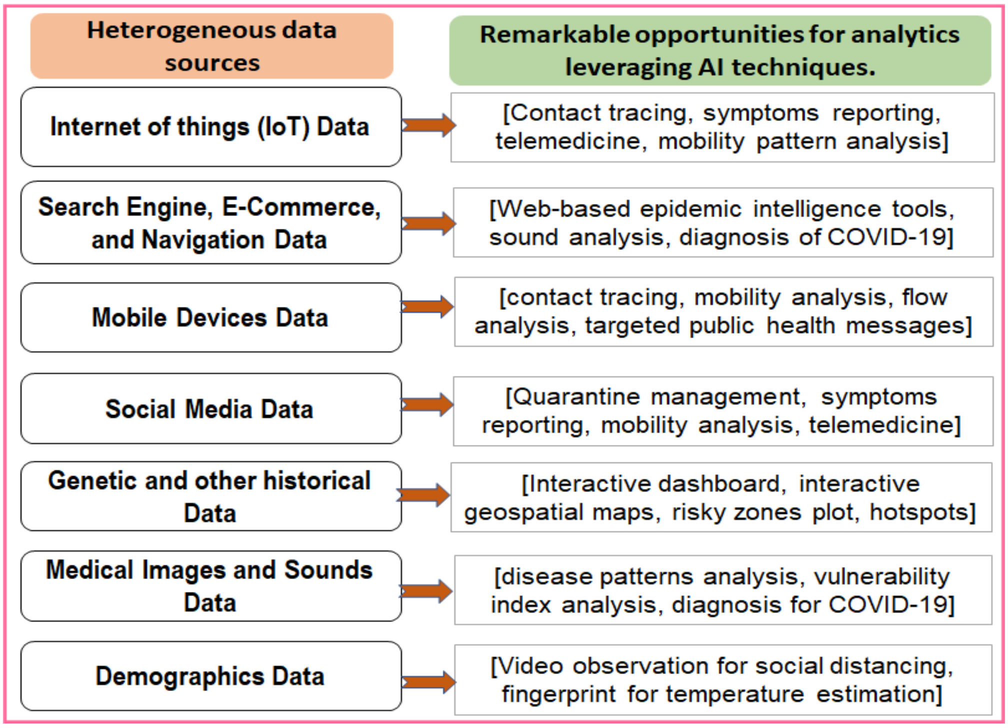

Figure 10. Overview of AI-supported analytics on heterogeneous sources data.

Data reported in Figure 10 can be collected from a variety of devices, apps, and search engines, to name a few. IoT data can be collected from wearable sensors [65], contents, and other related data can be gathered from e-commerce websites [66], mobile data can be gathered from mobile carriers/service-providers, social media data can be collected from SN service providers [67], historical data can be gathered from the hospitals websites/repositories [68], medical images and sounds data can be collected with wearable devices or automated machines, and demographics data can be obtained from trusted clinics/hospitals [69]. The logistic regression based models can assist in identifying hotspots in any territory based on the certain environment parameters and underlying conditions [70].

3.4. Perspective 4: Healthcare-Related Services and AI Role

Besides AI use in data analytics, ECS, and EDLC described earlier, AI can be highly useful to assist in carrying out diagnosis and trend analysis to assist mankind in an effective way [71–73]. In this perspective, we discuss the possible use of AI in healthcare-related services that can have a direct impact on the virus virulence in any country. These services have unique utilities such as lowering hospital burdens [74], caring for elderly patients [75], separating the more risky people [76], and preventing people from being infected with COVID-19 [77]. To this end, we describe many healthcare-specific services of AI in Figure 11. We invite interested readers to the previous study for more details about each service in the context of ongoing pandemic [78].

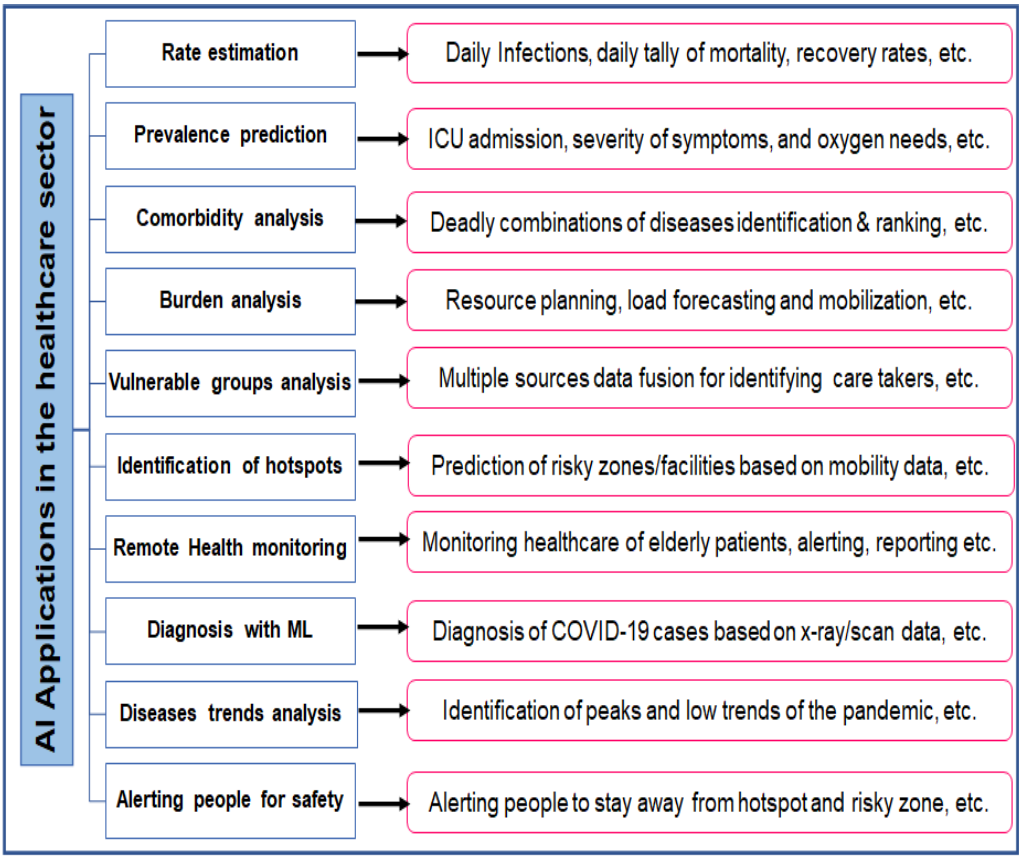

Figure 11. Overview of AI-supported services in healthcare in COVID-19 context.

3.5. Perspective 5: General Epidemic Services and AI Role

In this perspective, we shed light on AI use in other sectors that were directly impacted by the COVID-19 pandemic. For example, predictions about when aviation industries can return to normal [79], how much transportation use reduced in each country due to COVID-19 [80], and recommendations of show/music to alleviate people's stress during this pandemic [81]. AI can play a vital role to access the risk and challenges of any sector during these unprecedented and unanticipated times [82]. In some sense, AI is lowering the human involvement in many sectors through automated and real-time decision making abilities [83]. For example, in south Korea, AI-powered robots were installed at the airports that were carrying similar tasks (i.e., temperature checking, mask status analysis and alerting, social distance monitoring and alerting in case of breaches, and preventing cluster formation of people at one place etc) as humans do [84]. In the new normal, AI use can possibly increase in many diverse sectors. For example, performing analytics using AI based on spatial-temporal data can be handy to predict and prevent future pandemics [85]. In addition, AI experiences can be applied to other epidemics to fight them effectively. We present general epidemic related services of AI in Figure 12.

AI uses in all six perspectives lay a solid foundation for future studies in the same area. It enables researcher and developers to understand the applicability of AI in different contexts. Furthermore, it provides conceptual foundations of AI use in different aspects related to pandemic and AI role in each aspect. Furthermore, these concepts can be exploited to devise new techniques for each services. In addition, there is a chance of improvising each AI technique on COVID-19 data that is relatively new and requires ample work to make sense of it.

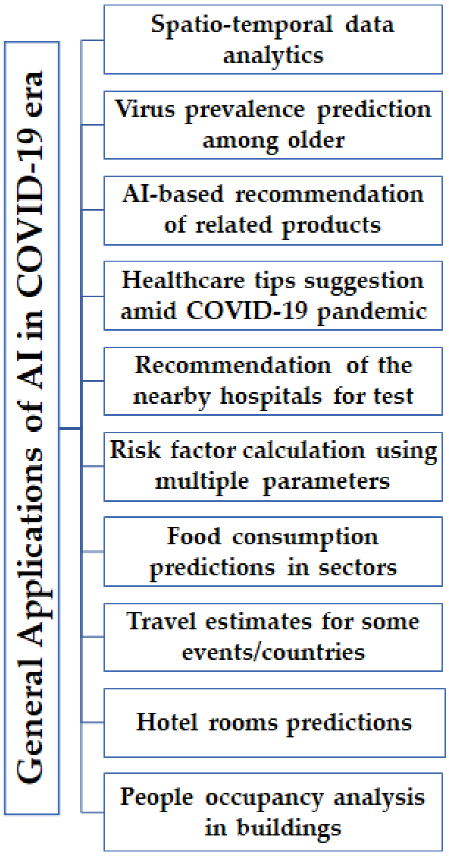

Figure 12. Overview of AI-supported general services in COVID-19 context.

3.6. *Perspective 6: AI Role in Drug Design and Repurposing against COVID-19*

Besides the AI use in the five different perspectives cited above, AI/ML has also been extensively used in computer-aided drug design and repurposing existing drugs against COVID-19 receptor proteins [86,87]. Monteleone et al. [88] discussed the role of AI in drug repurposing with therapeutics analysis for treating infected individuals with COVID-19. In this regard, we summarize the findings of recent SOTA studies in Table 1.

Table 1. Summary of the AI uses/applications in designing drugs and repurposing existing drugs against COVID-19.

Ref.	Discussions about AI Use in the Era of COVID-19 along with Models Details and Purpose Achieved in the Context of COVID-19.	
	AI Technique Used	**Purpose in the Context of Designing Drugs and Repurposing Existing Drugs**
Zhou et al. [89]	Fully connected feedforward neural network (FNN)	Drug repurposing for precision medicine and personalised treatment
Walters et al. [90]	Quantitative structure–activity relationships (QSARs)	Drug discovery by predicting the physical properties and biological activity of molecules
Patronov et al. [91]	Deep neural networks (DNN)	AI-based generative models for drug design to combat the COVID-19
Arora et al. [92]	Deep neural networks (DNN)	Protein synthesis, molecular changes, time management in laboratory for drug discovery
Bhati et al. [93]	ML integrated with PB	Sampling of relevant chemical space for target proteins analysis to make pandemic drugs
Kabra et al. [94]	Combined AI approaches	Finding possible drug candidate to treat COVID-19 patients with antiviral drug
Bai et al. [95]	Genetic algorithm	3D drug design of protein targets for treating COVID-19 patients
Liu et al. [96]	Graph convolutional network (GCN)	Drug repositioning framework to quickly identity potential drugs for COVID-19
Delijewski et al. [97]	Gradient boosting tree (GBT)	Identification of zafirlukast as one of the repurposing candidates for COVID-19
Haneczok et al. [98]	Graph-CNN	Prediction of molecular property and identification of SARS-CoV-2 3CLpro inhibitors

4. Data Challenges While Applying Ai in the Era of Covid-19

AI has played a vital role in many aspects to curb this disease spread. Meanwhile, the true applications were hindered by data that is not perfect and complete in many regards. We present a taxonomy of the challenges related to data that can possibly hinder AI use in Figure 13. These challenges need to be resolved to truly benefit from AI techniques. Some of these challenges can be solved by AI itself. For example, multi-model mechanisms can be used to make sense of heterogeneous sources data, feature engineering can be employed to filter redundant/less-important data before applying AI, data manipulation can be reduced by using advanced form of AI (i.e., federated learning), synthetic data can be generated by projecting original data using AI, and dimensionality can be reduced using many AI techniques.

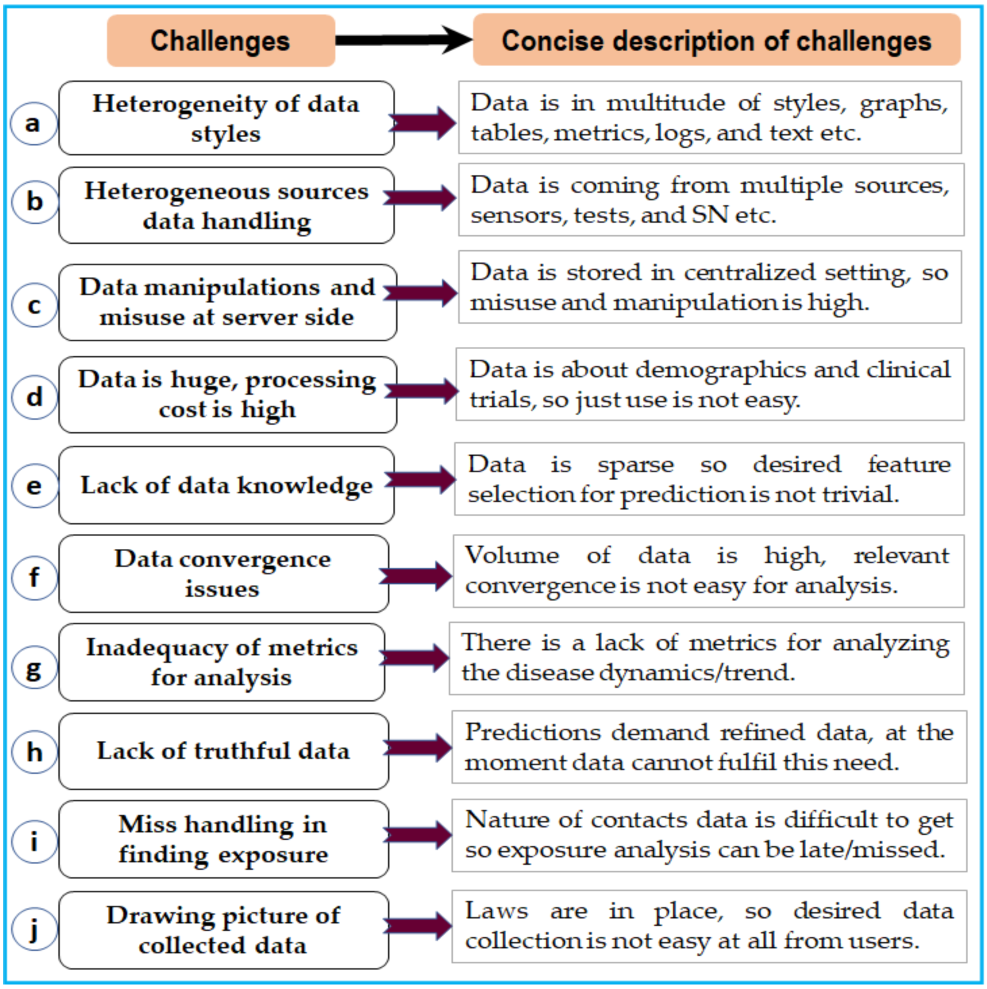

Figure 13. Challenges involved in applying AI in the COVID-19 era due to data issues.

Concise description about each challenge, indicators, and possible solutions are described as follows.

- *Heterogeneity of data styles*: During this pandemic, the data of diverse types is being collected. For example, in South Korea, when a person is confirmed to have a COVID-19, his/her data (contacts, place, demographics, and 14 days visits to every place, etc.) is collected in heterogeneous formats. For example, the routes information can be in graph form, buying items can be in tabular form, and facilities he/she has visited can be in matrix form. Hence, fusing this heterogeneous data from different contexts to find the potentially exposed people is very challenging. It requires parsers and unified format conversion to deal with diverse data that is very challenging.

- *Heterogeneous sources data handling*: During this pandemic, the data can originate from different sources. For example, in South Korea, fine-grained and sufficiently detailed data is collected to curb the disease spread. For example, healthcare sectors are constantly acquiring data from law and enforcement agencies, credit card companies, and SN etc. Hence, handling this heterogeneous sources data during pandemic time is very challenging. It requires interfacing and transparent policies and data-driven approaches to address this challenge.
- *Data manipulation and misuse*: During this pandemic, a huge amount of personal data is being collected on a daily basis. For example, mobility data, trajectory information, buying data, and social interactions, to name a few. Hence, it increases the chance of manipulation and misuse. It requires legal, organizational, and technical measures to address this challenge.
- *Data volume*: During this pandemic, a huge amount of data is being collected on a daily basis about people. For example, in South Korea, before entering any facility, data is being collected along with explicit identity information. Similarly, cellular networks data is used to perform crowd analysis, and identifying people at controversial places. Hence, handling of such higher volume of data is challenging, and it requires usage of high performance computing model. Additionally, it requires low-cost reduction and compression techniques to address this challenge.
- *Lack of data knowledge*: During this pandemic, a huge amount and diverse types of data is being collected from heterogeneous mediums. AI experts and analytics companies have limited knowledge of data structures and formats. For example, temporal and spatial data can be in different formats and styles. Hence, converting such a data into consistent styles prior to AI application is very challenging. It requires domain expertise and visualizations techniques to address this challenge emerging in pandemic times.
- *Data convergence issues*: In this pandemic, data was being collected from different sources, and in different styles (e.g., graphs, matrix, tables, etc.). Correlating/converging different subjects data gathered from different sources and styles is challenging. For instance, analyzing the characteristics of each subject based on data he/she produces or consumes using different sources is an extremely difficult task. It requires pre-processing and similarities-based approaches to address this challenge emerging in pandemic times.
- *Inadequacy of metrics*: In this pandemic, the majority of data analytics was performed using existing metrics that yields imprecise results considering the huge dynamics of COVID-19. For instance, analyzing disease spread based on daily cases and ambient conditions is difficult in the absence of desired metrics. It requires new metrics or amendments in the existing metrics to make them more suitable for use.
- *Lack of truthful data*: In this pandemic, huge variations were observed in each territory regarding the disease severity, symptoms combination, and virus effect on the different age groups. For example, disease characteristics observed in South Korea exhibit large differences to those observed in Japan. Hence, to clearly understand the disease dynamics, there is a lack of truthful data, although some companies/researchers generated synthetic data that is close to the original data for understanding/modeling of the COVID-19 dynamics. Moreover, synthetic data may yield imprecise results in the absence of evidence-based truthful data [99]. This challenge can possibly be solved through data sharing with domestic and international firms, and analyzing data with advanced AI techniques.
- *Mishandling in finding exposure of contacts*: To accurately find the contacts of an infected person, close monitoring of all subjects in outdoor environments is paramount. For example, it requires monitoring of who met with whom? for how long he/she met? what was the nature of contact (e.g., had dinner/lunch or just crossed), whether he/she was wearing masks perfectly or not? and how often he/she met with each other. To capture and analyze all these aspects with fine-grained data collection about each subject can be highly difficult, and it can lead to hidden/silent transmission of COVID-

19. This challenge can possibly be solved through data collection from heterogeneous sources, and analyzing data with advanced AI techniques and integrated platforms.

- *Data collection in a fine-grained manner*: Due to the nature of this pandemic (i.e., spread through close contact), data about people should be collected in a fine-grained manner. Meanwhile, in some countries, data protection laws are in place, therefore, fine-grained data collection is not allowed. Due to which virus can spread, containment is not easy at all. For instance, the recent pandemic spread at a wider scale in European nations due to general data protection regulation (GDPR), which restricts data collection about subjects without their explicit permission. This challenge can possibly be solved through amendments in laws considering the severity of the virus for public safety.

5. Discussion on AI and Latest Technologies Use and Future Research Directions

In this section, we concisely discuss AI use/services in COVID-19 context based on actual data and purpose of using AI, latest technologies that have been used in the era of COVID-19, synergy of AI with other emerging technologies, and promising research directions for future endeavours.

5.1. Discussion on AI Use in the Context of COVID-19

So far, we have reported the coverage of AI-based analytics in the COVID-19 era from six perspectives such as ECS, EDLC, EHHSD, HCSAIS, GEAIS, and AI role in drug design and repurposing against COVID-19. We have rigorously and thoroughly analyzed the scope of AI in all six aspects. This concise overview will enable future research in this area with clear directions/gaps. Specifically, we highlighted the data related challenges that need to be resolved to yield higher adoption of AI, as AI has already demonstrated effectiveness in many aspects related to the COVID-19 [100–105]. Thus, we summarize AI use based on actual data used/processed, AI models applied, and purpose/service achieved in COVID-19 context in Figure 14.

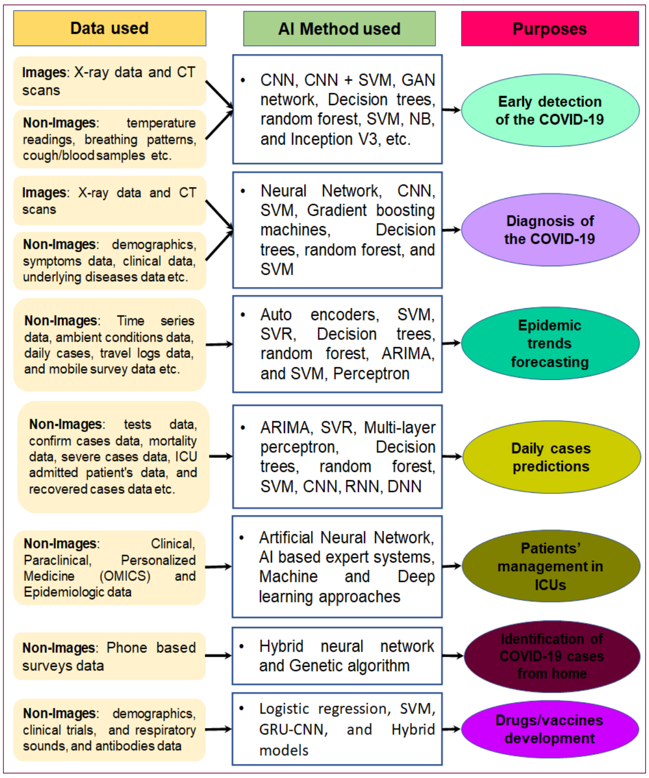

Figure 14. Practical uses of AI to fight with the ongoing pandemic.

Apart from AI unique services cited above, they can be extremely useful in preventing diseases by predicting high risk facilities, and identification of lethal combination based on geographic data that can lead to a higher number of deaths. Furthermore, AI can be handy to analyze protein sequences that can assist in developing potential vaccines for future pandemics. Furthermore, many unique aspects such as robustness, efficiency, large data handling, and reduction in time and cost make AI more attractive for many applications in the healthcare sector. In many countries, AI has been integrated as a main module with decision support systems (DSS) to efficiently fight this pandemic. Apart from the AI services explained above, we describe various promising applications of the AI in the era of COVID-19, keeping AI techniques used in loop in Table 2.

Table 2. Comprehensive overview of the AI use/applications in the era of COVID-19 discussed in recent SOTA studies.

Ref.	Discussions about AI Use in the Era of COVID-19 along with Models Details and Goals Achieved in the Context of COVID-19.	
	AI Technique Used	**Purpose in the Context of COVID-19 Pandemic**
Pinter et al. [106]	Multi-layered perceptron	Predictions of mortality rate and infected cases
Aminu et al. [107]	Deep neural networks	Detection of people with COVID-19
Magar et al. [108]	Ensemble techniques	Virus–antibody sequence analysis and patients' Identification
Zeng et al. [109]	Extreme Gradient Boosting (XGBoost)	Forecasting of patient survival probability
Ashraf et al. [110]	Machine & deep learning models	Predict the severity of disease or chances of death
Shah et al. [111]	Convolutional neural network (CNN)	COVID-19 detection from X-ray images
Prakash et al. [112]	Autoregressive Integrated Moving Average	Impact analysis of various policies
Rathod et al. [113]	AI Prediction models	Effective crisis preparedness and management
Ullah et al. [114]	Logistic Regression and Support Vector Machine	Classification of patients with/without COVID-19
Rathod et al. [115]	SVM, RProp, and Decision tree	Detection of abnormal data for effective analysis
Hu et al. [116]	Spectral Clustering (SC) algorithm	Feasible analysis model for the treatment & diagnosis
Rashed et al. [117]	Long short-term memory (LSTM) network	Provides public awareness about the risks of COVID-19
Singh et al. [118]	ResNet152V2 and VGG16 CNN	Reduce the high false-negative results of the RT-PCR
Saverino et al. [119]	Digital and artificial intelligence platform (DAIP)	Changes implementation in rehabilitation services
Peddinti et al. [120]	Convolutional Neural Network (CNN)	Detection of COVID-19 cases in public places
Malla et al. [121]	Ensemble deep learning model	Real-time sentiment analysis of COVID-19 data
Lella et al. [122]	Convolutional Neural Network (CNN) model	Respiratory sound classification for patient identification
Haleem et al. [123]	Artificial neuronal networks (ANN)	Predictions of survival of COVID-19 patients
Hashimi et al. [124]	Deep learning models	Tracking and identifying potential virus spreaders
Amaral et al. [125]	Artificial neuronal networks (ANN)	forecasting and monitoring the progress of Covid-19
Zgheib et al. [126]	Collection of ensemble learning methods	Detecting COVID-19 virus based on patient's demographics
Ferrari et al. [127]	Bayesian framework	Predictions about the behavior of the COVID-19 epidemic
Almalki et al. [128]	COVID Inception-ResNet model (CoVIRNet)	Automatic diagnosis of the COVID-19 patients
Umair et al. [129]	VGG16, DenseNet-121, ResNet-50, and MobileNet	diagnosis of the virus at early stages via X-rays and transfer learning
Tamagusko et al. [130]	EpiEstim framework	Analysis of the population's mobility during the COVID-19 pandemic
Arvanitis et al. [131]	Ensemble learning methods (RF, SVM, and ANN)	short-term and accurate prediction of effective reproduction number (R_t)
Hussain et al. [132]	Ensemble learning methods (RF, SVM, and ANN)	Analysis of public attitudes on Twitter & Facebook toward COVID-19 vaccines
Kumari et al. [133]	Combination of multi class SVM and CNN models	Contact less authentication system and face mask identification
Talahua et al. [134]	OpenCv's face detector and MobileNetV2 architecture	identifying whether people are wearing face masks or not
Yu et al. [135]	GCNN ResGNet-C under ResGNet framework	Effective diagnosis of COVID-19 from lung CT images
Nayak et al. [136]	Lightweight and robust CNN scheme	Faster and accurate diagnostics of COVID-19 patients
Bekhet et al. [137]	Lightweight CNN architecture	Recognizing COVID-19 patients with a 96% accuracy
Keicher et al. [138]	Lightweight clustering method	Patients outcomes prediction admission to ICU, need for ventilation and mortality
Alshazly et al. [139]	Deep network architectures and transfer learning strategy	CT images-based diagnosis of COVID-19 infected people in an automated way
Carvalho et al. [140]	Convolutional features & genetic algorithms	Screening and diagnosis of COVID-19 patients
Fu et al. [141]	Lightweight DenseANet architecture	Distinction between pneumonia and COVID-19 patients using CT images
Bougourzi et al. [142]	Pre-trained XG-boost classifier	Analysis of sensitivity of the COVID-19 patients from CT images data
Song et al. [143]	Details relation extraction neural network (DRENet)	Person-level diagnoses of COVID-19 using CT images
Alruwaili et al. [144]	Inception-ResNetV2 deep learning model	Visualization of the lungs' infected regions using CXR images
Wang et al. [145]	Inception transfer-learning model	Extraction of radiological features for timely and accurate diagnosis of COVID-19
Jha et al. [146]	logistic regression, SVM, Random Forest, and QSAR	Robust drugs discovery and extraction of features combating COVID-19
Abbas et al. [147]	DeTraC deep convolutional neural network architecture	Classification of COVID-19 chest X-ray images
Sedik et al. [148]	CNN & convolutional long short-term memory (ConvLSTM)	AI-powered COVID-19 detection system using X-ray and CT data
Bhardwaj et al. [149]	Inceptionv3, DenseNet121, Xception, and InceptionResNetv2	Quick and highly accurate automated COVID-19 detection
Muneer et al. [150]	Deep hybrid NN models (GCN-GRU and GCN-CNN)	Prediction of RNA degradation from RNA sequences
Ali et al. [151]	Keras Classification model (also called Keras classifier)	Classifying COVID-19 spike sequences from geographic location
Ahsan et al. [152]	Histogram-oriented gradient (HOG) and CNN	Detect of COVID-19 from the chest X-ray images using model fusion
Raji et al. [153]	Convolution Neural Networks using medical modalities	Robust detection of the virus by using the pre-trained models
Teli et al. [154]	shallow and simple CNN-based approach, named TeliNet	Robust classification of CT-scan images of COVID-19 patients
Jacobs et al. [155]	Generative deep learning models	Small molecule drug design using scalable deep learning for COVID-19
Madhavan et al. [156]	Res-CovNet: A hybrid methodology	Classification of multiple diseases using X-ray images
Shorfuz et al. [157]	IoT-enabled deep learning-based stacking model	Analysis of chest CT scans for diagnosis of COVID-19 encounters
Shankar et al. [158]	Cascaded recurrent neural network (CRNN) model	Detection and classification of the existence of COVID-19
Saranya et al. [159]	Recurrent NN utilized the TensorFlow Keras framework	COVID-19 mortality prediction using electronic health records
Alhudhaif et al. [160]	CNN model built on DenseNet-201 architecture	Determination of COVID-19 pneumonia from X-ray images
Aboutalebi et al. [161]	COVID-Net CXR-S, a convolutional neural network	Predicting the airspace severity of a COVID-19 positive patients
Zhao et al. [162]	convolutional neural network (CNN)	COVID-19 identification from a small subset of training data

5.2. Discussion on Latest Technologies Used to Fight with COVID-19 Pandemic

Beside AI, numerous other latest technologies such as blockchain (BC), federated learning (FL), few short learning (FSL), robotics, and confidential computing (CC) have also played a vital role in this pandemic. For example, BC technology has promising characteristics such as transparency, immutability, verifiability, and privacy-preservation which makes it suitable for data sharing securely between different entities [163]. In addition, it can be used to monitor the personal data flows in the healthcare environments. FL is an emerging technology in which data in not shared, instead model results are shared only. It can be highly beneficial to ensure individual privacy. Furthermore, it enables model results sharing at a wider scale without privacy disclosures [164]. FSL enable machine learning model's training from a few data samples. It has a lot of applications in analyzing the dynamics of COVID-19 by extracting knowledge using a limited data [165]. Robotics were used to deliver the test samples from testing sites to hospitals, and many other innovative applications [166]. In addition, they were also used to check people's temperature in the streets. Some countries used robotics to monitor people's mobility during the rush hours. CC techniques were employed to secure the personal data since it can use the data without accessing actual values. All these technologies have played a vital role in serving mankind during this deadly pandemic. We summarize the role of the seven latest technologies that were used in this pandemic as follows.

- Blockchain (BC): The BC technology has been widely used in addressing the challenges of privacy in healthcare sectors [167,168]. The unique capabilities of the BC such as decentralization, transparency, immutability, and traceability makes it useful for alleviating privacy problems of data storing, distribution, and utilization phases. BC has been rigorously used in this pandemic for transparency and verifiability related purposes [169].
- Decision Support Systems (DSS): DSS can play a vital role in lowering the burden of the medical staff [170]. They can be extremely useful for the ETL (extract, transform, and load) purposes and performing the desired screening tasks in an automated ways. DSS can be very helpful in lowering the burden of healthcare workers and planning resources accordingly.
- Explainable AI: It is very recent technology with a wide range of practical applications in the diagnosis and analytics [171]. It can be extremely useful in identifying the hidden routes of disease transmission and vulnerable communities analysis.
- Internet of things (IoT): IoT has revolutionized the medical sector with unique abilities of remote monitoring, connected healthcare, and constant tracking [172]. IoT can be highly useful in symptoms reporting, remote analysis of patients, and patients monitoring in ICUs, etc.
- Confidential computing and zero knowledge proofs: Both these techniques have higher utility in data distribution with different stakeholders [173]. These techniques enable data utilization with higher privacy guarantees. These solutions can be widely acceptable to address the privacy implications of the data distribution with domestic and international researchers.
- Natural language processing: It can be highly useful in the analytics phase of the EHS for symptoms extraction and sentiment analysis [174]. It can also be useful for symptoms clustering and forming a unified taxonomies of epidemic diseases.
- Search Engines (SE): The SE has played a vital role in devising the common symptoms of the infectious diseases, and it can assist in identifying the origin of pandemics. The tools can be employed to recommend helpful tips to the people to reduce the chaos created by pandemic.

In order to fight COVID-19, every country has implemented digital solutions and launched many projects. For instance, South Korea has implemented an integrated platform named epidemic investigation support system (EISS), in which data about infected patients is collected and shared with relevant agencies [61]. Furthermore, South Korea has implemented many smartphone apps for contact tracing, quarantine monitoring, and logging with the help of different ministries [175]. China has used plenty of AI techniques and DSS in response to COVID-19 [176]. Pakistan has launched a web-based portal to report the statistics of virus, and multi-criteria based data-driven testing strategy [177]. Singapore has implemented an app for social interactions recording that can be used later if someone get infected with COVID-19 [178]. Some countries have used AI and drones etc. to curb the spread of COVID-19. In the U.S., national COVID cohort collaborative (N3C) project is being launched in which multiple organizations are collaborating on clinical data related to COVID-19. In addition, the N3C project aims to answer important research questions that in return will assist to combat the COVID-19 pandemic [179]. Many countries have developed a variety of digital solutions during this pandemic to keep their citizens safe [180–183].

IoT and various smart sensing technologies are also playing a key role in the pandemic arena, leveraging COVID-19 pandemic related data for various purposes such as remote monitoring, quarantine management, and symptoms reporting [184–186]. A number of survey studies have discussed the IOT role in the ongoing pandemic [187,188]. In this regard, we summarize the role of IoT in COVID-19 pandemic reported by the SOTA and recent studies in Table 3.

Table 3. Summary of IoT and various smart sensing technologies role in fight against the COVID-19 pandemic.

Ref.	Discussions about AI Use in the Era of COVID-19 along with Models Details and Purpose Achieved in the Context of COVID-19.	
	Data Sources	**Purpose Achieved in the Context of Lowering the Effects of COVID-19 on General Public**
Sharma et al. [189]	Wearable sensors	Timely and accurately predicting COVID-19 positive cases to control the spread of COVID-19 pandemic
Khan et al. [190]	Camera sensors	Monitoring and countering the spread of ongoing pandemic using IoT sensors data in close indoor spaces
Awotunde et al. [191]	Sensing technologies	Advising patients about their health conditions preventive measures suggestions to saving lives amid the pandemic
Abdulkareem et al. [192]	Medical devices	AI and IoT based clinical decision support systems for COVID-19 pandemic handling in smart hospitals
Jayachitra et al. [193]	Handheld devices	IoT-based cognitive system with 100% prediction accuracy of COVID-19 infection using multimodal data
Herath et al. [194]	Thermal cameras	IoT-based system to detect & control the ongoing pandemic inside the hospital environment
Mukherjee et al. [195]	Medical devices	IoT-cloud-based healthcare predictive model in order to quickly detect COVID-19 using eKNN
Akbarzadeh et al. [196]	Wearable sensors	Notifying end-users when breaking the social distance guidelines in the situation of COVID-19 pandemic
Petrović et al. [197]	Sound sensors	A cost effective IoT-based practical solution for reducing the spread of COVID19 in indoor settings using cough sounds
Alamri et al. [198]	IoT sensors	Providing real-time information to the users about potential events that can affect the public transport in COVID-19 times
Poongodi et al. [199]	COVID-specific sensors	A robust health-based fully connected IoT systems in order to strengthen full COVID-19 administration using location data
Kent et al. [200]	Mobile sensors	IoT-based solution for hospitals in order to improve health monitoring and providing timelier healthcare for patients
Krishnan et al. [201]	Multiple sensors	Checking the availability of the mask in initial stage and monitoring the students' temperature in the latter stage
Mylonas et al. [202]	IoT sensors	Analyzed the effects of COVID-19 pandemic on a multiple schools in Greece for monitoring energy and noises
Bhowmick et al. [203]	IoT sensors	Process and help us monitor the health of older people in clouds based on different medical IoT sensors data
Herath et al. [204]	IoT sensors	Prevention of the COVID-19 pandemic using IoT-based platform in a smart city environments
Herath et al. [205]	IoT sensors	Monitoring the symptoms of COVID-19 infected patients, and detecting the patient's activities using mobile app
Lastovicka et al. [206]	IR and ultrasound	Contactless solution for automatic induction of disinfection intelligent hand sanitizer to lower spread of COVID-19
Rajasekar et al. [207]	RFID tags	IoT-based automated tracking and tracing method for identification of the possible contacts of COVID-19 patients
Alhmiedat et al. [208]	Wearable sensors	Slowing the spread of COVID-19 locally and across the country by allowing individuals to maintain social distances with others

5.3. Synergy of AI with other Emerging Technologies in the Context of COVID-19

In recent years, AI has been increasingly used in combination with emerging technologies such as IoT, IoMT, cloud computing, fog/edge computing, and federated analytics, to name a few for accomplishing multiple goals [209,210]. Ahuja et al. [211] discussed AI use from three different perspectives such as drug discovery, public communication, and integrative medicine in the context of COVID-19. Márquez et al. [212] discussed the joint use of AI and big data in the era of COVID-19. According to the authors, these synergies between disruptive technologies can facilitate obtaining relevant data that, in return, is helpful for health-related decision-making. Anjum et al. [213] discussed the emerging technologies to fight the COVID-19 pandemic. The authors have discussed the role of AI and IoT-assisted drone technology, these synergies between emerging technologies can pave the way to fight future infectious diseases using technology. Ahmad et al. [214] discussed the role of AI in COVID-19 pandemic by performing analytics on data stemming from COVID-19 pandemic. The authors discussed the synergies between various emerging technologies for healthcare decision support leveraging IoT sensors. Lainjo et al. [215] discussed the big data and AI synergies that have helped various nations in improving the pandemic situations and reducing the adverse impacts of COVID-19 on economies. Bazel et al. [216] discussed the synergies between AI and three other emerging technologies (i.e., IoT, blockchain, and big data technologies) in healthcare in order to prevent the spread of COVID-19. Swayamsiddha et al. [217] presented a comprehensive analysis of AI-aided detection of COVID-19 using heterogeneous sources of data (i.e., AI-enabled imaging). Deshpande et al. [218] discussed the promising applications of AI leveraging audio signals data. The authors have demonstrated the diagnosis and screening of COVID-19 patients using audio-based analysis. Despite these promising applications, AI is a promising solution for supply chain management in the post COVID-19 era [219]. A comprehensive discussion on synergy between blockchain and AI, along with their benefits and limitations, has been reported in the recent literature [220]. Recently, Deepti et al. [221] demonstrated the gamut of synergistic applications including AI, cloud-enabled IoT, connected sensors and actuators, and ubiquitous Internet to form connected communities that, in return, can help to fight the COVID-19 pandemic [221]. Furthermore, AI is an important pillar of industry 5.0 [222,223]. A relatively new concept, artificial intelligence of things (AIoT), has emerged as a new concept for addressing the potential limitations of IoT in healthcare 4.0 [224]. Considering the promising applications of AI in the healthcare sector, its synergy with other technologies is likely to increase in the near future for accomplishing multiple goals. Hence, it has become an emerging avenue of research in recent years to serve the mankind effectively.

For the convenience of readers, we provide the summary of the important AI-related developments (adapted from [225]) reported in the published surveys in Figure 15. The analysis presented in Figure 15 shows that AI has contributed significantly to multiple areas (e.g., drug design and development, diagnosis, and surveillance, to name a few). On the other hand, this analysis can enable researchers to contribute more to areas that have been given less attention in previous studies.

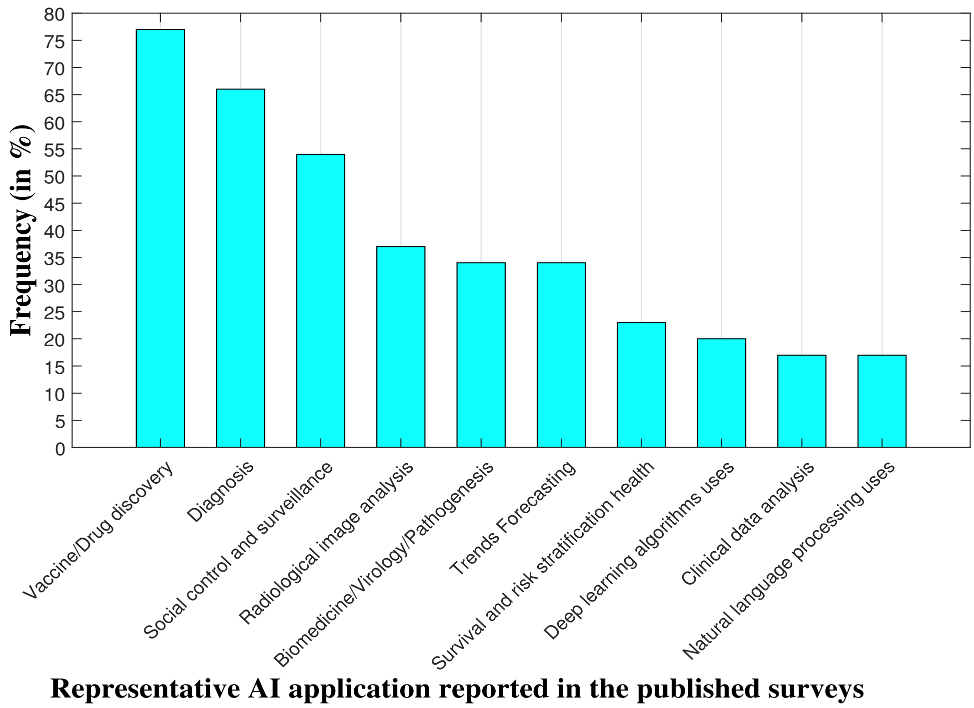

Figure 15. Statistics of AI related developments reported in the prior surveys [225].

Besides the unique AI applications cited above, many surveys on AI topics have been published, and each survey has tried to demonstrate the AI uses from different perspectives.

To aid subsequent research in this regard, we systematically summarize the findings of most recent surveys that have focused on AI applications in the context of COVID-19 in Table 4. The analysis presented in Table 4 clearly demonstrates the existing developments in review articles. Our review is an enhanced version of these surveys as we discuss AI's role more broadly compared to these studies. This analysis is helpful to quickly and conveniently grasp the research status of AI in the COVID-19 era.

Table 4. Key findings of most recent surveys that have focused on AI applications in the context of COVID-19.

Ref.	Pub. Year	Review Type	Key Findings Concerning COVID-19 Pandemic
Nadeem et al. [226]	2020	Literature survey	Discussion of AI applications and data sources to fight against Covid-19 via technology
Abd-Alrazaq et al. [227]	2020	Scoping review	Discussion about AI technology use during the ongoing COVID-19 pandemic
Raza et al. [228]	2020	Meta-analysis	Discussion from broad spectrum of AI to combat COVID-19 by analyzing current SOTA studies
Chen et al. [229]	2020	Rapid review	Discussion and review of the critical aspect of AI applications for COVID-19 era
Enughwure et al. [230]	2020	Systematic review	Analyzed 15 SOTA studies and showed AI has many potentials in combating COVID-19 pandemic
Chiroma et al. [231]	2020	Bibliometric study	Discussion on ML-based technologies to fight the COVID-19 pandemic from multiple perspectives
Bullock et al. [232]	2020	Literature review	Reviewed many datasets, resources, and tools required to facilitate AI research in the era of COVID-19
Fong et al. [233]	2020	Literature review	Discussed the role of AI as a technological enabler from four different perspectives in the era of COVID-19
Latif et al. [234]	2020	Systematic Review	Discussed many public datasets/repositories that are used in order to track the spread of COVID-19 and mitigation strategies
Chawki et al. [235]	2021	Systematic review	Discussed about how AI can be utilized to analyze the social and clinical patterns of a COVID-19 outbreak to save people
Gunasekeran et al. [236]	2021	Scoping review	Discussed many applications of AI, telehealth, and relevant digital health solutions amidst the COVID-19
Syeda et al. [237]	2021	Systematic review	Discussed many studies concerning COVID-19 that have utilized AI-based methods in different themes
Zhao et al. [238]	2021	Systematic review	Discussed and summarized 50 applications of AI, robotics, and other digital technologies in the era of COVID-19
Kamalov et al. [239]	2021	Literature review	Discussed AI applications from four perspectives such as medical diagnostics, forecasting, contact tracing, and drug development
Safdari et al. [240]	2021	Scoping review	Discussed about determining the most favorite and effective data mining tools in COVID-19 era
Nirmala et al. [241]	2021	Literature survey	Pinpoints various AI applications that are effective to fight against the COVID-19 pandemic
Rasheed et al. [242]	2021	Literature review	Discussed the role of AI from three perspectives such as analyze, prognosis, and tracking of the COVID-19 cases
Senthilraja et al. [243]	2021	Literature review	Discussed and find that AI is useful not only in treatment of infected patients with COVID-19, but also for proper health monitoring
Kumar et al. [244]	2021	Literature review	Discussed the development of COVID-19 classification tools & drug discovery models for infected patients using AI
Chen et al. [245]	2021	Literature survey	Investigated the scope of AI in COVID-19 era from the five aspects (i.e., virology, diagnosis, drug analysis, and transmission)
Dogan et al. [246]	2021	Systematic review	Analyzed the role of AI/ML for transmission prediction, diagnosis, and drug/vaccine development in the pandemic arena
Alafif et al. [247]	2021	Systematic review	Analyzed the role of ML/DL towards COVID-19 diagnosis and treatment and discussed findings of SOTA in the pandemic arena
Singh et al. [248]	2021	Comprehensive review	Discussed about the COVID-19 prevention and detection using different types of biosensors.

Recently, AI has been widely used in COVID-19 drug design and repurposing on different datasets. Tang et al. [249] used AI techniques to predict molecules and leading compounds for each target. The dataset used in the study is available at the link (https://github.com/tbwxmu/2019-nCov (accessed on 15 November 2021)). Similarly, some other studies have also used real-world datasets to find the molecular structures for 3CLpro [250,251]. The data used in these studies can be found at link (https://www.insilico.com/ncov-sprint (accessed on 15 November 2021), https://github.com/ml-jku/sarscov-inhibitors-chemai (accessed on 15 November 2021)). More details about datasets used in drug design can be learned from Chen et al. [245].

5.4. Future Research Directions

The promising research directions that need further exploration from the research and development point of view are described in Figure 16. Besides the other directions, privacy preservation is one of the hot research topics in the pandemic era [252,253].

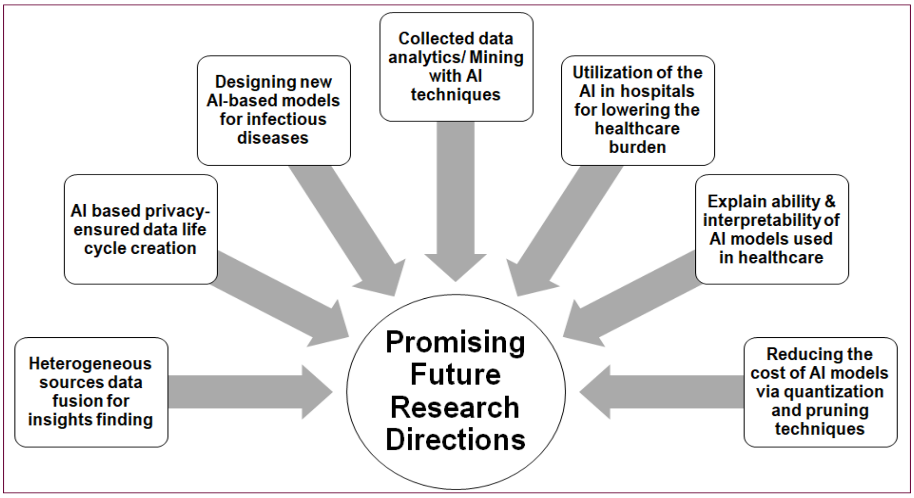

Figure 16. Promising research directions in the COVID-19 era leveraging AI.

As shown in Figure 16, fusion of heterogeneous sources data for insight (i.e., contacts of an infected individual, stay points of an individual, and co-relation of the symptoms with underlying diseases, etc.) finding is a promising avenue for research in the near future [254]. During the pandemic, there is an emerging need to secure all phases of the data lifecycle in order to prevent privacy breaches [255]. However, the existing approaches mainly ensure security of one/two phases. Therefore, more practical and robust AI-powered privacy preserving approaches are needed to secure personal data in the post COVID-19 era. In the ongoing pandemic, many AI models have been used for multiple purposes. Moreover, designing low-cost AI models and metrics for COVID-19-like pandemics is an emerging avenue for future research [256]. Apart from the potential avenues of research cited above, performing analytics on the collected data in order to extract insights is a promising area of research due to huge data collection in the ongoing pandemic [257,258]. As the healthcare industry is aiming to shift from the hospital-centered approach to patient/device-centered approach, therefore, AI-based methods for supporting the cause are needed in the near future. Furthermore, exploring the potential of other latest technologies (i.e., blockchain, privacy by design, federated learning, swarm learning, few-short learning, deep/machine learning, etc.) to serve mankind in an effective way compared to the recent past is an emerging avenue of the research. Finally, critical analysis of AI use from ethical point of view in the context of ongoing pandemic has become more emergent than ever [259–261]. Besides the AI applications cited above, joint use of AI with the IoT/IoMT has become a popular research area [262–265]. Recently, researchers have started working on reducing the 'black-box' nature of AI models through explain-ability and interpret-ability concepts [266–269]. Hence, it is worth exploring the AI use in COVID-19 context from this perspective [270]. In addition, most of the AI techniques, especially deep learning techniques, are computationally expensive. Hence, it is an emerging research area to lower the computing burden of these techniques via pruning and quantization techniques [271–274]. Besides the areas cited above, another promising avenue for future research is sentiment analysis of COVID-19-related tweets [275], informative tweets detection related to COVID-19 using deep learning [276], reviews analysis [277], topic modeling related to COVID-19 aspects [278], COVID-19 pandemic and vaccine-related rumors detection [279], opinion analysis related to COVID-19 [280], and awareness prediction [281], to name a few. In these areas, AI can play a vital role with data stemming from the ongoing pandemic and corresponding surge in SN use across the globe. Therefore, further research and development are likely to expand in this regard (e.g., AI towards COVID-19) in order to take full advantage of the integrated technologies to serve humanity.

Lastly, the COVID-19 pandemic has evolved into an endemic, and the new normal may be to live with the virus for a few more years. Therefore, we must recognize and advocate caution that such pre-emptive measures (e.g., heavy reliance on the digital tools, contactless services, work from home, remote health monitoring with AI tools/applications, distance/remote learning [282], and buying online, to name a few) are ultimately worthwhile. Considering the evolution of COVID-19 in various mutations across the globe, preparedness is the key to preventing any public health crisis, and COVID-19-endemic countries must be ready for the challenges that COVID-19 might bring unanticipated strain on medical infrastructure time and again. Furthermore, some tropical diseases (TDs) have been neglected amid the prevalence of COVID-19 because most funds are being redirected towards COVID-19 [283]. Therefore, COVID-19 effects on medical systems are long-lasting. The contactless services are increasing significantly amid the ongoing pandemic, and hybrid healthcare services will likely increase in the post-COVID-19 era [284]. Most companies are moving towards zero user interface (ZUI) technologies propelled by the ongoing pandemic in order to meet the hygiene requirements [285]. The cashless and contactless smart vending machines are being integrated with the mobile device to reduce people-to-people contact [286]. Furthermore, new normal activities are constantly emerging in which companies are deploying crisis strategies to retain their stakeholders and business. Companies are re-opening swiftly, focusing more on digital transformations, implementing digital platforms/tools for improved consumer services and ease in working, to name a few operational changes [287]. Besides these technical developments, researchers are emphasizing the need for research in COVID19-induced brain dysfunction (CIBD) to improve the mental health of large populations of infected/uninfected individuals [288]. Despite these highlighted areas and developments, AI's role in COVID-19 and post COVID-19 era can offer a proven method to further strengthen the impact of healthcare services/applications on population health, which is more necessary than ever in the post-COVID era [289–292]. To this end, further developments are needed to lower the effects of this pandemic and to serve mankind effectively in these unanticipated and challenging times.

6. Conclusions and Future Work

This paper has demonstrated the role of data-driven analytics leveraging AI in the era of COVID-19. Specifically, we have discussed the role of AI from six different perspectives in the pandemic arena that can assist early researchers to grasp the research status conveniently. To the best of author knowledge, this is the first article that has presented various possible and demonstrated applications of Artificial Intelligence (AI) related to the COVID-19 pandemic. It continues to discuss challenges facing the field and proposes future avenues of research to follow. The six unique perspectives in which AI's use/role was presented are, (i) AI role in seven different epidemic containment strategies (a.k.a non-pharmaceutical interventions (NPIs)) such as contact tracing, quarantine monitoring, social distance monitoring, disclosing patients' information, reporting symptoms and other data via wearable devices, data collection at the time of check-ups, and mining and analytics on collected data, (ii) AI role in data life cycle phases (i.e., collection, storage, pre-processing, analytics, use, distribution, archiving, and deletion) employed for epidemic handing in digital solutions, (iii) AI role in performing analytics on heterogeneous types of data stemming from this pandemic, (iv) AI role in the healthcare sector in the context of COVID-19 pandemic, (v) general-purpose applications of AI in COVID-19 era, and (vi) AI role in drug design and repurposing against COVID-19. Furthermore, we discussed the various challenges related to data that can hinder the application of AI in the ongoing pandemic period. We have concisely presented the role of emerging technologies other than AI, and promising future research directions in the post-COVID-19 era. Furthermore, we have demonstrated the actual use of AI based on available data and utility in these pandemic times. We have described the findings of recently published SOTA studies that have demonstrated the role of IoT and various smart sensing technologies in order to fight against the COVID-19 pandemic. Furthermore, we discussed the synergy of AI with other emerging technologies in order to lower the effects of COVID-19 on the general public and economies. With this comprehensive overview, we aim to update researchers and developers with the existing services of AI, and possible research gaps/opportunities that AI can provide in the near future, and data-related issues that we may face while applying

AI models on it. Unfortunately, COVID-19 is creating many complex clinical implications for people having underlying diseases such as diabetes, pneumonia, and heart disease, to name a few. Hence, we may need to deal with the clinical implications emerging from the prognosis of COVID-19 using AI, mastering the "fearful symmetry" [293]. In the future, we aim to explore the development-related challenges of AI in the COVID-19 era. Finally, we intend to explore AI's role and applications in the post-pandemic era. Recently, federated analytics has emerged as a new paradigm for performing analytics without centralizing data [294–296]. To this end, we intend to explore the role of federated analytics in the pandemic and post-pandemic arena. In addition, studying the role of federated learning in the context of COVID-19 is also a very hot research area in recent times [297–299]. We intend to explore the role of these emerging technologies to combat this unanticipated pandemic in future work.

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