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# Africa's spatial data science landscape in the context of covid-19 pandemic

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**Abstract** The emergence of Covid-19 pandemic in late 2019 presented daunting challenges for designing and implementing sustainable solutions at both local and global levels. The situation was dire in many developing economies with limited resources and vulnerable healthcare systems especially in Africa. Spatial data science (SDS) can be adopted and utilized to assist countries and local communities in understanding and effectively responding to Covid-19 pandemic. This article's study reviewed recent literature with the main goal to assess the application of this data-driven and technology-oriented modern approach in addressing Covid-19 in the African continent. Findings indicate that while examples of applications involving traditional geospatial technologies especially geographic information systems are abound, the use of more advanced SDS elements is limited and fragmented. Additionally, various studies leveraged SDS to address one or more complex questions against the backdrop of challenges largely influenced by the digital divide within Africa and across the globe. The article identifies and discusses these challenges as well as opportunities for increased use of SDS in Africa to understand and respond to disasters like Covid-19 and other complex problems. The argument is made for a more complete use of multiple elements of SDS.

**Keywords** Spatial data science · GIS · Africa · Urban · Health · COVID-19

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## Introduction

Covid-19 began in late 2019 in China, and quickly spread to virtually every part of the world. The rate of infection has slowed substantially in recent months, but symptoms, after-effects, and prevention and treatment solutions remain important to the global community, which has lost more than 6.5 million lives to the pandemic (https://coronavirus.jhu.edu/map.html). The full magnitude and impact of Covid-19 in health and other areas like social, economic, and environmental continues to unfold and manifest in unforeseen ways and promises to become one of the defining features of this decade (The British Academy 2021). OECD (2021), for example, highlights short-term but considerable reduction in pressures on the environment with potential for continuation, along with discussing short-term and lasting effects on economies and budget items of countries.

Science has a critical role in supporting countries and communities as they design timely, comprehensive, and credible Covid-19 decisions and responses that align with changing knowledge of the pandemic (Hassaan et al., 2021; Sarfo & Karuppannan, 2020). Different fields of science especially health, sociology, data, and geographic information, to name a few, have been called upon to guide global response to the pandemic, and a balancing act of integrating knowledge from multiple areas has yielded a mosaic of national and community-level solutions (Franch-Pardo, 2021). Spatial data science (SDS), a subtype of the broader field of data science that is concerned with the spatial dimension of reality holds potential to integrate interdisciplinary knowledge and extend our understanding of Covid-19 (Smith & Mennis, 2020). The distinctive nature of spatial data makes SDS particularly important in advancing how urban areas can mitigate health disasters such as Covid-19 (Anselin, 2015). This is partly because urban area datasets are typically spatial, big, and accompanied by volunteered observations such as geotagged photos of the urban landscape yielding a labyrinth of information about how people interact with each other and the city.

Worldwide, scholars and others have leveraged SDS in various ways and degrees to answer a variety of real-life questions that present challenges to traditional tools and methods. Through a review of existing literature, we investigated the role of this data-driven and technology-oriented approach in addressing the rapidly and continually changing knowledge and contexts of Covid-19 in Africa with a focus on urban areas. In this work, we mainly focused on literature that represents the range of recent work addressing the Covid-19 pandemic through SDS. We anticipate that reviews of this nature can contribute to the ongoing discourse of the value and applications of SDS for addressing societal issues with global relevance. Our work also adds to understandings of the role that SDS plays currently and proposes future directions for maximizing SDS applications in Africa. The unique focus on the nexus of SDS, global pandemic, and Africa provides a perspective that has not yet been emphasized in the literature.

First, we considered vulnerability and resilience issues in the unique contexts of African urban areas in the face of Covid-19. This was followed by a review of Africa's response to Covid-19 along with a look at negative and positive effects of the pandemic at the continental scale. We also surveyed literature to examine how SDS has been utilized to further our appreciation of the pandemic across the continent where many countries are disadvantaged by the digital divide. Within this context, we invite the reader to consider how SDS could be better utilized in Africa, particularly within cities seeking to develop Covid-19 knowledge and science-based responses to the pandemic. By identifying and reviewing a survey of studies that have applied geospatial technologies to address urgent questions about Covid-19 across Africa in near real-time, this article demonstrated how researchers are employing various elements of SDS to support pandemic response across the continent. The results of this review also serve to dispel the notion that African countries have insurmountable digital data and information technology access issues. Finally, we concluded with a reflection that encourages others to employ SDS to better create, manage, and disseminate broad and deep insights into the continent.

## Dynamics of Africa's urban population and vulnerability to COVID-19

Forster and Amman (2018) present two established views in the study of African cities. On one hand, African cities are compared to cities in the global North. This comparison results in African cities being portrayed as chaotic spaces, unmanageable, products of spontaneous and/or failed planning, corrupt governments, and crime havens (Davis, 2006). The second view of African cities describes these spaces as thriving places with the innovative potential, stemming from the creativity and the entrepreneurial attitudes of African dwellers (Pinther et al., 2012; Forster and Amman, 2018). This latter view mostly references large cities which are primarily capital centers such as Accra (Ghana), Pretoria (South Africa), Nairobi (Kenya), Luanda (Angola), Harare (Zimbabwe), and Gaborone (Botswana). There is also a developing body of literature that focuses on externally-funded new technology-based cities built around the periphery of Africa's large metropolitan centers serving information technology needs (van Noorloos & Kloosterboer, 2018).

An unconcealable reality is the unprecedented growth rate of the African urban population in the last three decades (Fig. 1). This rapid growth rate

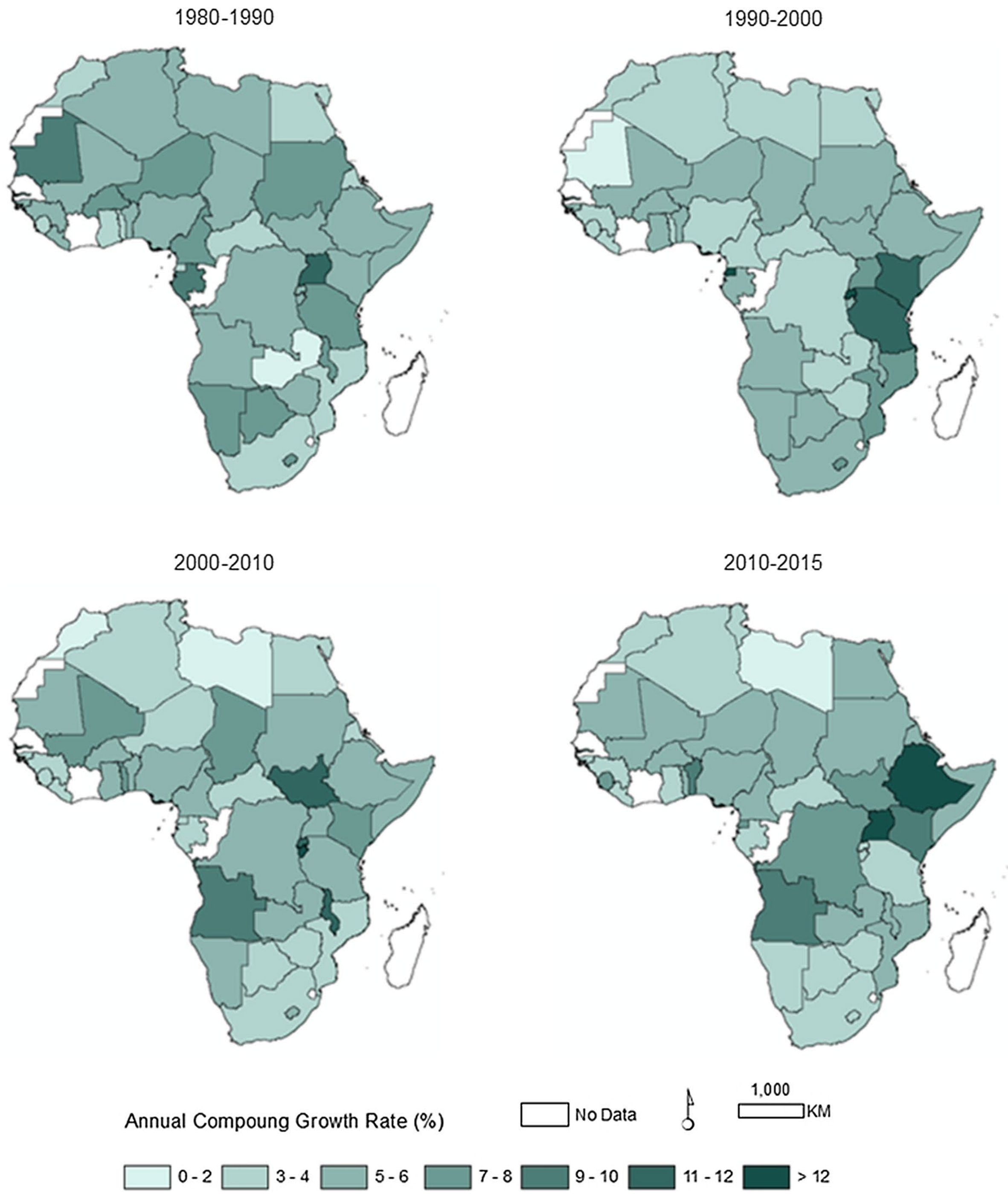


**Fig. 1** Annual compounding growth rate of Africa's urban population from 1980 to 2015 (Source OECD https://read.oecd-ilibrary.org/development/africa-s-urbanisation-dynamics-2020_8d1e7da0-en#page1)

has attracted significant attention from development practitioners, social theorists, and the scientific community. With a current growth rate of 8%, safe estimates indicate that by 2030, approximately 50% of the African population will live in cities (Dodman, et al., 2017; Förster & Ammann, 2018); and that the African urban population may well exceed 60% by the year 2050 (Vearey, et al, 2019). This means that Africa's urban population is expected to more than triple over 40 years, from 395 million in 2010 to 1.339 billion in 2050 (Guneralp, et al., 2017). This growth of Africa's population in urban spaces and the differing perceptions of Africa cities makes African urban areas particularly vulnerable to disasters, such as Covid-19.

The ability of African countries to provide services and address the needs of the rapidly growing urban population will depend in large part on how well cities and their populations are understood. In times of public health crises, real-time information on people, their locations, movements, and health situations will require not just availability but also coordination and integration of information into interoperable systems for efficient and effective responses. In a recent study, the Research Initiative for Cities Health and Equity in Africa Network emphasized the need to understand spatial dynamics of the African urban population for public health interventions (Vearey, et al., 2019). To get to this point, there are notable developments in the African urban population that merit attention.

First, Africa's urban population has an expansive rather than compact form resulting, in falling urban population densities and a higher rate of land use change than population itself (Dodman, et al., 2017). The authors highlight the example of Accra (Ghana) where this city's urban land doubled in a 15-year period between 1985 and 2000. In 2030, it is expected that by virtue of this unprecedented spatial expansion, the continent's megacities–with a metropolitan population of 10 million—are expected to increase from the current seven (Cairo, Lagos, Kinshasa, Accra, Johannesburg–Pretoria, Khartoum, and Nairobi) to nine–adding Luanda and Dar es Salaam to the list (Guneralp, et al., 2017). But what does this spatial expansion mean for public health? In addition to greater distances from the traditional urban core and bringing more agricultural land under urban usage, this spatial expansion also means dispersed population, automobile dependency, and a greater area to deliver services and communicate public health information (Brenner & Schmid, 2015; Dodman, et al., 2017).

Related to spatial expansion is the fact that in the last three decades, growth of Africa's urban population has been occurring in small to mid-sized towns. Mabin, et al. (2013) call this change "the moving urban frontier" citing the spatial expansion of mid-sized towns such as Mombasa (Kenya), Maputo (Mozambique), Kano (Nigeria), Maseru (Lesotho), and Dar es Salaam (Tanzania). What does it mean when small towns become mid-sized towns and mid-sized towns grow into one million resident metropolitan centers? Unprecedented growth in small towns and villages is expected to transform rural landscapes into built-up areas with urban character and functions. If Guneralp, et al. (2017) are right, the African population overall will be 'more concentrated than ever.' This could result in what Vearey et al (2019) call an "urban advantage" where the concentrated populations lend themselves to efficient delivery of services and communication.

Another notable development is the changing structure of the African urban population itself. Vearey et al (2019) cite a looming demographic youth bulge stemming from the fact that 30–40% of children and adolescents globally are projected to be living in Africa by 2050. As most of this population change will occur in cities, this could create another urban advantage with the urban fabric comprising a young, more informed and healthier population. In addition, the greater usage of mobile phones and access to social media platforms could also enhance communication of public health information, ability to gather, analyze, and disseminate information in real time, and across various media and platforms.

Sharifi and Khavarian-Garmsir's (2020) review of research on Covid-19 and cities, including though not limited to African cities, found four foci: (1) environmental quality, (2) socio-economic impacts, (3) management and governance, and (4) transportation and urban design. The review further emphasizes that these areas of focus are not examined evenly but rather that environmental quality (particularly air quality) and socio-economic impacts account for 60% of the research conducted by the time of review. Within this review spatio-temporal analysis is referenced regarding privacy concerns and South Korea's efforts to integrate spatial data while protecting citizen privacy. Sharifi and Khavarian-Garmsir (2020) emphasize that big data is central to effective urban responses to disruptive events, such as Covid-19, but SDS which is an ideal approach for handling this data is surprisingly not specifically identified in this body of work. Since African cities present socially and spatially differentiated landscapes with significant internal differences, there is need for a place-based and SDS supported understanding of cities' and countries' strategies to address downstream effects of disasters such as Covid-19 pandemic.

## COVID-19 management and impact on Africa

### Response to Covid-19

Covid-19 reached Africa about three months after it was first detected in Asia. Africa's response was swift, reactive, and proactive as significant public awareness was raised before the continent registered any pandemic cases. Years of fighting serious diseases such as HIV/AIDS, cholera, and Ebola provided valuable lessons, which helped shape how African countries confronted the pandemic (Oppong et al., 2021). Countries identified and adapted successful Covid-19 control mechanisms from other world regions and benefited from sustained support by the Africa Task Force for Novel Coronavirus, which was established by the Africa Centers for Disease Control (Africa CDC) to coordinate continent-wide response efforts (Ihekweazu & Agogo, 2020). After the first case was confirmed in mid-February 2020, and the coronavirus began spreading across Africa, albeit relatively slowly, countries openly shared timely and credible Covid-19 information that includes cumulative case totals, potential treatment solutions, and how citizens could mitigate spreading the coronavirus in public, work, and learning environments (Ihekweazu & Agogo, 2020; Oppong et al., 2021).

The multidimensional and complex nature of the pandemic demands concurrent solutions across health, social, cultural, economic, education, and other sectors. While African countries offered Covid-19 screening and diagnostic tests, traced contacts of infected individuals, and cared for patients in healthcare facilities, they simultaneously implemented public health and social measures like social distancing, mask mandates, and lockdowns. Using locally produced test kits proved to be cost-effective and empowering for responsible countries (Oppong et al., 2021). In high-risk urban areas in Zimbabwe and Somalia, for example, authorities invested time and effort to disinfec Covid-19 potential problem areas such as public transport stations and informal settlement structures-while in Rwanda they installed portable hand-washing stations at strategic locations to help reduce transmitting the coronavirus (Dzirutwe et al., 2020; Shahow, 2021; Uwiringiyimana, 2020). According to Oppong et al. (2021), many African countries also employed sophisticated modern technologies to address the pandemic. This includes using drone technology to expedite delivery of Covid-19 test samples especially from remote areas, geographic information system (GIS) maps to display and analyze at risk groups, map-and graph-supported dashboards to publicly communicate changing Covid-19 information (see for example, https://www.arcgis.com/apps/dashboards/3b3a01c1d8444932ba075fb44b119b63), and robots to reduce health risks to frontline healthcare workers. Additionally, the authors point out that some countries also drew upon information communication technology (ICT) to virtualize aspects of commerce, tourism, and education.

### Impacts of Covid-19

Despite response efforts to keep impacts minimal, Covid-19 has compounded Africa's problems. Healthcare spending has gone up across the continent where there are currently close to 12 million cumulative cases, and almost 257,000 deaths due to the pandemic (https://africacdc.org/covid-19/). Questions and falsehoods raised about the safety of lifesaving Covid-19 jabs have negatively impacted other disease immunization programs limiting vaccination coverages and likely increasing morbidity and mortality rates especially for vulnerable children (Galal et al., 2022). During pandemic lockdowns, alcohol and drug abuse became prevalent as many youths and adults engaged in these and other socially unacceptable behaviors to while away too much time at their disposal (Mukwenha et al., 2022). In addition to curfews, lockdowns restricted movements within and between places causing additional ripple effects on informality, agriculture, tourism, the supply chain, and other income-generating opportunities, which all suffered with serious implications for the security of household livelihoods (UNECA, 2020).

As surprising as it seems, Covid-19 pandemic also presented opportunities to create positive change in various sectors. In healthcare and public health, Covid-19 motivated African countries to urgently improve their infrastructures; provide sufficient medical equipment to treat or manage various health conditions; train and employ more professionals while controlling brain drain; offer resources (e.g. flexible policies) that support good public health; and conduct more scientific research to extend our understanding as well as find lasting solutions for the pandemic and other diseases (Oppong et al., 2021; UNECA, 2020). There are two Covid-19 research activities that helped reaffirm Africa as an equal and valuable partner in finding rigorous answers to global problems. One took place at the onset of the Delta variant whereby South Africa helped produce scientific data about how effective and safe the J&J/Janssen vaccine was thereby encouraging its overall acceptance by people of color (Kumwenda-Mtambo et al., 2021). The other was completed by Botswana, which stepped into the limelight as the first country to identify and raise alarm about Omicron, a highly contagious Covid-19 variant that quickly spread to many countries across the globe (Gavin, 2022).

Owing to Covid-19 pandemic, remote work and distance education are now widely accepted options around the world. By eliminating stress causing commute time, which can be quite significant in Africa's increasingly congested urban areas, home-based working and learning arrangements can improve the overall well-being of workforces and students (MacLeod et al., 2022). Since the arrangements typically require synchronous online interactions, countries have been pushed to expand or upgrade the underlying ICT (Matlali, 2020). Strong ICT is also crucial for on-demand delivery services (e.g. Uber Eats), which became popular and helped vitalize Africa's e-commerce during lockdowns (Banga, 2020; Oppong et al., 2021). As schools, colleges, and universities could not support in person learning during these periods, students with limited access to distance education technology were clearly disadvantaged in that they could not effectively participate in academic activities (Matlali, 2020; Woomer et al., 2021). Be that as it may, various forms and degrees of distance education can be convenient, flexible, and enjoyable for many students who typically walk for miles to get to school in Africa where natural disasters (e.g. flooding) and civil disturbances (e.g. workers' protests), for example, can easily disrupt traditional classroom learning.

Different ways in which the world responded to Covid-19 pandemic offer learning opportunities and powerful models to effectively raise awareness, control, or possibly end other serious diseases across Africa. They include compelling daily updates about incidence, deaths, hotspots, and other Covid-19 variables as well as moving oral stories about personal experiences publicly shared (e.g. via social media) by patients and families that lost loved ones to the pandemic (see for example: https://www.wvi.org/stories/dac2020-africa-youth-voices-times-covid-19). The strategies helped inform citizens about the spatial extent and gravity of Covid-19 along with encouraging them to look past the pandemic, and practice more healthy living (e.g. exercising, and cutting back on unhealthy habits like smoking) which has potential to reduce national health budgets, an important goal for many developing economies.

## Spatial data science in COVID-19 research

SDS holds importance and value to public health as it provides the ability to develop deep understanding of the dynamics and impacts of diseases across multiple scales, for example. SDS integrates many elements of geographic information science and technology (GIS&T) that render tools like GIS attractive in answering complex questions about spatial reality (Carto, 2021). While some of these elements (e.g. geovizualization) are basic yet effective, maximizing SDS typically includes the use of advanced methods. There is a fuzzy division between GIScience and SDS (Fig. 2), a perspective that probably motivated Anselin's (cited in DiBiase (2018)) argument that "GIScience [is] morphing into spatial data science." Although debatable, we consider Anselin's point plausible given that a clear and comprehensive SDS body of knowledge is yet to be developed. While distinguishing between GIScience and SDS is important, the focus of this work is to examine how SDS has been applied Covid-19 research in Africa.

SDS geovisualization tools such as online dashboards created by the Center for Systems Science

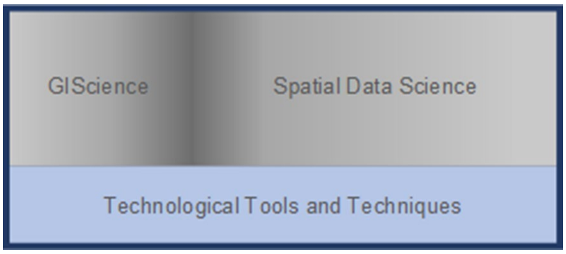


**Fig. 2** SDS is more contemporary and broader than GIScience. The two sciences are underpinned by similar spatial principles and concepts as well as technological tools and techniques such that the division between them is increasingly blurry

and Engineering (CSSE) at John Hopkins University https://coronavirus.jhu.edu/map.html) and Africa CDC (https://africacdc.org/covid-19/) have proven useful to many scientists, government officials and others wishing to explore, analyze and explain the spatial and temporal dynamics of Covid-19 cases, deaths and vaccinations, for example. However, the growing number of applications and push towards SDS as the go-to digital approach for transitioning from spatial data to informed decisions, policies, and actions, have arguably produced Covid-19 information and knowledge inequities between geographic regions. This is largely because SDS is partly motivated and sustained by data, and thus predisposed to achieve greater success including providing compelling information to manage Covid-19 more effectively in data rich than data poor regions. While on one hand this is concerning, there is conversely an intriguing and important opportunity to design and conduct research that can effectively inform, motivate, and prepare scholars and practitioners to successfully navigate the landscape of Covid-19 data especially in data disadvantaged parts of the world.

Recognizing the digital divide between world regions including disparities in access to supercomputing technology typically needed in SDS projects, we anticipated that we would discover more Covid-19 research on Africa that has employed GIScience or more precisely, GIS than SDS. In this section, we describe our findings from a review of the scholarly literature. The findings are based on querying Google Scholar, PubMed Central, and other scholarly databases using variations of the keywords 'Covid-19 and spatial data science' and 'GIS, Africa and

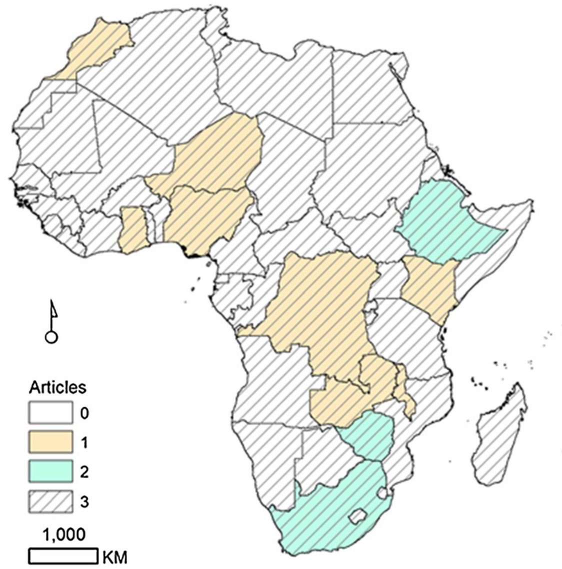


**Fig. 3** Geographic locations of the regions examined in the COVID-19 research involving SDS/GIScience readily accessed in our work. Note that three articles covered the entire continent

Covid-19.' The query process was limited to English language articles and as such does not capture representation of literature presented in other commonly used languages in the continent such as Portuguese and French. However, the intent was not to create a comprehensive list of SDS/GIScience-supported Covid-19 studies but rather to develop a representative picture of how different SDS elements have been utilized in readily accessible research on Covid-19 in Africa (Fig. 3). The query process sought to investigate the breadth of SDS/GIScience supported Covid-19 research. Some countries (e.g. South Africa) within Africa have relative significant depth in SDS/GIScience supported Covid-19 research but through this exploration of the breadth of this research body across the continent the query sought to identify the variety of ways in which SDS/GIScience support our understanding of the pandemic.

Kurnia and Kerski (2021) identify eight major elements of SDS: (1) data engineering, (2) spatial analysis, (3) machine learning (ML), (4) artificial intelligence (AI), (5) big data analytics, (6) modeling and scripting, (7) visualization and exploration, and (8) sharing and collaboration (Fig. 4). Since data are not necessarily easily accessed, we add data collection or the broader geodatabase element to explicitly

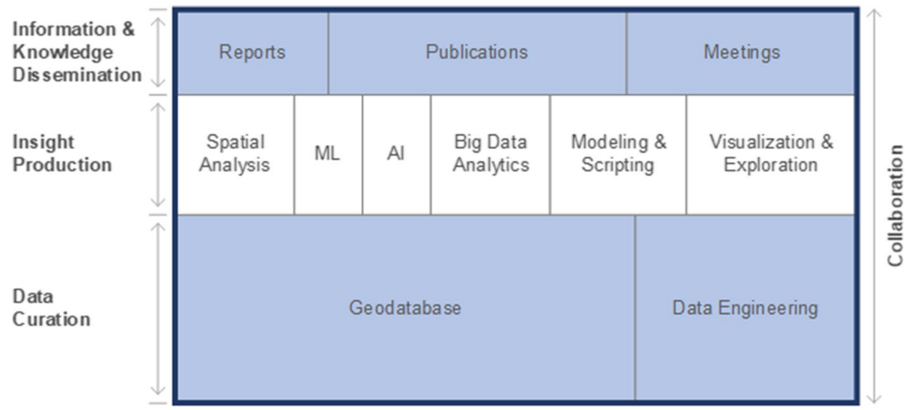


**Fig. 4** The main SDS elements identified by Kurnia and Kerski (2021) can be placed into three groups about data curation, insight production, and information and knowledge dissemination all of which can involve collaboration between various stakeholders. The complexity, importance, and usage level of each block can vary between projects, which can intentionally omit one or more blocks in the top two layers

highlight the critical importance of curating data. Each of these elements of SDS is described here with reference to its representation in the scholarly literature. Table 1 lists reviewed literature together with study regions and SDS elements employed. Just as there are many GIS projects that employ one or more but not all capabilities (e.g. mapping and analytical) of the technology, there is no requirement or expectation for SDS-powered research to use all the building blocks of this science. As can be gathered from Table 1 and subsequent paragraphs, different SDS elements were used to varying degrees or not at all by various scholars.

## Sharing and collaboration, ML, AI, and big data analytics

The sample of scientific reviewed here did not apply ML or AI techniques. Evaluating applications of big

**Table 1** Study regions and SDS elements employed in reviewed literature

| Authors | Study Region | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Alene et al. (2021) | Ethiopia | • | • | • | • | | | | • | • |
| Arashi et al. (2020) | South Africa | • | • | • | • | | | | • | • |
| Bello et al. (2021) | Zimbabwe | • | • | • | • | | | | • | • |
| Bushira (2021) | Ethiopia | • | • | • | • | | | | • | • |
| Chimoyi et al. (2021) | South Africa | • | • | • | • | | | | • | • |
| Fasona et al. (2021) | Nigeria | • | • | • | | | | | • | • |
| Gondo and Kolawole (2022) | Zimbabwe | • | | • | • | | | | | • |
| Hassaan et al. (2021) | Africa | • | • | • | • | | | • | • | • |
| Impouma et. al. (2021) | Africa | • | • | | | | | • | | • |
| Layati et al. (2020) | Morocco | • | | • | | | | | • | • |
| Muchiri et al. (2022) | Kenya | • | | • | • | | | | • | • |
| Ngwira et al. (2021) | Malawi | • | | • | | | | | • | • |
| Onafeso et al. (2021) | Africa | • | • | • | • | | | • | • | • |
| Phiri et al. (2021) | Zambia | • | • | • | • | | | | • | • |
| Samen (2021) | DR Congo | • | • | • | • | | | | • | • |
| Sarfo et al. (2020) | Ghana | • | • | • | • | | | | • | • |
| Tchole et al. (2020) | Niger | • | • | • | • | | | | • | • |

Blank cells indicate that the SDS element was not employed, or its use is indeterminate. (1) geodatabase, (2) data engineering, (3) visualization and exploration, (4) Spatial analysis, (5) machine learning (ML), (6) artificial intelligence (AI), (7) big data analytics, (8) modeling and scripting, and (9) sharing and collaboration data analytics is somewhat tricky given what 'big data' and 'big data analytics' entail. While big data is described by many Vs (Ranjan, 2019), the most common and relevant here are volume, variety, velocity, and veracity with the last two respectively denoting data production speeds and quality. It follows that big data analytics is basically about applying non-traditional or advanced analytical techniques to large amounts of a wide range of datasets often generated rapidly (Anselin, 2020; Usery, 2019). Since most studies handled COVID-19 statistics covering entire countries or larger regions, it is reasonable to suggest that they met several criteria of big data. However, without specific information about the total sizes (i.e. volume) or quality (i.e. veracity) of their datasets, we cautiously identify only those studies that extended over the entire continent as having leveraged big data analytics to some extent.

## Geodatabase

Geodatabase was one of the two most used SDS elements. All reviewed studies collected one, or more, COVID-19 variables shared through mass media since the onset of the pandemic, that is, cases, recoveries (Layati et al., 2020), vaccinations (Muchiri et al., 2020), and deaths. Additional data was obtained from primary sources specifically questionnaires and household surveys. The additional data focused on COVID-19 misinformation (Chimoyi et al., 2021) and sources and uses of potable water (Gondo & Kolawole, 2022). National (e.g. health ministries) and international (e.g. World Health Organization and Humanitarian Data Exchange) agencies offered secondary sources of data, specifically human settlements (Alene et al., 2020; Bello et al., 2021; Gondo & Kolawole, 2022), transportation networks (Phiri et al., 2021), human mobility patterns (Onafeso et al., 2021), socioeconomics (Gondo & Kolawole, 2022; Hassaan et al., 2021; Ngwira et al., 2021), demographics (Alene et al., 2021; Hassaan et al., 2021; Muchiri et al., 2022; Ngwira et al., 2021; Onafeso et al., 2021; Samen, 2021; Sarfo et al., 2020; Tchole et al., 2020), administrative boundaries (e.g. Samen, 2021; Sarfo et al., 2020), health services (e.g. hospitalizations) (Bushira, 2021), armed conflicts (Samen, 2021), climate variables (Alene et al., 2021; Onafeso et al., 2021), topographic factors (Phiri et al., 2021), and COVID-19 mitigation measures (Tchole et al., 2020). Maintaining these datasets in geodatabases supports better curation and enables concurrent access by multiple distributed individuals, which can be a huge advantage in collaborative efforts such as in most reviewed studies. With the exception of Chimoyi et al. (2021) and Hassaan et al. (2021) who explicitly used the term geodatabase, it is, however, difficult to tell whether other scholars employed this mechanism to store and/or manage their datasets.

## Data engineering

Despite the role played by data engineering in transforming datasets differing in scale, format, quality, and other characteristics such that they can be integrated in insight producing operations, many scholars did not share a lot of details about this element. Nonetheless, we gathered that data engineering tasks generally involved data cleansing (Samen, 2021), data transformations (Alene et al., 2021; Impouma et al., 2021; Tchole et al., 2020), feature extractions (Alene et al., 2021; Phiri et al., 2021), aggregations of tabular (Hassaan et al., 2021; Sarfo et al., 2020) and spatial (Impouma et al., 2021) data, data migration (Fasona et al., 2021), and data resampling (Alene et al., 2021).

## Spatial analysis, and modeling and scripting

An argument can be made that each analysis or modeling exercise was designed to address at least one of four pressing questions: (1) What is the spatial or temporal pattern of COVID-19 infections and/or fatalities? (2) What is the likely trajectory of this pandemic? (3) Which factors favor or influence the spread of COVID-19? and, (4) How effective are certain strategies in preventing or containing the spread of COVID-19? There are many ways to facilitate the use of geospatial data to answer each question. Within this sample of the literature Layati et al. (2020) and Bello et al. (2021), opted to explore, analyze, and interpret COVID-19 dynamics captured in map and graph visualizations. Answers to the second question are typically derived from predictive modeling, and represent a powerful means with which public health officials and others can proactively respond to COVID-19 in ways that minimize societal impacts. The future picture of the pandemic was determined using spatial autocorrelation (Arashi et al., 2020; Samen, 2021), semiparametric (Ngwira et al., 2021), and growth curve (Arashi et al., 2020) models. Although foresight is important, Sarfo et al. (2020) and Bushira (2021) placed emphasis on the recent past, and interpolatted the spatiotemporal variability of COVID-19 using inverse distance weighting (IDW) models. Other scholars conducted modeling exercises which involved kriging to fill pandemic data gaps (Chimoyi et al., 2021) as well as visualization of COVID-19 incidence patterns (Hassaan et al., 2021), infection vulnerabilities, and fatality risks (Alene et al. 2021).

Finding robust answers to the third question can enhance our understanding of social, economic, environmental, or political determinants of COVID-19 incidence, which is important in tackling the pandemic on multiple fronts. Hassaan et al. (2021) discovered their solutions through ordinary least squares (OLS) regression and geographically weighted regression (GWR). Although the authors initially listed 14 factors likely at play across Africa, they found that only five were significant. Juxtaposing the short list against one developed for Zambia through decision-tree analysis (Phiri et al., 2021) revealed expected variations in the types and number of COVID-19 factors considered important at continental and national scales. Like Phiri et al (2021), many scholars also examined one or more COVID-19 determinants at individual country levels. The scholars executed proximity analyses involving Euclidean buffers and distance measurements to understand how human mobility patterns (Sarfo et al. 2020) and differential access to various mitigation resources (Gondo & Kolawole, 2022; Muchiri et al., 2022) affected the spread of COVID-19. Buffer analysis was also combined with spatial query to locate COVID-19 cases due to close contacts with the intention of encouraging self-isolations (Bello et al., 2021).

Besides quarantines, African countries have also utilized lockdowns, curfews, and other COVID-19 mitigation and management measures to varying extents and successes. For example, Bushira (2021) deployed the newly developed COVID-19 Hospital Impact Model for Epidemics (CHIME), and found that social distancing would, and did, reduce the number of hospitalizations and pressure on the healthcare system in Ethiopia. While Kenya had five different COVID-19 vaccines at its disposal, a Bayesian conditional autoregressive (CAR) model determined the country's vaccination coverage to be only 17% raising questions about general perceptions, accessibility, and the overall effectiveness of this mitigation strategy (Muchiri et al., 2022). Mutombo et al. (2021) discuss many factors that include the barrage of false pandemic information, which are perceived to be encouraging vaccine hesitancy in Africa. Chimoyi et al. (2021) addressed Covid-19 misinformation directly through the collection and analysis of questionnaire data. They uncovered the spatial distribution of misinformation hotspots, which were in urban areas with high social media activity in South Africa. The demand for true or authentic COVID-19 information is clearly widespread, and, appears to have motivated concerted design and implementation of a scalable system that can seamlessly ingest appropriately engineered big data from all African countries, and more importantly, produce and disseminate authoritative information and knowledge about the pandemic (Impouma et al., 2021).

## Visualization and exploration

Four types of visualizations were used to reinforce telling spatial stories about the pandemic, that is, maps, tables, charts, and graphs. Point maps helped scholars to visualize the spatial distribution of individual COVID-19 cases (Bello et al., 2021) or their totals by region (Onafeso et al., 2021). Point maps also supported the visualization of the locations of vaccines (Muchiri et al., 2022) and sources of communal water (Gondo & Kolawole, 2022) encouraging interpretative analysis of access to these resources crucial in fighting the pandemic. The most common map type created was the choropleth, which found use in communicating and appreciating regional differences in demographic variables (Muchiri et al., 2022); COVID-19 vaccinations (Muchiri et al., 2022), cases (Arashi et al., 2020; Bushira, 2021; Fasona et al., 2021; Onafeso et al., 2021; Phiri et al., 2021; Samen, 2021; Tchole et al., 2020), deaths (Alene et al., 2021; Ngwira et al., 2021), vulnerabilities (Alene et al., 2021; Fasona et al., 2021), and risks (Ngwira et al., 2021); as well as residuals from regression models (Hassaan et al., 2021). In lieu of vector maps, Layati et al. (2020) exploited raster or surface maps generated through interpolation techniques to acquire insight into the spatial densities of COVID-19 cases, deaths, and recoveries. This map type was also instrumental in appreciating the trends of COVID-19 incidence (Sarfo et al. 2020) or their determinants such as distances to airports, towns, and borders (Phiri et al., 2021).

The combination of tables, charts, or graphs with maps allowed scholars to see and understand COVID-19 issues from multiple perspectives. Tabular content generally included attributes of units of analysis (e.g. districts and provinces), epidemiologic data, as well as inputs and results of spatial analysis or modeling. Complementing tabular and map content with a simple but fit-for-purpose pie chart allowed Gondo and Kolawole (2022) to bring further attention to household disparities in access to indoor water which promotes COVID-19 prevention behaviors such as regular handwashing. Through a point plot incorporating error bars, Muchiri et al. (2022) managed to gain visual ideas about the levels of uncertainty in estimating plotted populations within one hour of vaccination sites. Like Muchiri et al (2022), Hassaan et al. (2021) and Onafeso et al. (2021) created regression model graphs which similarly conveyed multiple information with potential to attract multiple uses. The graphs included scatterplots of observed versus predicted COVID-19 incidence and fatalities (Hassaan et al., 2021), and daily versus outbreak reports of the pandemic (Onafeso et al., 2021). Hassaan et al. (2021) drew upon their graph to evaluate the predictive power of a GWR model. Both Tchole et al. (2020) and Ngwira et al. (2021) graphed COVID-19 cases and deaths, the former using bar graph representations which showed rates stratified by age and gender, and the latter by means of line graphs expressing cumulative totals by month. Curvilinear graphs seemed valuable for highlighting the estimated number of COVID-19 cases due to a single human superspreader (Tchole et al., 2020). Using these graphs also worked effectively for Bushira (2021) who was interested in visualizing the trajectories of daily hospitalization due to the pandemic.

## Discussion

This review sought to survey the use of SDS to study Covid-19 pandemic in Africa, with particular interest in African cities. Although the review sampled literature from across the continent, it was limited to English language articles. As such, this representation has limited discussion of SDS applications in COVID 19 studies on Africa gathered from articles published in other official and national languages (e.g. French, Portuguese, and Swahili). Despite this limitation, SDS potentials are evident in the collection of literature surveyed.

There are multiple challenges that can impact effective use of SDS in addressing complex global disasters. The most readily evident limitation of current SDS research regarding Covid-19 in Africa, as observed in recent literature reviewed, is the geographic unevenness of studies. There are obvious geographic concentrations on South Africa and Ethiopia, for example, which are possibly an artifact of the search terms used to query scholarly databases, but also likely a result of the unevenness in wealth, research infrastructure, and other foundational features necessary to both respond to Covid-19 and simultaneously study the pandemic using SDS. Finding and reviewing at least two relevant articles from each country could go a long way toward telling a richer SDS and Covid-19 pandemic story about Africa. Of course, this might require building a research team comprising individuals who can review literature available in Africa's multiple official languages.

Wing (2020) highlights some of the problems associated with the main driving force behind SDS studies, that is, data. She argues that critical research data can be an expensive commodity, which makes it difficult to access. Furthermore, data can be unstructured and thus in need of considerable engineering time, as well as unreliable such that it is difficult to faithfully represent or effectively make sense of and find robust answers to complex problems (Wing, 2020). Little information exists on the scope and gravity of these and other data issues or their solutions for traditionally data poor countries in Africa, many of which do not have open data policies, which are valuable to promote credibility and widespread access and utilization of data among many benefits (Mutuku & Tinto, 2019).

System interoperability within and between countries presents additional challenges to advance the use of SDS for studies of Africa and African cities. Abiding by the collectively developed spatial and health data standards such as the African Union Health Information Exchange Policy and Standards for Digital Health Systems can help organizations and countries seamlessly share and exchange datasets between systems (Mamuye 2022). However, despite Africa CDC's collaborative-oriented response to Covid-19 pandemic, variations in economic development have yielded disparities in investment in research infrastructure and allocation of resources to fully operationalize digital health systems across African countries (Hampshire et al., 2021). While wealthier countries like South Africa, Nigeria, and Egypt may have the resources necessary to implement such systems, which are required for SDS, the reality in lower income economies can undermine this capacity development effort constraining effective data generation, integration, and analysis.

Another challenge to using SDS to study Covid-19 in Africa is heavy dependence on nationally aggregated data. This was the case in studies that focused on a single country's experience with Covid-19 as well as those that looked at within continent comparisons (i.e. Hassaan et al., 2021; Impouma et. al., 2021; Onafeso et al., 2021). Sub-national scale analysis can combine data from multiple cities of varying sizes and arrangements thereby overlooking potential challenges and opportunities present in urban spaces and to urban populations. This approach was used to address Covid-19 largely through examinations of broader scale administrative units (e.g. districts and provinces). It could mask within-country variation, making differences between rural areas and cities invisible, and reducing cities to singular population centers instead of intentionally integrating cities' internal variations and dynamism into SDS applications. Since many African cities are becoming expansive and simultaneously smaller sized cities are growing, there are different potentials for responding to and managing global health crises that must be considered. While increases in urban population may lead to improved access (e.g. to vaccines) than would be possible with highly dispersed rural populations, if the urban spaces are themselves expansive the challenges for ensuring access within a city can be heightened.

## Conclusions

This article presented an overview of recent uses of SDS to improve our understanding and fix issues related to Covid-19 in Africa. Particular attention was given to gaps in literature as they relate to applications of SDS and city-relevant considerations in studies of spatial dynamics of pandemics and similar disasters. The intention was to invite readers to consider how the dynamics of cities including challenges of data quality and aggregation could intersect with advances being made in SDS to improve applications of this scientific approach in disasters. The article identified other challenges of using SDS in COVID-19 research such as different levels of economic development and technological advancement in different African countries, and system interoperability. While these challenges exist, we contend that a combination of factors makes possible the use of SDS in understanding and mitigating disasters such as COVID-19 in Africa. These include advances in applications of geospatial technologies such as GIS, GPS, and drones, changing dynamics of urban population featuring younger, more informed, and healthier citizens, availability of large volumes of city-level spatial data, improvements in communication technologies, and improving national economies. But widespread use of SDS in solving problems across Africa will require better coordination to open space for more effective data standardization and sharing.

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### Declarations

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## References

Alene, M., Yismaw, L., Assemie, M. A., Ketema, D. B., Mengist, B., Kassie, B., & Birhan, T. Y. (2021). Magnitude of asymptomatic COVID-19 cases throughout the course of infection: A systematic review and meta-analysis. *PLoS ONE, 16*(3), e0249090.

Anselin, L. (2015). Spatial data science for an enhanced understanding of urban dynamics. *The Cities Papers*.

Anselin, L. (2020). Spatial data science. In *International encyclopedia of geography: People, the earth, environment, and technology*, ed. D. Richardson, N. Castree, M. F. Goodchild, A. Kobayashi, W. Liu, and R. A. Marston. New York: Wiley. https://doi.org/10.1002/9781118786352.wbieg2015.

Arashi, M., Bekker, A., Salehi, M., Millard, S., Erasmus, B., Cronje, T., & Golpaygani, M. (2020). Spatial analysis and prediction of COVID-19 spread in South Africa after lockdown. arXiv preprint arXiv:2005.09596.

Banga, K., (2020). Can the digital economy help mitigate the economic losses from COVID-19 in Kenya? available online: https://set.odi.org/can-digital-economy-help-mitigate-economic-losses-from-covid-19-in-kenya/.

Bello, I. M., Moyo, T. N., Munyanyi, M., Akpan, G. U., Isibor, I., Sunganai, L. C., & Mkanda, P. 2021. Use of geographic information systems web mapping application to support active case search to guide public health and social measures in the context of COVID-19 in Zimbabwe: a preliminary report to guide replication of methods in similar resource settings. *The Pan African Medical Journal*, 38.

Brenner, N., & Schmid, C. (2015). Towards a new epistemology of the Urban? *City, 19*, 151–182.

Bushira, K. M., & Ongala, J. O. (2021). Modeling transmission dynamics and risk assessment for COVID-19 in Namibia using geospatial technologies. *Transactions of the Indian National Academy of Engineering, 6*(2), 377–394.

Carto 2021. What is spatial data science? Accessed at https://carto.com/what-is-spatial-data-science/

Chimoyi, L., Mabuto, T., Dube, T., Ntombela, N., Nchachi, T., Tshisebe, D., & Setswe, G. K. (2021). The geography of COVID-19 misinformation: using geospatial maps for targeted messaging to combat misinformation on COVID-19. *South Africa. BMC Research Notes, 14*(1), 1–6.

Davis, M. (2006). *Planet of Slums*. Verso.

DiBiase, D. (2018). Is Giscience converging with data science? Should it? ESRI Education Blog. Available at https://community.esri.com/t5/education-blog/is-giscience-converging-with-data-science-should/ba-p/893016

Dodman, D., Leck, H., Rusca, M., & Colenbrander, S. (2017). African urbanization and urbanism: Implications for risk accumulation and reduction. *International Journal of Disaster Risk Reduction, 26*, 7–15.

Dzirutwe, M., Bulawayo, P., & Cawthorne, A. (2020). Zimbabwe turns water cannon on coronavirus. *Reuters*. Retrieved from https://www.reuters.com/article/us-health-coronavirus-zimbabwe/zimbabwe-turns-water-cannon-on-coronavirus-idUSKBN21L24B.

Fasona, M. J., Okolie, C. J., & Otitoloju, A. A. (2021). Spatial drivers of COVID-19 vulnerability in Nigeria. *Pan African Medical Journal*, 39(1).

Förster, T. & C. Ammann. (2018). African cities and the development conundrum: Actors and agency in the urban grey zone. In *African Cities and the Development Conundrum*, edited by Till Förster and Carole Ammann, 10:3–25. Brill. http://www.jstor.org/stable/https://doi.org/10.1163/j.ctvbqs4gq.8.

Franch-Pardo, I., Napoletano, B. M., Rosete-Verges, F., & Billa, L. (2021). Spatial analysis and GIS in the study of COVID-19. A review. *Science of the Total Environment, 739*, 1–10.

Galal, B., Lazieh, S., Al-Ali, S., & Khoshnood, K. (2022). Assessing vaccine hesitancy in Arab countries in the Middle East and North Africa (MENA) region: a scoping review protocol. *British Medical Journal Open, 12*, e045348. https://doi.org/10.1136/bmjopen-2020-045348

Gavin, M. D. (2022). Inside the lab that identified Omicron: For years Botswana's scientists have been on the cutting-edge of research. Think global health. Retrieved from https://www.thinkglobalhealth.org/article/inside-lab-identified-omicron.

Gondo, R., & Kolawole, O. D. (2022). Household water access and COVID-19 in Karoi town. *Zimbabwe. Scientific African, 16*, e01145.

Guneralp, B., Lwasa, S., Masundire, H., Parnell, S., & Seto, K. C. (2017). Urbanization in Africa: Challenges and opportunities for conservation. *Environmental Research Letters, 13*, 1–9.

Hampshire, K., Mwase-Vuma, T., Alemu, K., et al. (2021). Informal mHealth at scale in Africa: opportunities and challenges. *World Development, 2021*(140), 105257. https://doi.org/10.1016/j.worlddev.2020.105257

Hassaan, M. A., Abdelwahab, R. G., Elbarky, T. A., & Ghazy, R. M. (2021). GIS-based analysis framework to identify the determinants of COVID-19 incidence and fatality in Africa. *Journal of Primary Care & Community Health, 12*, 21501327211041210.

Ihekweazu, C., & Agogo, E. (2020). Africa's response to COVID-19. *BMC Medicine, 18*(1), 1–3.

Impouma, B., Wolfe, C. M., Mboussou, F., Farham, B., Saturday, T., Pervilhac, C., & Moeti, M. (2021). Monitoring and Evaluation of COVID-19 response in the WHO African Region: challenges and lessons learned. *Epidemiology & Infection, 149*, e98.

Kumwenda-Mtambo, O., Neely, J., & Smith, A. (2021). South African study shows high COVID protection from J & J shot. *Reuters*. Retrieved from https://www.reuters.com/business/healthcare-pharmaceuticals/safrican-study-shows-jj-vaccine-protects-against-death-co-lead-investigator-says-2021-08-06/.

Kurnia, C. & J. Kerski, (2021). Why should geographers care about data science? AAG Newsletter, April 2021.

Layati, E., Ouigmane, A., de Carvalho Alves, M., Murugesan, B., & El Ghachi, M. (2020). Spread mapping of Covid-19 in Morocco using geospatial approach. *Journal of Geographical Studies, 4*, 34–43.

Mabin, A., Butcher, S., & Bloch, R. (2013). Peripheries, suburbanisms and change in sub-Saharan African cities. *Social Dynamics, 39*(2), 167–190. https://doi.org/10.1080/02533952.2013.796124

MacLeod, K. E., Cole, B. L., & Musselwhite, C. (2022). Commuting to work post-pandemic: Opportunities for health? *Journal of Transport & Health*. https://doi.org/10.1016/j.jth.2022.101381

Mamuye, A. L., Yilma, T. M., Abdulwahab, A., Broomhead, S., Zondo, P., Kyeng, M., et al. (2022). Health information exchange policy and standards for digital health systems in africa: A systematic review. *PLOS Digit Health, 1*(10), e0000118.

Matlali, L., (2020). How can Africa prepapre its education system for the post-COVID world? https://www.weforum.org/agenda/2020/10/how-can-africa-pivot-its-education-system-using-enthusiasm-of-covid-reset/.

Muchiri, S. K., Muthee, R., Kiarie, H., Sitienei, J., Agweyu, A., Atkinson, P. M., & Alegana, V. A. (2022). Unmet need for COVID-19 vaccination coverage in Kenya. *Vaccine, 40*(13), 2011–2019.

Mukwenha, S., Murewanhema, G., Madziva, R., Dzinamarira, T., Herrera, H., & Musuka, G. (2022). Increased illicit substance use among Zimbabwean adolescents and youths during the COVID-19 era: An impending public health disaster. *Addiction, 117*(4), 1177–1178. https://doi.org/10.1111/add.15729

Mutuku, L. & Tinto, T. (2019) Open data around the World-Sub-Saharan Africa. In T. Davies, S. Walker, M. Rubinstein, & F. Perini (Eds.), The state of open data: Histories and horizons. Cape town and Ottawa: African Minds and International Development Research Centre. https://www.stateofopendata.od4d.net/chapters/regions/sub-saharan-africa.html Last accessed June 15th, 2022.

Mutombo, P. N., Fallah, M. P., Munodawafa, D., Kabel, A., Houeto, D., Goronga, T., et al. (2021). COVID-19 vaccine hesitancy in Africa: A call to action. *Lancet Glob Health, 10*(3), e320–e321. https://doi.org/10.1016/S2214-109X(21)00563-5.

Ngwira, A., Kumwenda, F., Munthali, E. C., & Nkolokosa, D. (2021). Spatial temporal distribution of COVID-19 risk during the early phase of the pandemic in Malawi. *PeerJ, 9*, e11003.

OECD. (2021). Policy responses to coronavirus (COVID-19): The long-term environmental implications of COVID-19. https://www.oecd.org/coronavirus/policy-responses/the-long-term-environmental-implications-of-covid-19-4b7a9937/. Last accessed June 15th, 2022.

Onafeso, O. D., Onafeso, T. E., Olumuyiwa-Oluwabiyi, G. T., Faniyi, M. O., Olusola, A. O., Dina, A. O., & Adagbasa, E. (2021). Geographical trend analysis of COVID-19 pandemic onset in Africa. *Social Sciences & Humanities Open, 4*(1), 100137.

Oppong, J. R., Dadson, Y. A., & Ansah, H. (2021). Africa's innovation and creative response to COVID-19. *African Geographical Review*. https://doi.org/10.1080/19376812.2021.1897635

Phiri, D., Salekin, S., Nyirenda, V. R., Simwanda, M., Ranagalage, M., & Murayama, Y. (2021). Spread of COVID-19 in Zambia: An assessment of environmental and socioeconomic factors using a classification tree approach. *Scientific African, 12*, e00827.

Pinther, K., L. Förster, & C. Hanussek. (2012) (eds.) Afropolis: City, Media, Art. Johannesburg: Jacana Media.

Ranjan, J. (2019). The 10 vs of big data framework in the context of 5 industry verticals. *Productivity*, 59(4).

Samen, O. C. (2021). Spatial propagation of COVID-19 in the democratic republic of Congo. *Africa Report, 59*, 49–64.

Sarfo, A. K., & Karuppannan, S. (2020). Application of geospatial technologies in the COVID-19 fight of Ghana. *Transactions of the Indian National Academy of Engineering, 5*(2), 193–204.

Shahow, A. A. (2021). Who's afraid of COVID-19? Somalia's battle with the virus. *The New Humanitarian*. Retrieved from https://www.thenewhumanitarian.org/analysis/2021/5/5/whos-afraid-of-covid-19-somalias-battle-with-virus.

Sharifi, A., & Khavarian-Garmsir, A. R. (2020). The COVID-19 pandemic: Impacts on cities and major lessons for urban planning, design, and management. *Science of the Total Environment, 749*(2020), 142391.

Smith, C. D., & Mennis, J. (2020). Incorporating Geographic Information Science and Technology in Response to the COVID-19 Pandemic. *Preventing Chronic Disease, 17*, 1–7. https://doi.org/10.5888/pcd17.200246

Tchole, A. I. M., Li, Z. W., Wei, J. T., Ye, R. Z., Wang, W. J., Du, W. Y., & Cheeloo EcoHealth Consortium. (2020). Epidemic and control of COVID-19 in Niger: quantitative analyses in a least developed country. *Journal of Global Health*, 10(2).

The British Academy. (2021). The COVID Decade: Understanding the long-term societal impacts of COVID-19. https://www.thebritishacademy.ac.uk/documents/3238/COVID-decade-understanding-long-term-societal-impacts-COVID-19.pdf Last accessed June 15th, 2022.

UNECA, 2020; United Nations. *Economic Commission for Africa. Policy brief: impact of COVID-19 in Africa*. Addis Ababa. https://hdl.handle.net/10855/43770.

Usery, E. L. (2019). Problems of Large Spatial Databases. *The Geographic Information Science & Technology Body of Knowledge* (2nd Quarter 2019 Edition), John P. Wilson (Ed.). DOI: https://doi.org/10.22224/gistbok/2019.2.13

Uwiringiyimana, C. (March 11, 2020). Rwanda keeping coronavirus at bay with campaign of public handwashing. *Reuters*. Retrieved from https://www.reuters.com/article/us-health-coronavirus-rwanda/rwanda-keeping-coronavirus-at-bay-with-campaign-of-public-handwashing-idUSKBN20Y2R8

van Noorloos, F., & Kloosterboer, M. (2018). Africa's new cities: The contested future of urbanization. *Urban Studies, 55*(6), 1223–1241.

Vearey, J., Luginaah, I., Magitta, N. F., Shilla, D. J., & Oni, T. (2019). Urban health in Africa: a critical global public health priority. *BMC Public Health, 19*(340), 1–4.

Wing, J. M. (2020). Ten research challenge areas in data science. arXiv preprint arXiv:2002.05658.

Woomer, P. L., Mulei, W. L., & Maina, S. L. (2021). An ICT strategy based upon e-teaching and e-learning in response to the COVID-19 crisis in Africa. *Journal of International Agricultural and Extension Education, 28*(2), 51–57.