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Smart Cities after COVID-19: Building a conceptual framework through a multidisciplinary perspective

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ABSTRACT

This study provides theoretical grounds for planning smart cities using multidisciplinary approaches, offering insightful suggestions to researchers and policy- and decision-makers. Its main purpose is to contribute to the debate on the new connotations of the smart city paradigm in the context of the COVID-19 pandemic. It will emphasize how the Internet of Things and related technologies will collaborate to develop an antivirus-built environment against future pandemics. In this context, the study proposes a conceptual framework that provides a futuristic vision of prevention control, contingency planning, and measures against future risks. Although a smart city ecosystem improves citizens' lives, building it may involve design, implementation, and operational challenges that must be addressed.

Introduction

The COVID-19 pandemic has undoubtedly compelled us to reconsider the future of cities and has also accelerated the smart urban transition as it has the potential for better resilience, efficiency, and sustainability [1,2]. During the pandemic, the use of technology for surveillance, remote checking, and coordinated control allowed for more seamless solutions especially when global lockdowns were implemented. Developments in information and communications technologies (ICT) provide services that assist and deliver convenience to humans in their daily lives [3,4]. The advent of the Internet of Things (IoT), big-data analytics, cloud computing, and artificial intelligence (AI) has helped establish a new interconnected world of ubiquitous computing devices [5–7]. Since the introduction of the smart cities concept, IoT has become a key pillar of its development, as it revolutionized the collection of data required for planning and decision-making. IoT provides a breadth of applications for education, planning, transportation, healthcare, building, and construction, all of which use large-volume and highly diverse data continuously collected by these devices. Here, the dominating presence of technology can play a relevant role in addressing new and existing societal challenges and providing value-added services in a way never imag-

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ined before [8–10]. Consequently, the pandemic raises an essential debate about implementing smart technology in urban planning and design.

The COVID-19 pandemic provides an opportunity to recognize and apply smart city technologies to improve social well-being and manage crises as a result of the obligatory shift of many human activities to digital platforms. However, certain positive trends have emerged in dealing with the challenges of such a crisis, with various city strategies being adopted in the fight against the pandemic. These strategies range from ambitions for tech-driven, surveillance-oriented systems to "economical innovations" by firms, consumers, and city governments [11–13]. As the world continues to struggle against the devastating effects of the COVID-19 pandemic, governments and organizations are discussing how to exploit new technologies to reduce its impacts as well as how to avoid or minimize future pandemics. In reality, the urban built environment configuration plays a major role before, during, and after epidemics. Emerging evidence has identified associations between urban attribute–related individual activities and infection risks. While globalization increases the likelihood of pathogen spread, a city's planning certainly influences its flow [14–16].

Smart city technologies have recently become the subject of extensive research and development in the literature. A large volume of relevant work has been published in different directions, proposing solutions, services, frameworks, and applications based on these technologies. The present research methodology is mainly based on a literature review that involves a synthesis of findings and other key aspects targeting the multidisciplinary perspective of smart cities. This study was conducted using different scientific databases such as the Web of Science, Scopus, and Science Direct and includes articles published until the first half of 2022. The inclusion of conference papers is justified, as the topic has been widely discussed at scientific events, reflecting its prominence. This study performed a search for scientific papers whose titles, abstracts, or keywords contained the terms "smart city" or "smart cities" and "COVID-19."

The fundamental focus of this study is the concept of smart cities and illustrations of smart solutions implemented in cities amid new environmental challenges due to the COVID-19 pandemic. The study presents a scoping critique paper of smart cities and their characteristics, layered architecture, and applications. The rest of this paper is organized as follows: Section 2 identifies key definitions and fundamental technologies. Subsection 2.1 describes essential components and the smart city layered architecture. Subsection 2.2 explains how smart technologies are operated within the smart city ecosystem. Section 3 analyzes the impact of the COVID-19 crisis on the smart city paradigm. Subsection 3.1 reviews the key aspects and the potential impacts. Subsection 3.2 presents the state-of-the-art solutions and tools in smart cities. Section 4 discusses open challenges and future directions. Section 5 describes the comprehensive conceptual framework of smart city technologies and implementation. Subsection 5.1 describes the technical dimension of smart cities. Subsection 5.2 proposes the holistic framework of smart city technologies and implementation to avoid future crises. Section 6 summarizes the paper with concluding remarks.

Definitions and fundamental technologies

The term "smart city" is a designation given to a developed urban area that incorporates data collection, information processing, and communication technologies to address various environmental, social, and economic challenges in large-scale urbanized areas. Smart cities are developed to provide a sustainable solution for residents' enhanced quality of life and efficient delivery of urban services through excellence in various strategic areas such as energy and resource consumption, asset management, mobility, and economy. Compared to traditional urban planning strategies, smart city innovations promote global sustainability by using urban and distributed technologies to create competitive, self-reliant cities that meet different residents' needs. They also integrate the operation of the urban infrastructure and services used in buildings, transportation, education, energy, and public safety [17,18].

Since 1990, governments and researchers have been using the term "smart cities" to highlight these qualities in cities and promote them as innovative. However, many issues are associated with this naming convention. Notably, the term "smart city" lacks a core definition as many researchers and experts have suggested different descriptions of smart cities, and the issue has remained a topic of debate in the literature [19–23]. Consequently, there is no universally accepted definition of smart cities, which may differ between countries or cities. Moreover, most of these definitions describe a smart city in terms of technological advancements, mobility, smart governance, quality of life, and sustainability but lack a connection with citizens' perspectives and expectations from such a term. Furthermore, "smart city" is a multidisciplinary concept whose definition must consider all its components and aspects [18,24]. Finally, there remains no universal definition for smartness. While smart initiatives were initially driven by ICT-enabled technologies and their integration with the physical infrastructure, nonphysical dimensions and components have also been recognized as important elements that are inextricable from the physical aspect. Such IoT devices will extremely prevail in urban computing and provide a continuous supply of vital data required to support the decision-making processes and all actions resulting from them. IoT devices must receive, filter, analyze, and manage gathered data in real-time before exchanging them with other devices to perform their respective operations [25–27].

Smart cities aim to construct a clean and sustainable environment to enhance the quality, performance, and interactivity of urban services; other objectives include resource optimization and cost reduction [28]. Deakin and Al Waer [29], in their work titled "From Intelligent to Smart Cities," listed the following factors that distinguish a smart city from its usual counterpart: (a) the application of ICT to elevate the city's living standards and environment, (b) the digitization of the city and its community, (c) the incorporation of ICT with the governance system, and (d) the territorialization of activities that

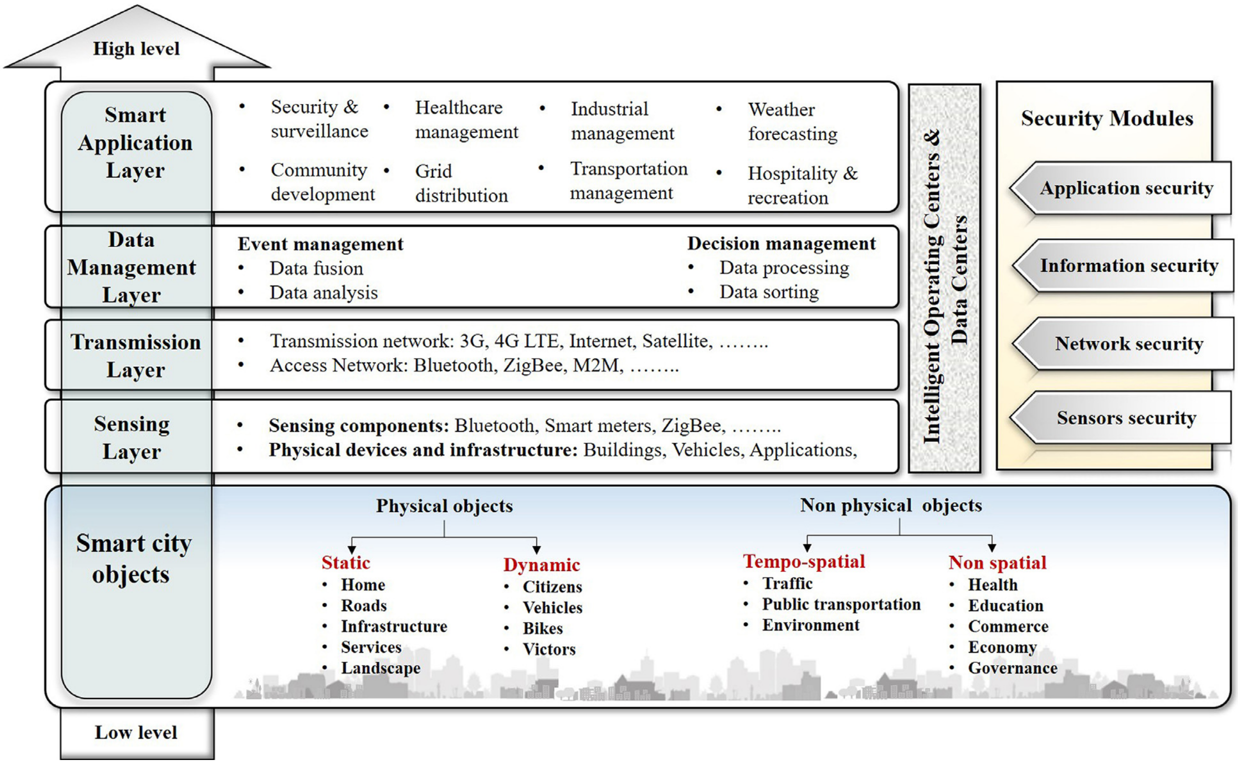

Fig. 1. Smart city layered architecture, adopted from [36–38].

foster innovation and enhance people's knowledge [29]. A smart city consists of an intelligent, interdependent network of devices, systems, platforms, and users. Pervasive, secure wireless connectivity and IoT enable the transformation of traditional cities into smart ones. The massive amount of information generated by the thousands of sensors and devices in a smart city requires big-data solutions and strategies [22,30]. These solutions allow smart cities to leverage superior capabilities by handling problematic data infrastructure more efficiently. This is achieved by providing appropriate approaches for data storage, security, analysis, visualization, and executive controls for huge volumes of data.

The smart city layered architecture

Smart cities pertain to the smart control of cities using various electronic sensors and advanced communication techniques. Citizens of smart cities and IoT devices are seamlessly connected, and the services are provided through private cloud networks. The centralized cloud database of the smart city infrastructure provides storage for all data collected from both users and devices in the ecosystem [11,31-35].

The abstraction of smart cities is highly complex because of the numerous elements involved as well as their diverse behaviors and properties. Typically, a smart city would consist of people, communities, buildings, roads, services, and others. Based on computer science conventions, the smart city architecture has four layers, the sensing layer, the transmission layer, the data management layer, and the smart application layer, as presented in Fig. 1. The top layer, the smart application layer, consists of the final products or services delivered from all ICT modules; this layer constitutes the foremost measure of smartness for stakeholders and users. The data management layer is responsible for processing and storing collected data that is vital for various operations in the application layer. The transmission layer, the most superior layer in the smart city architecture, transports data from the sensing layer to the data management layer. Because sensitive data protection is a key concern in any smart city, security modules are incorporated into each layer. The sensing layer is at the bottom of the architecture and performs data collection. Alongside these layers are the smart city objects layer and data centers, as well as the intelligent operation centers layer [36–38].

Ecosystem and components

Smart cities are intelligent enough to provide citizens with sustainable, eco-friendly urbanization along with intelligent solutions that can improve their lives. Fig. 2 presents the proposed smart city ecosystem, a key component of which is the application domains targeted by the smart city. These applications include smart agriculture, smart grid and energy

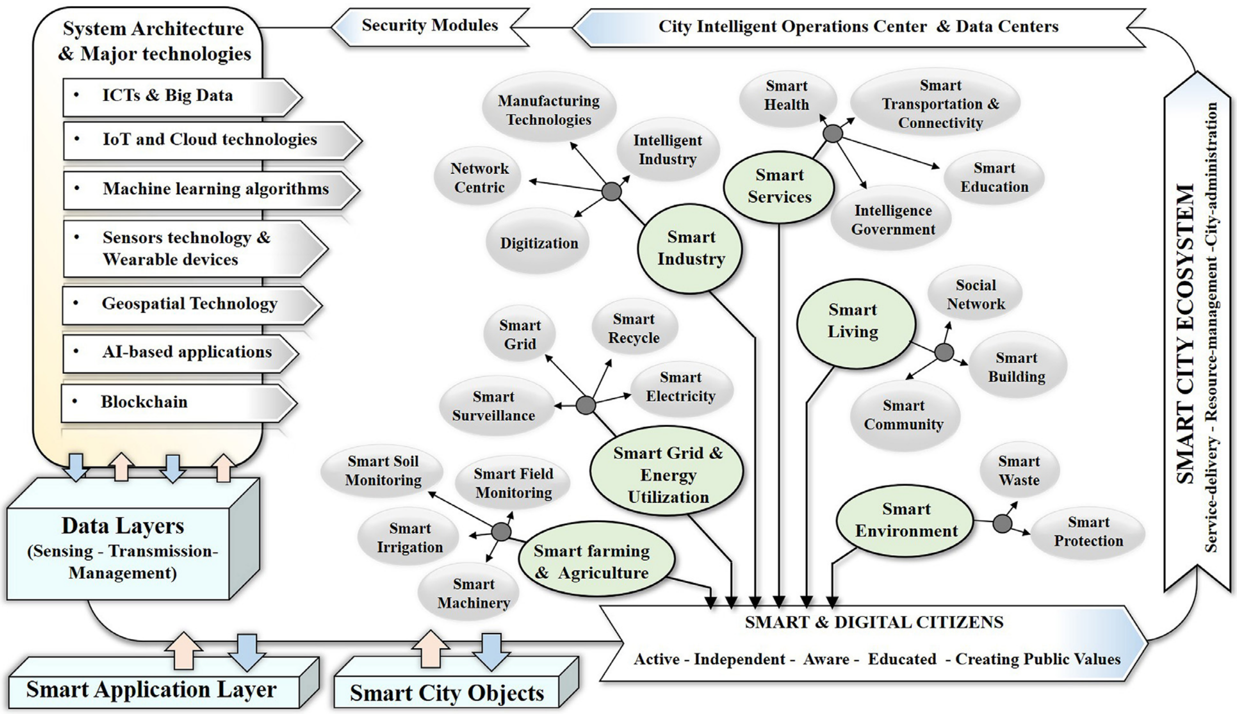

Fig. 2. Smart city ecosystem and components, adopted from [45–47].

utilization, smart industry, smart services, smart living, and smart environment. Another important component is smart citizens, who are the smart city's driving pillars and service recipients. This leads to a citizen-centric city that streamlines people's demands and provides solutions that meet these demands in the most sustainable ways [39–42]. According to [43–44], a smart citizen is characterized by five potential qualities: (a) an active participant in decision-making on issues related to public life, (b) an independent citizen who is flexible in choosing issues and controlling the data they generate, (c) an aware citizen with up-to-date information, (d) an educated citizen with the knowledge to suggest policies for better city life, and (e) a citizen who possesses values that are of communal interest and benefit the people [28,45].

Additional components in the ecosystem include major technologies, devices, and procedures involved in the smart city. Operations and data centers are necessary to enable scalable, agile infrastructure, which may include on-premises, cloud, colocation, and edge data services. To ensure a safe ecosystem, security modules are vital. The security of all data used and collected by IoT is a serious challenge with the rapid increase in cybersecurity breaches targeting IoT devices. Such security vulnerabilities in the IoT ecosystem negatively affect all stakeholders of the sector and may slow down the digitization and growth of smart cities.

Impacts of the COVID-19 pandemic on the smart city paradigm

The COVID-19 pandemic has delayed the growth of many cities because of the global economic recession associated with the forced lockdowns, reduced governmental revenues, and increased expenditures to tackle the pandemic situation. However, despite these factors, the COVID-19 pandemic necessitated several new procedures and services that influenced the urban policymaking and planning required in smart cities [11,48].

Short- and long-term effects

Existing and new digital technologies were proposed to supplement traditional measures in response to the first pandemic of the decade, during which AI-based digital technologies soon became the cornerstone of personal and professional life. Smart cities play different roles in the different stages of the pandemic: precrisis, during the crisis, and postcrisis. They also serve important roles in disaster planning for the post-COVID-19 "new normal." Using smart city platforms for intelligent prevention, epidemic management, information screening, and medical resource matching during the pandemic has attracted the attention of policymakers and scholars. Researchers from different disciplinary backgrounds relevant to city planning and design investigated the intellectual implications of applying the latest technologies that have evolved to address environmental hazards such as the coronavirus pandemic [49–50].

Table 1
Impacts of the COVID-19 crisis on the smart city ecosystem, adopted from [2, 30, 46, 48, 56-58].

Key aspects	Short-term impacts	Long-term impacts
Smart governance and management	Increased participation in decision-making through online citizen portals, efficient and fast public services, innovative planning approaches, and e-services.	The shift toward e-governments and digital transformations. Increased government authority.
Smart Healthcare	Development of e-health records and mHealth, diagnostic analytics portals, emergency medical services, UVC radiation and sanitizing tunnel, smart imaging system, face recognition, and telemedicine service.	Expanded use of IoT-integrated smart disease surveillance systems. Reformed healthcare delivery. Significant investments in enhancing public health capacity and response.
Smart Education	Integration of online learning solutions, and online exams, virtual labs, school monitoring, smart learning through video conferencing lectures, and teacher-student management platforms.	Substantial investments in e-learning platforms and technology. Development of comprehensive learning management systems.
Smart mobility	Improved accessibility, expansion of ICTs infrastructures, and real-time traffic management and monitoring.	Development of sustainable and innovative transport systems. The acceleration toward sustainable transport and logistics solutions.
System architecture and major technologies	Accelerated growth of broadband consumption and Web traffic. Greater demand for cloud and network stability. Cybersecurity is a major concern. IoT integration for close social monitoring.	Significant government investment in IoT technology. Sizable investments in reliable technology and high-speed connectivity.
Urban planning and road infrastructure	Preservation of essential infrastructure developments with some delays due to budget cuts and supply-chain issues. Integration of public security tools and safety alarms in public places during emergencies.	Considerable funding for growing the economy but with the risk of reprioritization. Increased development of social infrastructures (new hospitals, schools, and clean water projects).
Smart buildings	Faster dissemination of smart homes, smart ventilation, smart lighting, smart water supply, smart sanitation, smart fire detection, smart crowd control, smart parking, and smart monitoring. Smart office solutions for shared workspaces.	Increased public investment in crowd alert systems and temperature checks in buildings. Increased need for establishing contactless interactions, monitoring indoor air quality, and optimizing building sanitization. Higher demand for efficient employee tracking and communication.
Smart environment	Smart resource utilization. Smart solutions for water leakage and pollution detection and predictive maintenance planning. Investments in just-in-time waste collection, which uses sensors to optimize collection processes.	Sustainable use of resources, environmental protection, and disaster management. Increased investments in a green and clean environment.
Smart grid and energy utilization	Increased demand for renewables at a negative cost. Better awareness of air quality concerns. Significant pressure to transition to lower-carbon energy systems. Conversion to smart distribution networks that automatically monitor energy flows and automatically adapt to fluctuating supply and demand.	Increased demand for renewable, smart electrical and energy networks and smart meters; efficient utilization of energy subsystems; energy distribution through sensors; and storage. Increased need for solutions to reduce record-high energy prices driven by the global surge in energy demand after the worldwide economic recession. Increased demand for efficient energy storage as key to resilience.
Smart living and socioeconomic domain	Substantial impact on business enterprises that varies according to their region, sector, and scale. Increased need for reliable and secure high-speed connectivity to meet the expedited shift toward working and studying from home.	Questions remain on tracking essentials. Security versus privacy debate. Long-term substantial effects on supply chains and major industries.
Smart citizens	Increased need for engaged and educated citizens.	Wider awareness of smart solutions increased creative and flexible participation and efficient community interactions.

The COVID-19 crisis has become a global test of whether smart city technology can minimize its worst impacts. Cities that have implemented digitalization initiatives and practices had a better ability to react appropriately and increase their post-crisis resilience and sustainability. These technology-driven policies and actions should be integrated into the everyday life experiences at diverse scales in the urban environment, from individual buildings to urban spaces and units, neighborhood communities, and the city level to develop an antivirus-built environment against future pandemics [3,14]. However, large-scale technology deployment raises significant concerns regarding social exclusion, privacy, confidentiality, misinformation, and inefficient remote working and education [51–55]. Table 1 summarizes the potential short- and long-term impacts of the COVID-19 crisis on the smart city paradigm.

State-of-the-art solutions and tools

COVID-19 was an unprecedented health crisis and consequently its immediate impact was obvious in the accelerated developments of analytical tools and IoT adaptation in healthcare diagnosis, monitoring and decision making. However, the pandemic affected almost all aspects of life, necessitating the global need for new tools and technologies to cope up with the new, troubling challenges such as severe supply and demand variations, social distancing, distance education, and smart monitoring and surveillance [59, 60]. Table 2. presents some recent relevant success stories in the tools and IoT devices developed in the fight against COVID-19.

Open challenges and future directions

As smart cities will soon become the "new normal," the demand for smart technology development will continue to grow. Despite the evident benefits of smart cities, urban digital transformation has its challenges. Government authorities and key decision-makers must engage in the administration of different technical aspects such as technology deployment, communication networks, and data security protocols. They must also overcome the internal challenges associated with mapping out complex strategies involving various direct and indirect stakeholders such as citizens, public organizations, private enterprises, network and service providers, and IT infrastructure providers [11,46]. Academics and policymakers involved in the urban planning discussion are searching for the necessary economic and social inclusivity to develop their cities. Infrastructure is a key challenge facing smart city development; an advanced IT-based infrastructure is essential for deploying, operating, and maintaining the large grid of IoT sensors. It should be scalable and adaptable to abrupt advances in technology. This is a complex long-term transformation process that requires smart resource allocation, substantial funding, and full governmental support to successfully replace decades-old infrastructures [38,46,90].

Another key challenge for smart cities is associated with security issues. The expanding use of IoT sensors and the increased interconnectivity of mutually interdependent components of city infrastructure have increased vulnerability to cyber-attacks and security breaches. The attacks not only threaten data but may also cause substantial damage to the infrastructure. Solutions based on big-data analytics, blockchain, and encryption technologies are designed to handle increasingly more sophisticated cyber-attacks [1,35]. Smart city developers are investing in blockchain technology to improve cyber security and protect user privacy. As the blockchain network expands, blockchain nodes will require higher computation power. Future research can be conducted on how the power consumption of blockchain nodes can be minimized in a smart city environment. Nevertheless, blockchain is still in its initial stages and has its limitations, which are delaying its full-fledged adoption [91,92].

Another challenge is associated with privacy and human rights. As more people use technology in their everyday lives, governments and/or corporations in charge of the urban digitalization process have greater access to enormous IoT and user information, increasing privacy concerns and raising questions regarding confidentiality and citizens' ethical rights. Furthermore, other concerns include the potential for digitalization to widen inequality and social segregation, as not all people have equal access to technology. An additional challenge is related to the residents themselves. For a smart city to exist and develop, it requires "smart" citizens who are actively engaged and possess a solid understanding of the potential benefits and advantages of new technologies [93,94]. Smart governance is concerned with the adoption of ICT solutions and technologies into city governance practices in order provide the means to enable citizens, private and public organizations to communicate, collaborate, and access management data and information required for an effective participatory decision-making process. Table 3 summarizes the strategic challenges facing smart city development and the future research directions that may address these issues.

Conceptual framework for future smart cities

Urban planning and design have always evolved to effectively and efficiently confront public health risks and other security threats. Disease control is a long-standing objective in building smart city architecture. The presented literature review demonstrates the complexity and multidimensionality of the smart city concept. This section proposes two models of the conceptual framework for future smart cities in the fight against COVID-19. The first describes the technical dimension in terms of the stepwise data-processing pipeline that constitutes the backbone of efficient smart city architecture. The second integrates various dimensions to build a holistic framework that targets the multidisciplinary perspective of smart cities. This multiperspective vision is essential within the smart city context to allow decision-makers to coordinate the integration of data gathered from various smart city components and make optimum decisions on the best ways to combat COVID-19 and any future pandemics.

Technical dimension of smart cities

IoT-powered smart cities rely completely on the efficient management of sensors that can be embedded into buildings, roads, vehicles, devices, and human bodies, turning these physical objects into digitally connected entities [13,30,33]. The huge number of deployed IoT sensors generates a large volume of real-time data that is often geotagged, the processing of which requires extensive time and resources to leverage the advantages of smart city technologies. A comprehensive

Table 2
Recent tools, IoT devices and initiatives developed in the fight against COVID-19.

Domain	Service Category	Tool/ Methodology	Ref.
Health care	Wearable and implanted devices for Remote Patient Monitoring (RPM)	WHOOP COVID-19 identification strap. Measures respiratory rate using Resting Heart Rate (RHR) and Heart Rate Variability (HRV). Data is communicated to a mobile application and then forwarded to a cloud. The Scripps Research DETECT (Digital Engagement & Tracking for Early Control & Treatment) measure and transmit various predictors of health deterioration. Philips disposable patches and biosensors for early detection of COVID-19 and early patient deterioration detection.	[61–65]
	Smart hospitals	BOE Hefei Digital Hospital, China, all aspects of the patients are managed via IoT providing smart building services and sustainable energy management. The Helsinki University real-time locating system (RTLS) to collect and share anonymized location data about on-site movements. Cloud services are provided to enable doctors and nurses to remotely interact with COVID-19 patients.	[60,66]
	E-health records	Infermedica mobile application Symptom Checker which interviews home occupants and guides them about their current health. They have also developed an Alexa skill to integrate Symptom Checker with smart homes. Singapore HealthHub platform, which integrates personal health record management and the clinical data of patients and citizens.	[67, 68]
	Health care Regulation, risk assessment	The COVID-19 pandemic preparedness simulation tool: CovidSIM provide a realistic and easy-to-use simulation tool with the capacity to support decision-making in public and global health, epidemiology, and economy. FDA Approval for the Philips Lumify portable ultrasound device which has a transducer that needs to be connected to the user's smartphone. FDA Approval for Aidoc's AI-CT Algorithms FDA Cleared for COVID-19 detection.	[69–73]
Smart living	Quarantine Solutions	Amazon's Alexa Care Hub help people to remotely check in on their family members who they are not able to visit due to COVID-19 restrictions. Singapore mobile application called TraceTogether that helps with contact tracing by tracking the events when people with the application installed in their mobile devices are in close vicinity of one another.	[74–76]
	Working from Home	Google Workspace which is a rebranding of existing products with new features. It supports creating new documents within a room in Chat, Google's Slack-like chatrooms, without having to switch tabs	[77]
	Education	E-learning tools for synchronous interaction and conducting conventional classes via the Internet such as Zoom Video Communications, MS Teams, Google Meet and Cisco Webex Teams and Meeting. Asynchronous learning platforms, such as Discord, Google Classroom, webinar platform, Click Meeting, and the most popular social networks: Facebook and YouTube.	[78–80]
	IoT in Production	Smart industry and industry 4.0 allow an innovative and less human-dependent productive environment. AI solutions in IoT for agriculture, disease detection, and data-driven crop supply management.	[59, 60].
Smart Building	Indoor-Quality	Arup Group digital platform called Neuron that measures indoor air quality to predict or monitor high-risk conditions and allows remedies such as ventilation, UV light, or air purification to improve the indoor air quality. Thermal sensors for fever detection. Automated Robot-based building cleaning.	[59, 81]
	Contact Tracing	QR code-based contact tracing is utilized in shared places.	[82]
Smart Cities	Resilience	Japan's National Resiliency plan covers smart communications, sustainable energy systems, and resilient water networks.	[83]
	Initiatives	Singapore Trace Together mobile application that helps with contact tracing by tracking the events. Indonesia ICT-based smart city implementation is applied in five major cities to different extents. The use of CCTV to control people's mobility and dashboards to facilitate information sharing and management.	[84, 85]
Smart Transportation	In-vehicle Ambience	GM and Hyundai use UV light to clean the vehicle cabins. Uber facial mask detection initiative in their navigation application.	[86, 87]
	Smart Resource Management	Smart fleet management. NearForm smart logistics vaccination app to improve the management of inventory and resource allocation for COVID-19 vaccines. Vodafone support for COVID-19 vaccine roll-out in Africa using cellular and IoT tracking and monitoring technologies.	[59, 88, 89]

Table 3
Research challenges and future directions for smart cities, adopted from [2,11,60,61,93–99].

Aspect	Challenges	Future directions
Physical and IT Infrastructure	High infrastructure cost, operation and training cost, maintenance cost, and complex cost management. Network connectivity and integration issues. The need for IT infrastructure to be agile and scalable. Distributed computing, different stakeholders, maintenance, and management.	Cost-effective framework for enforcement, benefit-cost analysis. IoT research. Smart power grids. Interdisciplinary research and technical workforce.
Efficient Data-Processing and Analytics	Data bias and sharing concerns. Storage issues, data availability, and scalability. Lack of high-quality/high-quantity data. Lack of technology access. Lack of planner knowledge, standardization, and expertise.	Novel AI and machine learning models. Secure big-data solutions. Cloud, edge, and fog computing. Accurate real-time data analytics.
Security and Privacy	User privacy issues. Trust issues and data integrity. Communication and access control techniques. Cybersecurity and hacking of sensitive personal data. (De)anonymization of data. Infrastructure security issues and system failure.	Privacy-preserving solutions and differential privacy. Secure network protocols. Blockchain framework. Collaborative or federated deep learning. Adaptable access control techniques, hybrid access, and communication control mechanisms.
Legal and Ethical Issues	Lack of Smart Governance due to technology infrastructure constraints Lack of norms, policies, and timely legislation. Lack of standardization. Privatization and cultural issues.	IoT technologies for government-to-citizen (G2C), government-to-business (G2B) and government-to-government (G2G) processes through which the essential services and interactions of the private, public, and social organizations can be combined such that the city can function effectively. User privacy legislation and updated privacy/security policies. Public-private sector partnership.
People	Lack of skilled and experienced professionals. Educating and engaging the community. Social inclusiveness.	Online education/training platform that keeps citizens engaged and up to date. Smart city planning involves all groups of people, not just the technologically acquainted.

analysis of these geotagged IoT data provides important insights and knowledge about the surrounding environment that can be used to enhance the intelligent emergency management plan for emergencies and pandemics. Based on the literature [6,8,13,33,55,90,100], the framework of the data-processing pipeline in smart cities in the fight against COVID-19 is presented in Fig. 3.

The smart city data-processing pipeline includes various procedures for data collection, data preprocessing and cleaning, data analytics, data visualization and interpretation, and decision-making. Two approaches for data analytics are incorporated in smart city architectures [6,8,25]. The first is the edge computing architecture, which processes time-sensitive data at the edge nodes closest to the end user and away from the cloud servers. This provides a real-time data-handling model that can be independently scaled with the addition of new devices into the system. However, this distributed data-processing model has limited storage, bandwidth, and computational capabilities and requires robust security and authentication procedures. Meanwhile, the second model is cloud computing big-data analytics. This is a powerful, centralized data-processing model that is suitable for businesses and originations and requires great computational capabilities, the management of huge amounts of data, and the ability to obtain platform access or use cloud-hosted applications. Although many IT vendors are transitioning to edge computing, modern data-processing systems incorporate hybrid solutions that optimize the cost–need trade-offs in the system [25,90].

The great evolution in AI is progressively launching new opportunities for smart city developments [16,31,55,56]. Typical AI-based detection, tracking, and prediction algorithms are incorporated to provide optimal solutions for many applications in the fight against COVID-19, such as identifying disease clusters, monitoring patient recovery, providing personalized and prioritized health services, and predicting future outbreaks. However, AI models such as machine learning algorithms depend on recognizing patterns in the training data, which requires large amounts of data. This requires a multi-stakeholder collaboration involving the AI community, the public health community, system developers, and policymakers to formulate the problem; identify and exchange relevant data; share tools; and train, test, and deploy models.

Holistic framework

The COVID-19 pandemic and the regulations and technological tools adopted by governments to manage it have expedited the need to deal with organizational scenarios characterized by complexity and uncertainty. In this context, resilience is a key indicator used in smart city planning to assess urban sustainability and growth and to endure unpredictable environments by absorbing shocks and implementing changes to recovery. The Sustainable Development Goals provide some

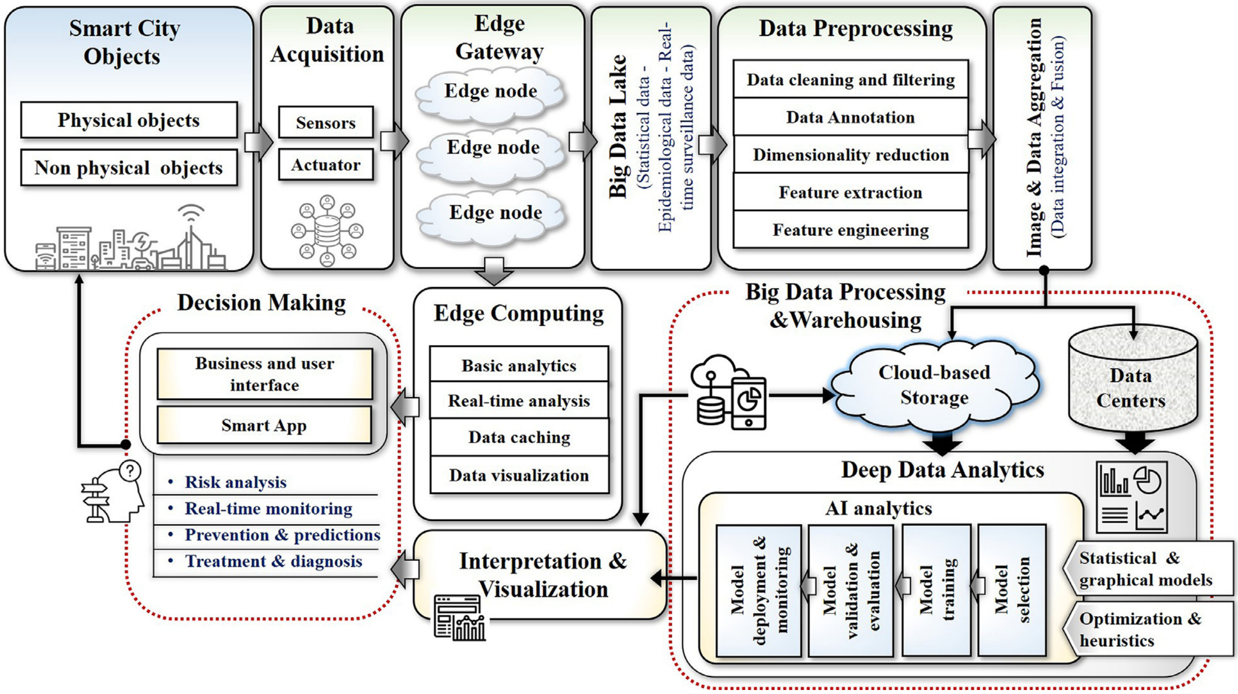

Fig. 3. Framework of the smart city technical dimension (data pipeline) in the fight against COVID-19.

guidelines to attain a sustainable future and consider smart cities as key players in developing inclusive urbanization and resilience (SDG 11). Resilience attitudes in smart cities can significantly help mitigate the adverse effects of the COVID-19 pandemic [101–104]. These sustainable, smart, and resilient entities should entail various proficiencies during the different stages of the pandemic, such as preparedness (pre-disaster), response (in-disaster), recovery (post-disaster), and adaptation (new normal). The preparedness stage refers to the prevention control and procedures implemented before the pandemic that can improve the overall system response. It can be extended to procedures taken for readiness against the succeeding waves of the pandemic. The response stage includes procedures taken during the disaster to absorb the shock and lessen its damage. The recovery stage pertains to reverting to the normal pre-disaster phase. The adaptation stage promotes further recoverability, as it tends to improve overall performance to ensure better planning and preparation against future pandemics and crises [105–109]. Fig. 4 illustrates the stages of the resilience-building cycle in smart cities.

Maione and Loia [48] proposed new categories accompanying the smart city paradigm triggered by the pandemic. These categories allowed “transforming” the meaning of the SMART acronym to consist of safety, mitigation, accountability, resilience, and traceability. Thus, the function of a smart city must closely relate to local needs and the availability of resources. In addition, the idea of a smart city varies from city to city; therefore, it is important to investigate what is efficiently and instantly available in each context. It is also essential that we connect the idea to possible rational alternatives, as accurate and timely decisions make a great difference during an outbreak [110–112]. As more communities prepare to utilize digital technologies in their fight against COVID-19, most experts believe that these solutions are here to stay and evolve. Changes associated with the smart city concept that was introduced during the pandemic will not only allow for greater epidemiological resistance but will also enable the completion of goals set for smart cities.

Finally, the COVID-19 outbreak is unprecedented and has opened several research challenges and opportunities for the future. The proposed multidisciplinary perspectives presented in this paper can be used to effectively and timely enforce measures and optimize resource utilization in critical situations. This conceptual framework is based on the integration of five different governing dimensions, each of which reflects a unique perspective of the situation (see Fig. 4). First is the technical dimension, which is illustrated in the flow-of-data pipeline and represents the backbone of the smart city paradigm. It emphasizes the system infrastructure architecture, smart technologies and devices, networking and routing protocols, and component interconnections and interactions. Second is the organizational dimension, which represents the module that relates to the capacity of organizations to prepare for, respond to, recover from, and adapt to any crisis. The third is the social dimension, which aims to reduce the negative effects that have emerged as society responds to the pandemic. Fourth is the economic dimension, which refers to the ability to minimize direct and indirect financial losses resulting from lockdowns and employment loss during the crisis as well as the ability to absorb and balance additional costs. The final dimension is the smart dimension, which involves COVID-19-related measures to overcome risk factors. The proposed framework aims to serve as a prominent step toward comprehensive research and the deployment of automated data-driven technologies

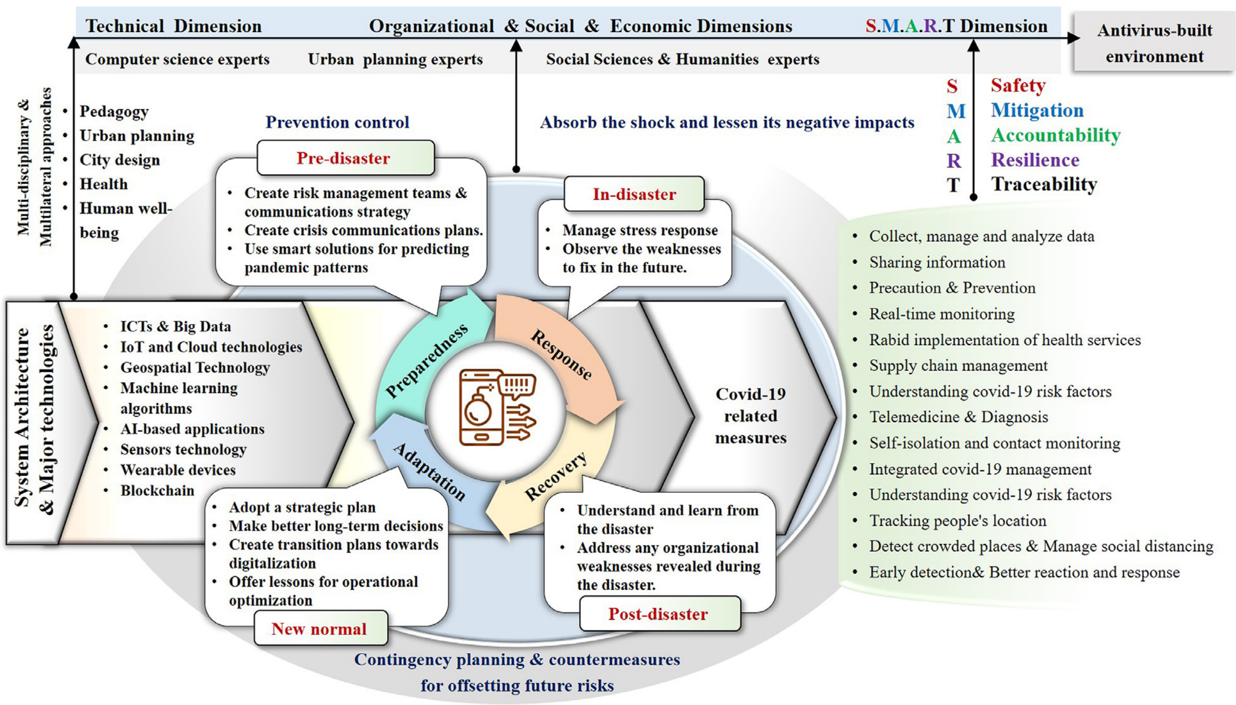

Fig. 4. A holistic framework of smart city technologies and implementation to avoid future crises.

in smart cities. Moreover, the multidimensional perspectives reveal the need to understand the smart city as a cultural, political, and social entity that requires advanced security and privacy models. Another potential challenge for urban theorists is the preservation of urban identity and character, which might be in jeopardy when conducting mass production and creating prototypes for building smart cities.

Final remarks and conclusions

The COVID-19 pandemic has provided new evidence of the importance of digital infrastructure. The smart city vision maintains the potential of integrating data from multiple organizations, diverse environments, and a wide variety of technologies. The present study discussed the various aspects of the modern technology used in the fight against the COVID-19 pandemic at different levels and from a multidisciplinary perspective. Among various concepts that utilize ICT in urban environments, the smart city paradigm stands out, owing to its comprehensive vision. IoT and smart connected technologies, together with data-driven applications, can not only play a crucial role in prevention, mitigation, or recovery but also enable the prompt enforcement of guidelines, rules, and administrative orders to contain future outbreaks. As a result, traditional cities should incorporate smart technologies and digital approaches along with a resilient mindset to support communities against future challenges and disasters. From a theoretical point of view, the COVID-19 crisis seemed to have pushed smart cities to include resilience thinking in their recovery strategies. If design, implementation, and operation challenges are addressed in the future, the implementation of smart cities can be beneficial. Powerful solutions must provide secure access and manage smart city data, communication, and infrastructure. If smart cities are developed in a structured way with proper planning and analysis, they will develop an antivirus-built environment against future pandemics. Nevertheless, we are still in the middle of the fight against COVID-19, and we are not yet certain when and how this crisis will end; this is a test of collective intelligence, adaptability, resilience, and human collaboration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Naglaa A. Megahed: Conceptualization, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. **Rehab F. Abdel-Kader:** Conceptualization, Supervision, Writing – review & editing.

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