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Review

Sensors for Sustainable Smart Cities: A Review

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Abstract: Experts confirm that 85% of the world's population is expected to live in cities by 2050. Therefore, cities should be prepared to satisfy the needs of their citizens and provide the best services. The idea of a city of the future is commonly represented by the smart city, which is a more efficient system that optimizes its resources and services, through the use of monitoring and communication technology. Thus, one of the steps towards sustainability for cities around the world is to make a transition into smart cities. Here, sensors play an important role in the system, as they gather relevant information from the city, citizens, and the corresponding communication networks that transfer the information in real-time. Although the use of these sensors is diverse, their application can be categorized in six different groups: energy, health, mobility, security, water, and waste management. Based on these groups, this review presents an analysis of different sensors that are typically used in efforts toward creating smart cities. Insights about different applications and communication systems are provided, as well as the main opportunities and challenges faced when making a transition to a smart city. Ultimately, this process is not only about smart urban infrastructure, but more importantly about how these new sensing capabilities and digitization developments improve quality of life. Smarter communities are those that socialize, adapt, and invest through transparent and inclusive community engagement in these technologies based on local and regional societal needs and values. Cyber security disruptions and privacy remain chief vulnerabilities.

Keywords: smart networks; digitization; smart transit; cyber security; smart city; smarter communities; smart sensors; smart meters; internet of things (IoT); facial recognition; cyber privacy

1. Introduction

"Smart Cities" or "intelligent cities" are the cities of the future that offer innovative solutions to improve the quality of life of urban communities in a sustainable and equitable manner. The idea of a "Smart City" represents more efficient cities that better manage their resources, services and technologies and, above all, put them at service of the citizens. People-centric planning will allow a better management and efficiency of the city through the deployment of smart infrastructure. By 2050, 85% of the world's population is expected to live in cities [1–3]. This means that in the following decades, urban centers will face a growing number of problems such as: (1) energy supply, (2) CO_2 emissions, (3) mobility systems planning, (4) raw materials and goods provision, and (5) the provision of health and security services to all the residents in these rapidly growing population centers [4].

To better respond to the increasing volatility driven by climate change, pandemics like COVID-19, and connected political and economic fluctuations, cities must be redesigned to increase their adaptive capacity and resilience [5]. Schemes and models of more liveable cities need to be created, where digital technologies are the key elements for the sustainable development and organic growth of cities [6]. Vulnerabilities of the shared economy in smart cities, such as transport services and their enabling technologies are being tested by the global pandemic and cyber security risks. However, new apps and internet businesses flourished, such as food delivery and online shopping [7–9].

Skepticism towards pervasive digitization, sensing, monitoring, and visualization capacities deployment, and other smart communication technologies used by both the private sector and government, arise, among other factors, from the concerns of citizens regarding the processing of their data, and, therefore, their privacy [10]. The use of new technologies such as artificial intelligence, where personal data play a critical role, are facing increasing challenges [11]. Support for the establishment of codes of conduct are being promoted by the industry itself, and use cases will be key so that its development does not suffer [1]. In the years to come, problems such as intentional disinformation, the evolution of so-called digital rights, or the consolidation of digital identity, must be addressed. The solutions oriented to solve these problems require a long-term perspective, which will steadily become more and more evident as Smart City implementations have become a norm across the globe [12].

With the incoming necessity of communities to become smarter, many applications have started to arise on different countries; and a literature revision that discusses such applications will be useful as a reference for future smart city implementations. In this review, the literature covering several applications of sensors for smart cities is summarized and discussed, in order to fulfill three main objectives: (1) To provide a revision of the most important Smart Cities implementations across the world; (2) To describe the main applications of sensors for smart cities across six main topics (health, security, mobility, water and waste management, and energy efficiency); and (3) To identify common challenges and opportunities of smart city deployments in the proposed six topics.

2. Literature Review

A systematic search of relevant scientific literature was conducted in this study through databases such as Scopus, Google Scholar, and IEEE Xplore. The literature search on sensors for smart cities was divided into six main sectors: health, security, water, waste, energy, and mobility. The criteria for selecting and revising relevant papers from each section, followed the PRISMA methodology [13], as well as these principles:

1. Recent (2010–2020) literature was reviewed to ensure a revision of the current state of the art of the technologies applied to smart cities environment; prioritizing papers published during the 2015–2020 period. Figure 1a shows the distribution of the years of publications of the revised papers for this review;
2. Among the selected literature for each section, the most cited papers, including journal articles and conference proceedings were revised extensively. Figure 1b presents the distribution of the number of references with an increasing number of citations of the revised literature. Papers from Q1 and Q2 journals were given priority over Q3 and Q4 journals; as well as journals with impact factors higher than 1.0. Figure 1 shows (c) the quartiles, and (d) journal impact factor of the revised papers in this this review. Additionally, Figure 2a shows the type of references (journal, conference proceedings, books, webpages, and theses) selected and its percentage;

3. In the six main sectors, preference was given to articles where the main topic was the use of sensors exclusively for the subject evaluated. A wide range of studies from the exploration of theoretical aspects up to practical applications were included. Figure 2b shows the percentage of revised papers under categories "Health", "Security", "Mobility", "Water", "Waste", "Energy", and "Smart Cities";
4. For each of the six sectors, different keywords were used to find relevant literature across each field. A list of keywords used for each section is presented as follows:
   (a) Health: Key terms were searched in the publication title, abstract, and keywords, and include: "smart city", "smart cities", "sensors", "wearable sensors", "body sensors", "smart health", "smart healthcare", "healthcare sensors", "healthcare applications", and "internet of things";
   (b) Water: The selection of the articles for the survey was carried out using the keywords "water" AND "sensors" AND "smart cities";
   (c) Waste: The selection of the articles for the survey was carried out using the keywords "waste" AND "sensors" AND "smart cities";
   (d) Mobility: Among the main keywords and combination of keywords used for this search were "mobility" AND "sensors" AND "smart cities". Other keywords such as "traffic", "vehicle", "pedestrian" AND "sensors" AND "smart cities" were also included;
   (e) Energy: The following keywords were included in the search: "energy consumption", "thermal comfort", "energy-consuming systems", "greenhouse gas emissions", "HVAC system", "lighting systems", "buildings energy consumption", "urban space energy consumption", "Key Performance Indicators", "Light Power Density (LPD)", "alternative energy source", "smart buildings", "smart lighting", "smart citizens", "ecological buildings", "virtual sensors", "BIM modeling", "energy consumption sensors";
   (f) Security: Keywords from this topic include: "Cybersecurity", "Sustainable Development", "Environment Security", "Society Security", "Human Security" AND "sensors" AND "smart cities".

Following the aforementioned principles, a total of 193 references were reviewed in detail; of which 129 come from journals, 46 from conference proceedings, 9 from books, 8 from web pages, and 1 from a Ph.D. thesis.

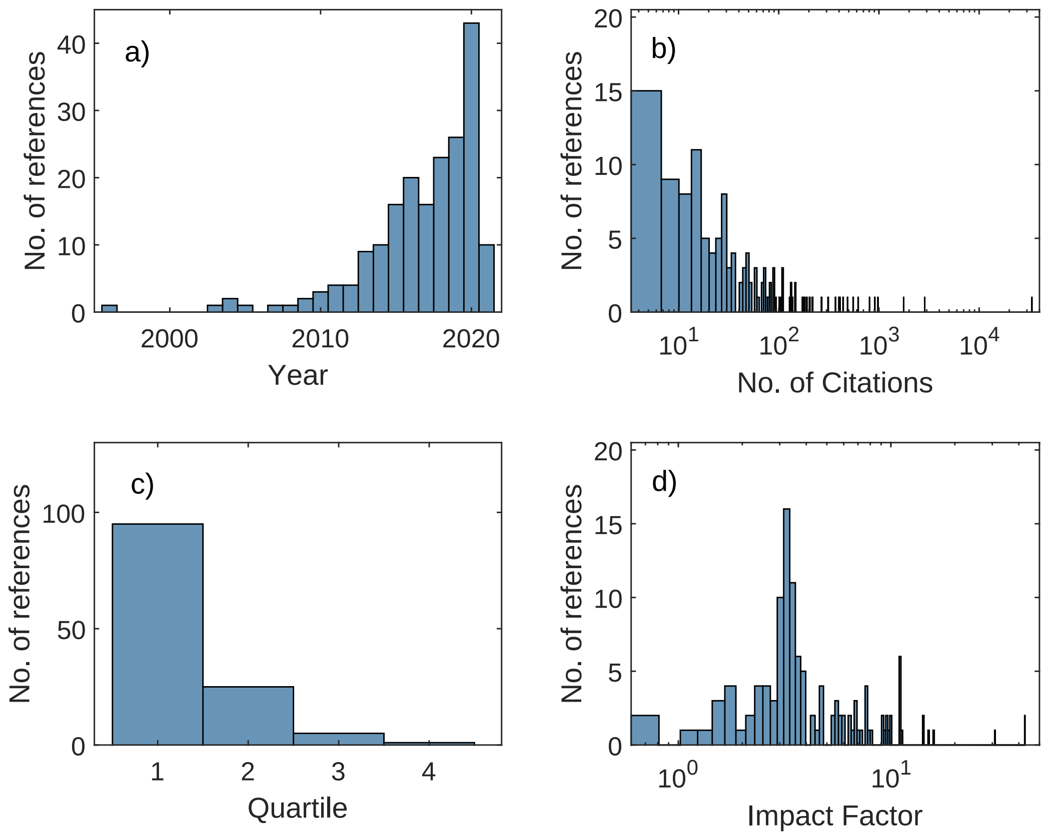

Figure 1. Histograms showing the distributions of different features of the papers selected for this review: (**a**) Year, (**b**) Number of citations, (**c**) Journal Quartile and (**d**) Journal Impact Factor.

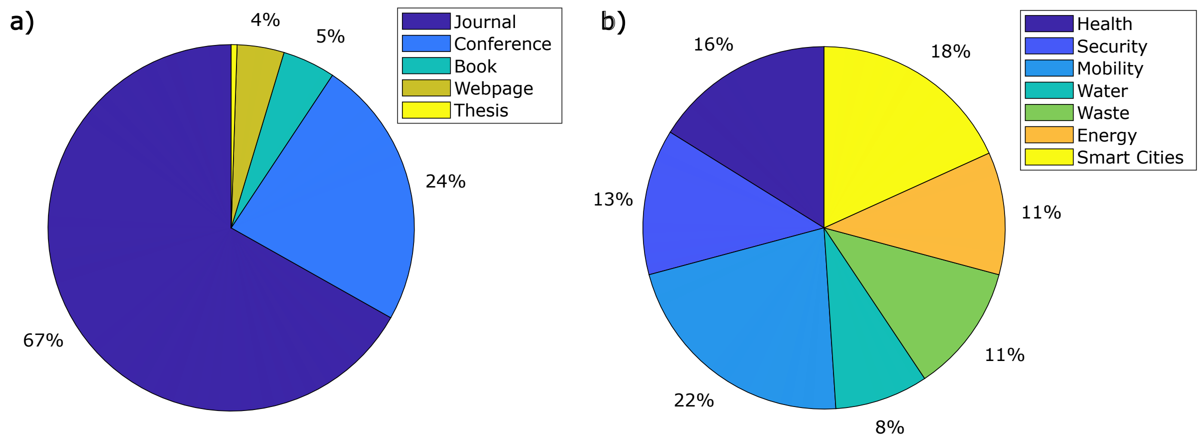

Figure 2. Pie charts representing the distribution of the (**a**) Type of reference and (**b**) Topic of the selected references for this review.

3. Results

3.1. Smart City

The goals of smart cities initiatives are to develop economically, socially, and environmentally sustainable cities [5,6,12]. Generally, the ideal model of a smart city is based on the incorporation of the following subsystems and technologies: distributed energy generation (micro-generation) [14], smart grids (interconnected and bidirectional smart networks) [15], smart metering (intelligent measurement of energy consumption data) [16], smart buildings (eco-efficient buildings with integrated energy production systems) [17], smart sensors (intelligent sensors to collect data and keep the city connected) [18], eMobility (implementation of electric vehicles) [19], information and communication technologies (ICT) [20] and smart citizens (key piece of a smart city) [21].

Cities constitute a complex socio-technical system [22,23]. In order to design the best solutions for cities, their inhabitants, social entities and governments need to be considered [2,3].

More pleasant spaces and places are required to live, boost competitiveness and productivity. To achieve this, the development of communication technology, such as 5G, is imperative. There also exists a growing need for initiatives of Industry 4.0 to permeate cities, since small or medium-sized enterprises (SMEs) represent the largest business fabric in developing countries [5]. In this sense, it is necessary to increase operators' access to reliable 5G infrastructure, allowing optimal deployment and economic rationality of the networks. In addition, governments are expected to provide access to resources and tools that facilitate the deployment speed and offer the necessary infrastructure for the latest generation networks [24].

3.2. Smart Cities in the World

In this section, some smart cities deployments across the world are presented. In Europe: Tampere, Helsinki, Amsterdam, Vienna, Copenhagen, Stockholm, Milton Keynes, London, Malaga, Barcelona, Santander, Paris, and Geneva [4,25–27]. In Asia: Singapore, Hong Kong, Shanghai, Beijing, Songdo, Seoul, and also smart cities in Taiwan, Indonesia, Thailand, and India [4,25,27–29]. In North America: Toronto, Vancouver, New York, Washington, and Seattle [4,25,27]. In South America: Medellin and Rio de Janeiro [27,30,31]. In Oceania: Melbourne, Perth, Sydney, Brisbane, and Adelaide [27,32].

The most common smart city project implementations across these cities include: development of collaborative business districts in Barcelona [21,25] and Hong Kong [4,27]; citizen security by traffic monitoring in Rio de Janeiro [4,31], and natural disaster monitoring in Singapore and Indonesia [29,33]; public service, smart government, and communication transformation in cities of China (Wuhan, Shanghai, Beijing, Dalian, Tianjin, Hangzhou, Wuxi, Shenzhen, Chengdu, and Guangzhou) [28]; adaptation of cultural spaces in Medellin [30]; citizen engagement and data enhancement in New York and Washington [27]; deployment of experimental testbeds and living labs in Santander [26] and London [27]; integration of local and foreign universities in Tampere [27] and Songdo [25]; deployment of smart green projects and policies in Seoul [27] and Toronto [4]; fiber optic and smart grids in Geneva [27]; energy efficiency and innovation enhancement in Vienna [27]; improved water consumption in Copenhagen, Hong Kong, and Barcelona [4]; deployment of electric charging stations in Malaga and Paris and Amsterdam [4]; Big data integration and analysis in India and Thailand [29]; wired communities, pedestrian mobility, and mass transit solutions in Sydney, Brisbane, Adelaide, Melbourne, and Perth [32]; carbon emission reduction in Seattle [25]; smart waste collection systems in Helsinki [25], Songdo [25], Barcelona [25]; smart parking in Milton Keynes [25]. Table 1 shows the main Smart City implementations reported in the literature for health, security, mobility, water, waste management, and energy efficiency, for the countries reviewed in this section. A more extensive search on smart city deployments around the world was performed using the results from the literature review, as well as information gathered from related websites [34–36]. The results of this search are presented in Figure 3.

Table 1. Smart cities implementations around the world.

City	Health	Security	Mobility	Water	Waste	Energy
Tampere [27]			Smart transportation			
Helsinki [25]			Car charging facilities		Automated waste collection	Smart grids
Amsterdam [4]	ICT in health, Health Lab					Clean energy generation
Vienna [27]			Smart parking, car sharing			Energy efficiency
Copenhagen [4]			Bike lane network	Water quality monitoring	Optimized waste disposal	Energy efficiency
Stockholm [4]				Water management policies	Waste management system	
Milton Keynes [25]			Smart parking, MotionMap app		Sensors in recycling centers	Smart metering app
London [27]			App for public transport		Smart Waste collection	
Malaga [4]			Electric vehicles, charging stations			Smart grids, clean energies, smart lighting
Barcelona [4]	Remote healthcare	Incident detectors at home	Traffic and public transport management		Smart Containers	Centralized heating/cooling
Santander [26]			Smart Parking, GPS monitoring	Smart park irrigation		Smart public lighting
Paris [4]	eHealth, smart medical records		Bike sharing, charging stations			
Geneva [27]			Smart transportation			Fiber-optic, smart grid networks
Singapore [33]		Siren alerts for natural disasters	Traffic maps, public transport apps	Apps for water consumption tracking		Apps for energy consumption tracking
Hong Kong [4,27]		Smart card IDs for citizens	Open, real-time traffic data		Smart waste management	
Shanghai [28,37]			Pedestrian movement analysis (Big data)			
Beijing [28,38]			V2E solutions, smart cards for transportation			
Songdo [25,27]	Remote medical equipment and checkups		Self-charging electric vehicle technology		Underground waste suction system	Smart buildings
Seoul [27]			Bus service based on data analytics			
Taiwan [39]		Smart defense system for law enforcement				
Indonesia [33]		Flood monitoring and report app				
Thailand [33]		Tsunami and flood monitoring		Water management app		
India [4]			Smart transport systems			Clean energy, green buildings
Toronto [28]			Smart urban zone growth			

Table 1. *Cont.*

City	Health	Security	Mobility	Water	Waste	Energy
New York [27]		Sensors deployment after 9/11 attacks				Energy efficiency using LEDs
Washington DC [27]			Bike sharing, smart stations			Sensor-based LED streetlights
Seattle [25]		Flood monitoring, law-enforcement cameras, gunshots GPS tracking	Smart trafic lights	Real-time precipitation monitoring		Reduction of CO_2 emissions
Medellin [30]			Outdoor electric stairs and air wagons			
Rio de Janeiro [31]		GPS/video monitoring installation in police cars	Traffic monitoring using cameras			
Melbourne [27]			Smart parking, open urban planning, metro Wi-Fi			Energy efficiency, smart grid, smart lighting
Perth [40]		Cyber-security and digital forensics				
Sydney [32]			ICTs in daily urban transport			
Brisbane [32]			Pedestrian spines			
Adelaide [32]			Wired communities			

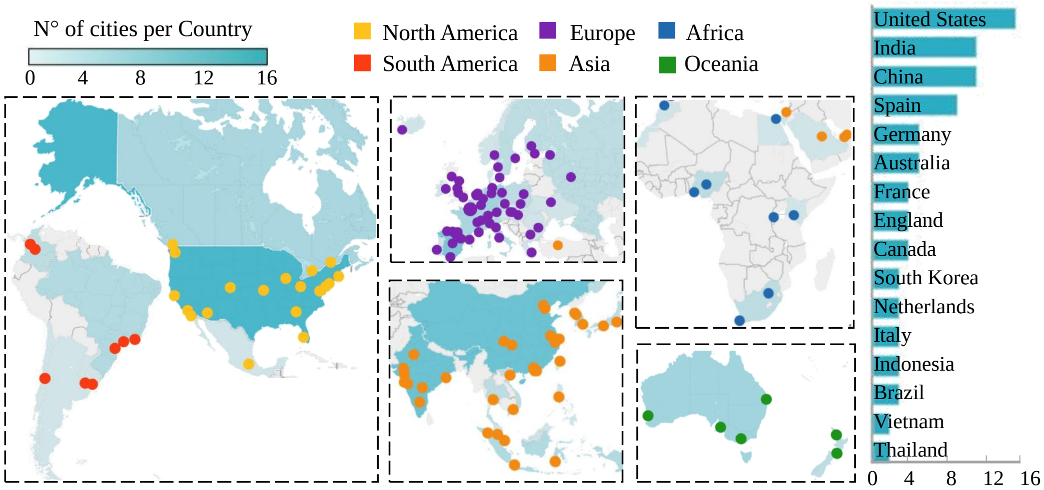

Figure 3. Map of smart cities across the world. The shade of color represents different number of smart cities per country. Cities are represented with colored points in the map, identified in six main regions: Africa, Asia, Europe, North America, Oceania, and South America. The bars on the right side show the countries with highest number of smart cities.

3.3. Sensors

The general architecture of an intelligent management system consists of readings (sensors), gateways (communication), and workstations (instructions, analytics, software, and user interface) [41–43].

3.3.1. Sensors for Health Monitoring

Healthcare has become a prolific area for research in recent years, given that new sensor technology allows real-time monitoring of the patients' state. Smart healthcare provides healthcare services through smart gadgets (e.g., smartphones, smartwatches, wireless smart glucometer, etc.) and networks (e.g., body area and wireless local area network), offering different stakeholders (e.g., doctors, nurses, patient caretakers, family members, and patients) timely access to patient information and the ability to deploy the right procedures and solutions, which reduces medical errors and costs [44].

Biosensors are fundamental when monitoring health, and different applications can be identified in medical diagnoses [45], and antigen detection [46], among others. Inorganic flexible electronics have witnessed relevant results, including E-skin [47], epidermal electronics (see Figure 4) [48], and eye cameras [49]. Some common materials used to create these sensors are carbon-based or conductive organic polymers, which present poor linearity [50,51]. However, more reliable, and flexible sensors have been created at lower cost, better linearity, and shorter response time, such as piezoresistive sensors integrating nano-porous polymer substrates [52].

New sensor developments are creating relevant opportunities in the health industry. Current procedures for sensing proteins are commonly based on noisy wet-sensing methods. A more robust procedure is carried out by means of graphene sensors that avoid the drifting of electrical signals, resulting in more stable and reliable signals. These sensors also reduce detection times [53]. Nonetheless, when having these robust sensors connected to the human body, one critical challenge is their communication through the wireless sensor network, since the IEEE 802.15.4 standard can hardly be adapted to multi-user interfaces [54]. Still, some solutions have been proposed, such as replacing the ultra-wideband (UWB) with a gateway, so sensor nodes stop and switch to 'sleep mode' until new information transmission is needed again. This allows lowering the energy consumption and collisions and increase the speed and number of users [55].

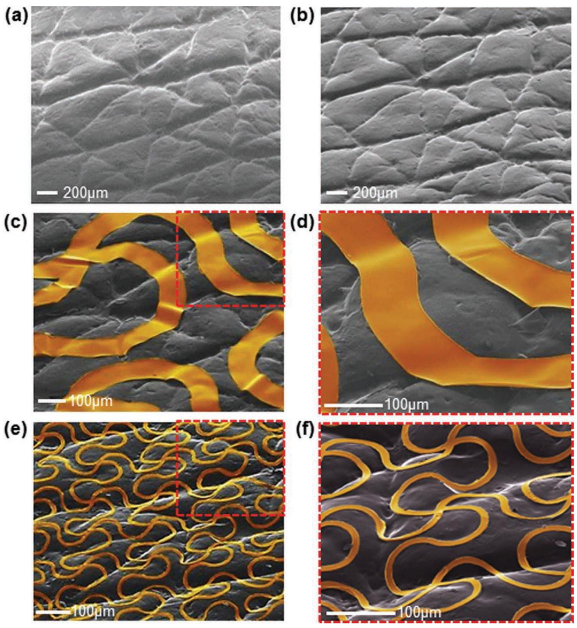

Figure 4. (**a**) Epidermal electronic system (EES) made of a skin replica created from the forearm, before and; (**b**) after application of a spray-on-bandage; (**c**) Colourized microscopy image of the EES with conductive gold films of 100 µm and; (**e**) its magnified view. (**d**) Microscopy image of EES with gold films of 10 µm and; (**f**) its magnified view [48].

3.3.2. Sensors for Mobility Applications

Three main systems of urban mobility: vehicles, pedestrians, and traffic, are considered in this section. Due to the increasing number of vehicles every year in urban settlements, traffic jams, pollution, and road accidents tend to increase as well [56]. These problems suggest that there is an emergent need for intelligent mobility solutions. One such solution is intelligent traffic control, oriented to avoid traffic jams and optimize traffic flow [18].

Due to repetitive starts and stops, fuel consumption and carbon emissions increase during traffic jams [18]. Therefore, providing solutions for traffic jams represents a direct positive impact in terms of urban mobility and air quality in cities. Moreover, heavy-duty vehicles (HDVs) and freight traffic release into the atmosphere large quantities of carbon emissions [57]. The automotive industry has put significant effort into developing more energy efficient powertrains (for example, hybrid electric vehicles). However, most HDVs are still fueled by diesel and providing optimal solutions to reduce the carbon emissions produced by these types of vehicles becomes a fundamental task [58].

Due to the COVID-19 pandemic, urban mobility underwent significant changes, such as a noticeable decrease in collective and individual transport, and with that a reduction in air pollution and carbon emissions [59]. This phenomenon has made governments and citizens consider future changes in post-lockdown mobility, to maintain cleaner environments in their cities. Applications in smart mobility include vehicle–vehicle (V2V), vehicle–infrastructure (V21), vehicle–pedestrian (V2P) [60], and vehicle–everything (V2X) connections (see Figure 5) [61].

Vehicles include several sensors needed for their proper operation, measuring several operational parameters of the vehicle, such as speed, energy consumption, atmospheric pressure, and ambient temperature [62,63]. Such parameters are used to optimize speed profiles to minimize vehicle energy consumption considering traffic condition and geographical information. To achieve this aim, a cloud architecture is implemented that retrieves information from vehicle sensors and external services. In [64], an eco-route planner is proposed to determine and communicate to the drivers of heavy-duty vehicles (HDVs) the eco-route that guarantees the minimum fuel consumption by respecting the travel time established by the freight companies. Additionally, in this case, a cloud computing system is proposed that determines the optimal eco-route and speed and gear profiles by integrating predictive traffic data, road topology, and weather conditions. Vehicle weight and speed regulation are also important to ensure road and passengers safety, helping in the avoidance of serious accidents [65]. Efforts in increasing pedestrian's safety are valuable contributions in improving urban mobility [66]. Regarding traffic, conventional traffic light systems are defined in a non-flexible structure, such that light transitions have defined delays and onsets [67]. Dynamic changes in traffic volume, congestions, accidents, and pedestrian confluence, should have been considered to provide an optimized traffic control [67].

Pedestrian´s movement and behavior in urban settings have been monitored mainly using cell phones, by monitoring call detail records (CDRs) [68], social media check-ins [37,69], MAC address reading [70], and smart cards detection in public transport [71]. Vehicle detection have been achieved by cement-based piezoelectric, induction loop sensors, measuring vehicle's weight-in-motion (WIM), and performing vehicle type classification [65], and ferromagnetic sensors buried in the asphalt for smart-parking solutions [72]. Vision-based sensors, such as infrared (IR) [67] and light detection and ranging (LiDAR) [73] have been used to detect the position of vehicles, pedestrians and buildings within a given proximity. Pedestrian–vehicle (P2V) oriented sensors also exist, such as the "smart car seat", a contact-free heart rate monitoring sensor oriented to ensure driver's well-being and safety [74]. Mobile phone apps have allowed P2V and V2P applications for collision prediction [66,75].

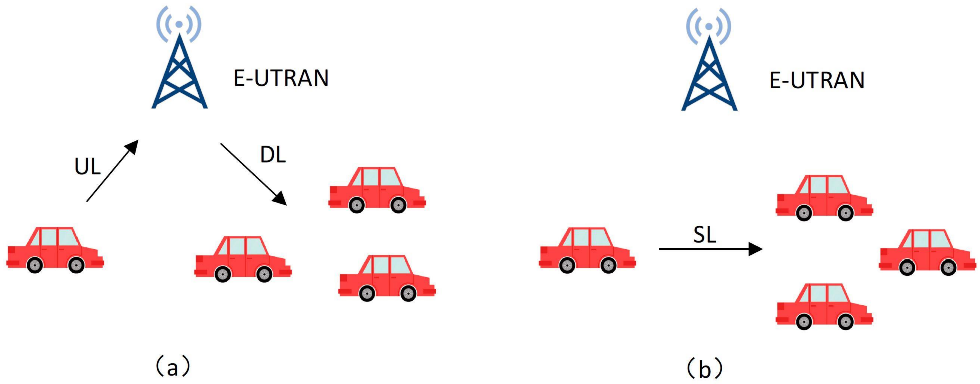

Figure 5. Two types of V2V connections: (**a**) from vehicles to vehicles with an intermediate transfer connection and; (**b**) directly from vehicles to other vehicles [61].

Recently, virtual sensors have been used to enhance innovative solutions especially in the electro-mobility sector. VSs have been introduced for operating in the sensor-cloud platform as an abstraction of the physical devices. In particular, a VS can logically reproduce one or more physical sensors, facilitating and increasing their functionalities, performing complex tasks that cannot be accomplished by physical sensors [76]. Differently from a real sensor, the VS is equipped with an intelligent component based on data processing algorithm to derive the required information elaborating the available input data from heterogeneous sources. Indeed, VS is typically used in services in which it is necessary to derive data and information that are not available or directly measurable from physical sensing instrumentation [77,78]. Although the use of such sensors has been explored in different domains or verticals of the smart city, the mobility sector is the one where they find large application. In the electric mobility domain, for instance, they are used to predict the personal mobility needs of the driver to estimate the duration and cost of the battery charging, to predict the energy demand of medium or long-range trips, etc. All these predictions are performed through ad-hoc algorithms able to process available input data from the electric vehicles, the users, and the charging stations [76–78].

3.3.3. Sensors for Security

The human and environmental security approaches are a very crucial ingredient to achieve sustainable development in smart cities. Security is referred to as a state of being free from danger or threat and for maintaining the stability of a system. Safety is a dynamic equilibrium, which consists in maintaining the parameters important for the existence of the system within the permissible limits of the norm. According to the United Nation's Human Security Handbook and Agenda 2030 Sustainable Development Goals (SDGs) [79] the types of insecurities endangering the sustainable development of humans and, hence, future cities are: food, cybernetic, health, environmental, personal, community, economic, and political, as the main core of a smart city.

Food security: The importance and technological challenges of the integration of urban food systems in smart city planning are discussed in [80]. High quality and sustainable production include smart hydroponics and gardening systems that gather information by sensors that measure pH, humidity, water and soil temperature, light intensity, and moisture [81]. Several methods are proposed to monitor the quality and safety of the food during production and distribution, including gas sensor array [82] for the analysis of chemical reaction occurred in spoiled food. Hybrid nanocomposites and biosensors have also been reported in food security context [83].

Cyber security: The main security challenges, including privacy preservation, securing a network, trustworthy data sharing practices, properly utilizing AI, and mitigating failures, as well as the new ways of digital investigation, are discussed in [11,40]. Design plane solutions are usually software-based and use diverse types of encryption techniques, including advanced encryption standard (AES) and elliptic curve cryptography (ECC) for crypto or level security and encryption, authentication, key management, and pattern analysis for the system-level security [84,85] (see Figure 6).

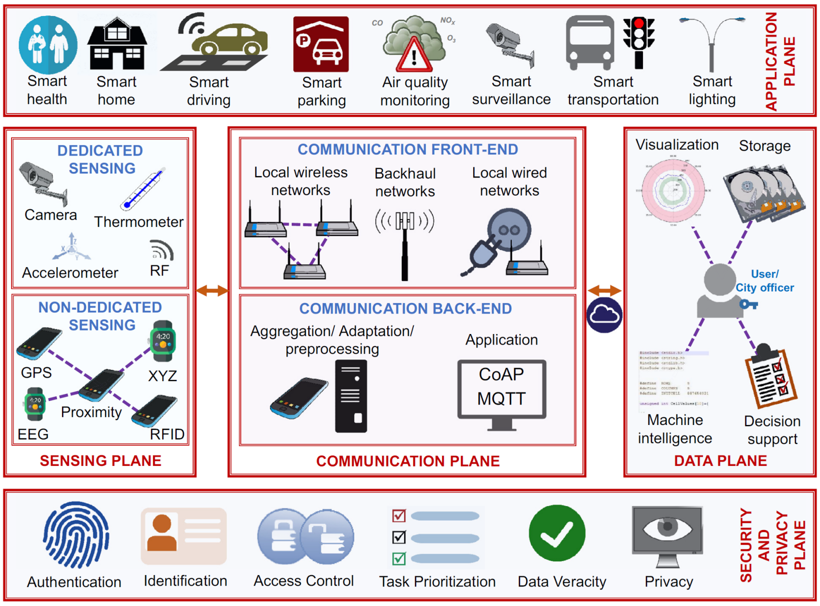

Figure 6. Smart city architecture defined in five planes: application (connects city and citizens), sensing (sensors measurements), communication (cloud services), data (processing and analysis) and security and privacy planes (assurance of security and privacy) [85].

Health security: In-body inserted devices are designed to communicate with health-centers and hospitals [55]. The privacy, security, and integrity of these sensors and the information on the health record concerning legal and moral issues are of great interest which is widely discussed in works such as [86,87].

Environmental security: In recent decades, the use of satellite remote sensing and in-orbit weather observation, disaster prediction systems have risen drastically. These tools are an integral sensing part of the future smart cities [88,89]. There is a wide range of sensors, including earthquake early detection systems which use vibration detection and monitoring soil moisture and density of the earth [90], radiation level detectors [91], tsunami inundation forecast methods assimilating ocean bottom pressure data [92]. These sensors are connected in a wireless network, offering a global prognosis of environmental threats. Continuous emission monitoring systems (CEMS) have helped develop market-based environmental policies to address air pollution [93]. CEMS are allowing better tracking of powerplant emissions in real time to inform decarbonization strategies for the grid [94]. Efforts to deploy cost-effective sensing capabilities so far have produced fragmented data, but new optimization and AI tools are being proposed to resolve this issue [95]. New smart sensing and visualization (e.g., satellite, LiDAR, etc.) capabilities are focusing on greenhouse gas emissions (GHG), for instance around the carbon capture potential of agriculture, forestry, and other land uses (e.g., natural climate solutions). Advanced monitoring, reporting, and verification (MRV) features will continue to play a major role in enhancing the transparency, environmental integrity, and credibility of subnational, national, and regional emissions trading systems (ETS) for the future integration of a global carbon market [96,97]. Regarding infrastructure and buildings, continuous monitoring to detect corrosion and minor damages to prevent a possible failure takes advantage of the integration of surveillance cameras, humidity, atmospheric, and stress sensors, among others [98]. A simple combination of vibration and tilt sensing devices provides one of the low-cost and high-efficiency techniques proposed for a wide range of structures [99].

Personal and community security: To detect anomalies, violence, and unauthorized actions, biometrics and surveillance cameras are widely used. Smart lighting systems are a useful and cost-effective tool that uses common sensors like light and motion detectors and can improve the security tasks [100]. Surveillance cameras, face-recognition systems, and global positioning systems (GPS), in combination with data handling systems, are increasingly common tools in the hand of law-enforcement agencies as smart public security strategy reported in [39]. Ref. [101] reviews the possible combination of different devices categorized in sensors, actuators, and network systems. The challenges presented by the growing use of such technologies and concerns for individual privacy is the topic of an emerging research area [102].

3.3.4. Sensors for Water Quality Monitoring

Water is an invaluable commodity and is necessary for any living being. Smart water management focuses mainly on making water distribution systems more efficient by applying sensors and telemetry for metering and communication [103,104]. It applies in three broad areas: fresh water, wastewater, and agriculture. Moreover, more holistic perspectives around shared resource systems, such as the water–energy–food nexus are also benefiting from new sensing capacities and smart management systems enabled by digital technologies to provide more sustainable, resource efficient use solutions [97]. The principal usefulness of smart water systems lies in controlling valves and pumps remotely [104] measuring quality [103], pressure, flow, and consumption [105].

Consumption monitoring includes metering and model applications to describe consumption patterns. Water loss management encompasses leakage detection and localization [105]. For water quality the focus is on measuring, analyzing, and maintaining a set of pre-established parameters. It is an integral real-time management involving stakeholders [106–108]. In the agriculture, the use of IoT devices is a common way to make irrigation more efficient and effortless [109–111]. Noise sensors and accelerometers are popular methods to detect leaks in water distribution infrastructure [105,106].

The use of electromagnetic and ultrasonic flow meters and sensors for measuring pressure are IoT technologies for water consumption rate analysis [103,108].

Sensors used to analyze the quality of the water are mainly applied for physical–chemical parameters such pH, temperature, electrical conductivity and dissolved oxygen [108,109], also oxidation-reduction potential and turbidity [112–114], and presence of toxic substances [115]. In some cases, novel probes, such as for residual chlorine [103] or nitrate and nitrite, were implemented (see Figure 7) [112]. Humidity sensors are applied to measure soil moisture and assist in managing the schedule programs of irrigation in agricultural lands [110,116,117].

Figure 7. Outer and inner view of an integrated IoT sensor for water quality monitoring applications. The sensor consists of a nitrite and nitrate analyzer based on a novel ion chromatography method, used for detection of toxic substances [112].

3.3.5. Sensors for Waste Monitoring

Smart waste management consists of resolving the inherent problems of collection and transportation, storage, segregation, and recycling of the waste produced. Use of smartbins, solutions for the Vehicle Routing Problem (VRP) and waste management practices have been reported [41,118]. The use of smartbins refers to the implementation of different kind of sensors in the bins used to collect waste, which provide quantitative and qualitative information about the bin content [119–121].

For the VRP, the proposals are algorithms for optimization of the routes, considering social, environmental, economic factors, peak hours, infrastructure, type and capacity of the collection vehicles and others, in an effort to save resources like money, time, fuel, and labor [121–123].

With this, researchers aim for an integrated, real-time management that involves the communities and all the stakeholders [124,125]. The principal use of sensors in smartbins is monitoring the volume, weight, and content of the bins. For monitoring the filling level of the container, the main approaches that have been used are ultra-sound (US) [43,119], and in some cases IR sensors [121,126]. A load cell is also used to detect the weight of the bin [124,127]. In the literature, various sensors are used to detect harmful gases [126], movements near the container [120], and metal sensors to separate metallic waste [128], and to measure humidity [126,128], as well as temperature [43,123]. The My Waste Bin IoT container presented in [43] is shown in Figure 8.

Figure 8. Front and back view of the My Waste Bin, an IoT smart waste container, enabling real-time GPS tracking and weight monitoring [43].

3.3.6. Sensors for Energy Efficiency

Energy is an essential resource for the operation of the many activities occurring in cities [14]; therefore, the efficient use of this resource is paramount to reduce costs and promote environmental and economic sustainability [129].

The main sinks of energy consumption in urban communities are those associated with industrial and transport activities, buildings operations, and public lighting. In this section, we focus on the sensors used to monitor the usage of energy ground transport in buildings and public lighting. Since sensors for industrial activities were covered in previous sections.

Ground transportation represents the main sink of energy consumption (∼45%) and the major source of air pollutants in urban centers [130]. Car manufacturers report the specific fuel consumption (SFC measured as L/km) of their vehicles using laboratory test protocols. However, they do not report these data for heavy-duty vehicles. Furthermore, the real vehicles' energy consumption is affected by human (driving), external (traffic, road, and weather conditions), and technological factors. For gasoline and diesel-fueled vehicles, the common strategies to measure real-world fuel consumption on a representative sample of vehicles are: (i) measuring the fuel's weight before and after a specific distance being driven (gravimetric method), and (ii) measuring instantaneous fuel consumption through the on-board diagnostic system (OBD method). This second alternative uses optical sensors to measure the engine RPM, pressure sensors to measure the inlet air flow. The engine computer unit (ECU) uses these measured data to determine the engine fuel injection time. In addition, a global position system (GPS) determines the vehicle's speed. Using all this information, the ECU reports via OBD the vehicle's instant fuel consumption. Currently, there are commercially available readers that read the OBD data and send the collected information to the cloud. Using these technologies, telematics companies monitor thousands of vehicles in operation [131–133]. Similar systems are available for electric vehicles. We recommend this OBD-based alternative to measure the real energy consumption in ground vehicles.

Buildings represent 40% of total energy consumption [134] and 30% of greenhouse gas (GHG) emissions [129,134]. The main physical and non-physical factors involved in indoor environment quality are shown in Figure 9 [134]. These factors are measured using wireless sensors [135,136], virtual sensors [137], and artificial neural networks [16]. Energy consumption in buildings is associated mainly with (i) thermal comfort (operation of heating, ventilation, and air conditioning-HVAC systems); (ii) indoor lighting; (iii) various electrical loads (operation of electric equipment); (iv) thermal loads (use of fuels for heating and cooking), and (v) indoor air quality (pollutant concentration, odor, and noise) [138,139]. Table 2 shows the variables used to grade these five aspects and the sensors frequently used to measure these variables. However, additional variables influence energy consumption, such as the occupation level [140], and the building's structural design [141], and outdoor conditions (temperature, humidity, pressure, and solar radiation). Therefore, additional sensors are used to measure them. Some research works have focused on designing intelligent building management systems (BMS) that use, in real-time, data from the sensors listed above and take actions oriented toward the reduction in energy consumption, such as turn lights off, closing doors and windows, etc. [142].

Public lighting systems represent almost 20% of world electricity consumption, and it is responsible for 6% of GHG [143]. Therefore, it is essential to centralize street lighting control and smart management to reduce energy consumption, maintain maximum visual comfort and occupant requirements [139]. The variable most used in lighting systems is the lighting power density (LPD) [138]. Neural networks, wireless sensors, algorithms, and statistical methods are used to estimate the energy consumption and the corresponding costs [129,135,136]. Environmental factors, pedestrians' flow, weather conditions, and brightness levels influence light intensity [129,144]. The urban space adopts the most advanced Information and ICTs to support value-added services to manage public affairs, connecting the city and its citizens while respecting their privacy [20,145].

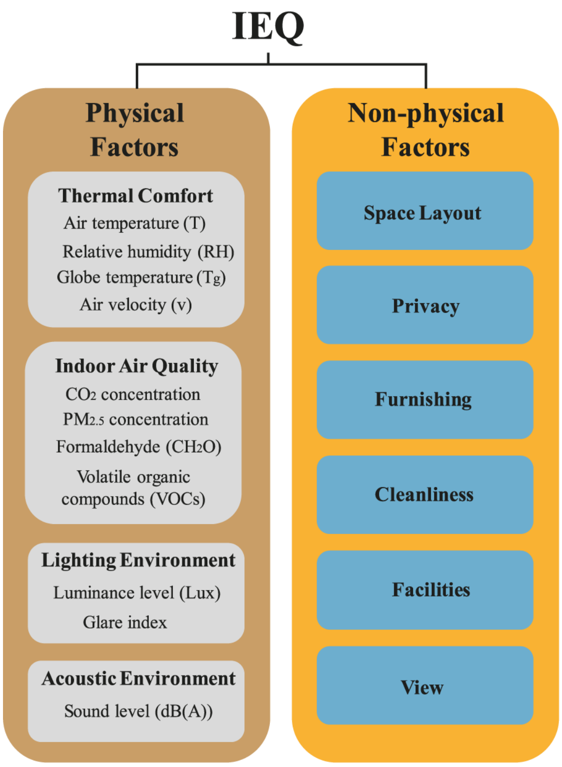

Figure 9. Physical and non-physical factors in IEQ studies [134].

Most of the time, the monitoring of the variables influencing energy consumption in buildings and public lighting is carried out wirelessly [18,129]. Various intelligent sensors [135], such as artificial vision, are used to measure temperature, relative humidity [17], electric current, gas flow, air quality [139], lighting, luminosity [129], solar radiation [139], and acoustic emission [146]. Measurement devices include light-dependent resistor (LDR) [139], IR radiation [140,147], semiconductors, magnets, and optic fiber. Intelligent sensors based on IoT are key to real-time monitoring of the many variables involved in energy management; these sensors can be adapted to microcontrollers and virtual sensors [129,137]. The main problem with wireless sensors is their battery life; therefore, alternative energy sources (thermal, solar, wind, mechanical, etc.) is vital, although these energies are usually available in minimal quantities [18].

Table 2. Sources of energy consumption in cities.

Sources of	Energy Consumption	Variable	Sensor	Application
Air Conditioning	Heat/Cooling	Temperature/Humidity	Thermohydrometer	Temperature and relative humidity
Indoor Air Quality	Air pollution/Concentration	CO_2/CO	NDIR (Non-Dispersive Infrared)	CO_2/CO Concentrations
		NO_2/NO		NO_2/NO Concentrations
		Air renovations	VQT airflow	HVAC system/equipment, building automation, vents
Lighting	Indoor/Outdoor	Presence	Passive Infrared (PIR)	Count/Occupation/Movement of people and vehicles/Temperature/Security
		Light	Light Depending Resistor (LDR)	Color/Resistance/Security alarms, Lighting On/Off
		Brightness Illumination	Phototransistor Photodiode	Home networks, Wi-Fi LED luminaires/Indoor lighting apps/Proximity Light level

3.4. Communication Technologies

Some of the most common communication technologies involve 3G, 4G LTE, and 5G Wi-Fi network connections [109,114]. In general, communication infrastructures can be classified as local area networks (LAN), wide area networks (WAN), and global area networks (GAN) [116]. LAN sensors can communicate with gateways through different protocols, such as: long range (LoRa) [107], Bluetooth [126], and low power radio [41]. Furthermore, new technologies have arisen in recent years, such as ZigBee [110] and narrowband internet of things (NB-IoT) [72]. On the other hand, gateways in WAN connections send the information to the cloud through SigFox, long range wide area network (LoRaWAN) [112], while GAN encompasses more complex technologies and all the cellular networks GSM-GPRS [121,148]. Other protocols include IP and API, TCP, Dash7 and MQTT [17], along with standards such as IEEE802.15.4, IEEE802.11.x, and IEEE1451 [135].

However, as the number of network nodes increase, interference problems can take place, particularly in very dynamic environments, such as health and mobility [149]. For instance, inter-body network problems depend on the number of sensors per network, as well as the body networks in a location, traffic, physical mobility of each body, and the location of nodes on the body [150]. In order to attenuate this problem, active and passive schemes have been proposed, which allow a high throughput and packet delivery ratio, as along with both a low average end-to-end delay and low average energy consumption for a single and multi-WBSNs [151,152]. Similarly, sharing data through connected vehicles can occur through incorporated or third-party systems [62], but accuracy and availability widely depend on the interface used [153]. As the number of users increases, the safety, access, and efficiency can be affected. Here, the vehicle itself is considered an integrated sensor platform [154], since it can work as a data sender, receiver, and router within the V2V or V2I communications used in ITS [19].

3.5. Applications

In the health section, sensors can be used in different multidisciplinary areas, for example: smart toilets, applications that monitor and direct physical exercise with the final objective of rehabilitation or prevention of injuries, and applications in health institutions [155,156]. For cycling sports, sensors are used most frequently in long-distance running and swimming [157]. There are different methods used to monitor the condition of patients, for example: monitoring the electrical activity of the heart using an array of electrodes placed in a sterile way on the body [158], monitoring of vital signs via wireless [159] for the tracking of the patient's location by issuing alerts if necessary, implementation of user-friendly interfaces to share information, based on wireless ECG sensors and pulse oximeters [159], implementation of a network-based multi-channel frequency EM for rehabilitation patients with exercises [160], design of a system with three sensors to monitor the ECG, body weight, and pulse of the patient [161], portable home health monitoring system using ECG, fall detection, and GPS to monitor people outside [162], e-health monitoring system based on the fusion of multisensory data to predict activities and promote the decision-making process about the health of the person [163]; all of these home health systems allow to monitor patient's activity in their homes.

In the mobility section, the most common ITS applications in reducing road traffic are related to accident detection [164,165] and prevention [40], identifying road traffic events [166] and studying the driving behavior and applying real-time feedback [167,168]. Interesting applications in urban mobility have been proposed as well, such as smart traffic lights [67], smart parking [72], collision prediction and avoidance [66], vehicle WIM detection [65], and mobility visualization through heatmap representations [169]. Heatmaps can also be obtained from analyzing mobility data from vehicles and pedestrians and reflect the behavior of different phenomena, such as average speed in the city [170], traffic jams location, frequency, and duration [171], and combined spatio-temporal traffic clustering and analysis [169].

For the water section, by analyzing parameters like soil humidity and nutrients, the design of efficient irrigation programs, including remote control or automatic irrigation systems, can be done, reducing water and energy consumption [42,127,172]. For example, a system that allows real-time monitoring of surface water quality in different aquatic environments [43], systems for monitoring the quality of the river that crosses a city [173], and the implementation of a system that could be used in pipelines networks to monitor the quality of water [122]. Distribution systems need to be regulated to ensure the required quantity and quality. The use of sensors to collect data in real-time can detect and locate leaks, which can affect the correct supply of water to a city or deteriorate the infrastructure around the leak [14]. The water distribution systems need to be monitored to ensure that correct water quality is distributed and for detecting pollutants [174].

In the waste section, the IoT system permits an onboard surveillance system, which raises the process of problem reporting and evidence good waste collection practices in real-time [135]. The use of mobile apps and software permit that truck drivers receive alerts from the smart bins that need attention, and also to get the optimal route to collect the garbage, reducing the effort and cost of waste collection [136–138]. With the collection of information about the filling level of the containers, it is possible to determine the best types and sizes of containers, areas that require greater or special collection capacity, and the timing of the collection [134–136,138]. The sensors can improve the automation in identifying and separating waste, allowing an increase in the processing speed for reuse and recycling to convert a smart city to a city with zero-waste [20,137]. All data collected from the bins and the analytics, in conjunction with the use of a GPS to know the coordinate position of bins, dumps, and fleet, can be used to manage in novel ways the collection and segregation of waste [17,129,136,138,141].

Finally, countries are looking to implement innovative technologies focused on minimizing energy consumption and improving their citizens' environment and welfare. For this reason, there are various applications in the areas of buildings, public lighting, and urban space such as counting, movement, and location of people and vehicles, security actions for citizens, fire detection in building enclosures [140], smart homes [135,147,175] and home networks [135,136], Light Emitted Diode-wireless (LED) indoor and outdoor lighting fixtures [18], geothermal technology [137], hygrothermal comfort [17], cybernetic cities, ubiquitous connectivity [176], HPCense (seismic activity), smart thermostat [18], indoor lighting apps [129], microgrids [139], structural health monitoring of buildings [18], ecological buildings [134], among others.

3.6. Study Cases

This section describes experimental results of study cases implemented by the research groups of the co-authors of this review, developed in Tecnologico de Monterrey, under the Campus City initiative. Figure 10 shows a visual representation of the study cases discussed in this section.

Health. In this study, by using EEG electrodes and Bluetooth, brain signals from students were recorded to assess learning outcomes under different modalities [177]. The aim of the work was to propose EEG sensing as a support in education by inferring the state of the brain. The results showed that machine learning models based on the EEG recordings were able to predict with 85% accuracy, the cognitive performance of the students, and it could also be used to identify unwanted conditions, such as mental fatigue, anxiety, and stress under different contexts in the healthcare sector.

Security. PiBOT is a multifunctional robot developed to monitor spaces and implement regulations in the context of the COVID-19 pandemic [178]. Such robot integrates video and thermal cameras, LiDAR, ultrasonic, and IR sensors to allow object and people detection, facemask recognition, temperature maps, and distance between persons estimation. It also integrates automated navigation algorithms, teleoperation control modes and cloud connection (IoT) protocols for data transmission. The robot is also able to generate and send real-time data to a web server about people count, facemask misuse, and safe distance violations.

Mobility. The following study presents the results from the analysis of accessibility to different services (health and education) in the urban environment of the city of Monterrey, Mexico [179]. The software tools used in this study enabled to obtain quantitative representations of the accessibility of the city when using different transport modes (walking and cycling). The results from this work showed low accessibility to medical services, but acceptable accessibility to educational services in the city. The study found that the use of bicycles and other micro mobility vehicles can enhance the accessibility to services in the city.

Water. A recent study from one of the co-authors studies the presence of SARS-CoV-2 RNA in different freshwater environments (groundwater and surface water from rivers and dams) in urban settings [180] from the city of Monterrey, Mexico. The detection and quantification of the viral loads in such environments were determined by RT-qPCR in samples acquired from October 2020 to January 2021. The results of the study demonstrated the feasibility of the presence of SARS-CoV-2 in freshwater environments. It also found that viral loads variations in groundwater and surface water over time at the submetropolitan level reflected the reported trends in COVID-19 cases in the city of Monterrey.

Waste. A recent collaboration between Tecnologico de Monterrey and industrial partners from Smart City Colombia [181] and SmarTech [182] has started for the development of smart solutions for cities. This collaboration proposes the use of a smart recycling implementations using an urban mechanism for intelligent disposal (MUDI). The MUDI is a GPS monitored vehicle that establishes optimal routes for collection of recycled material, while informing both the recycler and the citizen through an app about the final disposal of said materials.

Energy. Using engine sensors, information about the fuel consumption associated to the operation of the A/C in light-duty vehicles was monitored via OBD for a five-month period [131]. Results showed that specific fuel consumption due to A/C usage is higher at lower speeds of the vehicle and it is lower at higher driving speeds; and shows the potential of proposing solutions towards vehicle energy efficiency by analyzing information coming from engine sensors through the OBD port.

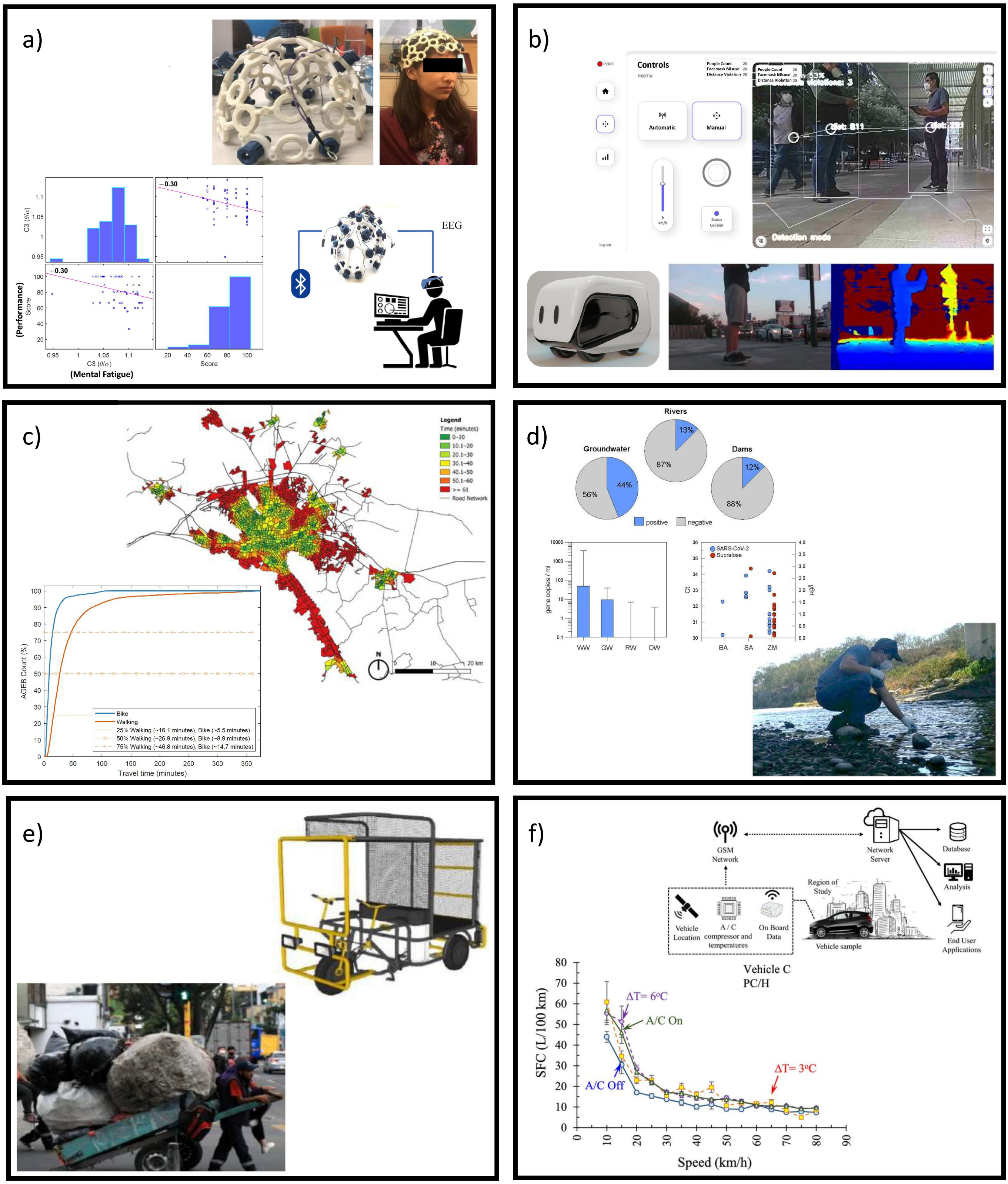

Figure 10. Study cases of smart cities implementations in Tecnologico de Monterrey, (**a**) Health: EEG monitoring for educational services; (**b**) Security: Space monitoring in the context of COVID-19 pandemic; (**c**) Mobility: Urban accessibility analysis in Monterrey City; (**d**) Water: Detection of SARS-CoV-2 RNA in freshwater environments from Monterrey City; (**e**) Waste: GPS monitoring and app for recycling vehicles; (**f**) Energy: Impact of A/C usage on light-duty vehicle's fuel consumption.

4. Challenges and Opportunities

Advances in the use and implementation of sensors and their application for the development of smart cities will allow residents to access a better quality of life. Even though the use of wireless sensor networks provides valuable data that are used for a better management of resources, there are still areas of opportunity for improvement. Although different areas within the smart city face specific challenges, a common opportunity is the development of new sensors and new approaches to the problem of detection, prevention, or anticipation of the dangers which future smart cities can face.

A major challenge in health applications is privacy and the secure transmission of data, a concern for which different studies have been conducted. One example is a decentralized mobile-health system that leverages patients' verifiable attributes in order to run an authentication process and preserve the attribute and identity [183]. Another study designs two schemes that focus on the privacy of medical records. These schemes ensure that highly similar plaintexts can be transformed into distinctly different ciphertexts and resist ciphertext-only attacks. Nevertheless, important performance metrics, such as computation overhead, network connectivity, delay and power consumption, are ignored [184]. Low-cost wireless sensor networks also help to achieve a direct communication between a user's mobile terminals and wearable medical devices while enforcing privacy-preserving strategies [149]. In addition, a study presented a big health application system based on big data and the health internet of things (IoT). This study also proposed the cloud to end fusion big health application system architecture [185]. One last study modifies the design of sensor networks in a way that each one can manipulate four symbols (quaternary) instead of two (binary), resulting in more efficient systems [186].

With respect to mobility, ITS are used in smart cities, having a positive impact on saving resources, such as time and workforce, while reducing the use of fuels and emissions into the atmosphere. ITS image-based mobility applications are simple and inexpensive, but face decreased efficiency during lightning and weather changes [18]. Another challenge is faced by flexible traffic control, as well as collision avoidance systems as high speed detections and data exchange are needed for successful V2V, V2P, V2I, and V2X protocols [18,38,66]. This information exchange process is susceptible to security threats, such as malicious attacks or data leaks [61]. To address these challenges, more reliable sensors and faster data transfer protocols need to be implemented.

In smart security, there is a big effort on detection, prevention, or anticipation of the dangers that citizens and infrastructure of the smart cities can face. Sensors for security present a tendency to improve the sensibility, resolution, and precision of the current sensors. Almost all services in a smart city use digital data and are completely dependent on the security and integrity of that data. Due to this reason, sensors must be hardened with effective security solutions such as cryptography and advanced self-protection techniques.

Regarding smart water monitoring, sensors are used to measure water quantity and quality data continuously and consistently. The obtained data can be processed and visualized in real-time to the end-users, or forecasts can be developed for the water agencies. These technologies allow minimization of the risks associated to poor water quality and deficiencies in water supply. Future sensors need to be improved in cost and energy consumption to withstand long periods of measurements without intervention, in addition to an enhanced robustness, to resist adverse environmental conditions.

Solid waste management is crucial in any town or city, but take a new role in the smart city scheme, and it is focused on a more clean, tidy, and healthy environment for living, using sensors and IoT technologies to improve waste management [42,43]. Currently there are only sensors that can identify wet, dry, or metal garbage; however, it would be optimal to develop sensors that allow identifying waste in greater detail. For this reason, new sensors oriented to waste segregation need to be developed and implemented. Segregation is a key component in the waste management system, as it allows much of what is discarded to be recycled or reused, resulting in a reduction in the amount of garbage that reaches landfills [128,172].

Innovations in energy consumption monitoring in buildings, public lighting systems, and urban spaces using ICTs are an excellent option due to their adaptability. The literature proposes the implementation of virtual sensors by building information modeling (BIM), integrated with IoT devices including qualification tools to develop ecological buildings [134,187]. Intelligent lighting systems with sensors adaptable to weather conditions, hours of use and presence of people or vehicles [20] where the street lamps serve as Wi-Fi connection points, allowing interconnected networks over the entire urban area monitoring the quality of the environment, noise levels, and surveillance, among others. Battery or energy consumption, high volume of data storage and security, life span and replacement, size, cost, installation, and maintenance are the main deficiencies when designing a WSN. Studies have proposed the implementations of energy efficiency surveillance using multimodal sensors [188] and low power hardware systems [189]. The implementation of low-cost sensors and using energy harvesting are the most attractive technologies for buildings' sensors in the future. Artificial intelligence, big data, and machine learning [190,191] become essential due to the vast amount of data gathered and analyzed in the presented applications.

5. Conclusions

Following the reported trends of population growth and mobility to urban environments, it is clear that in the years to come, cities will face a constantly increasing need to satisfy the demands of their citizens [1]. Diverse strategies have been implemented in cities from all continents to move towards *smartness* as a means to enhance management of their resources, offer more efficient and trustable services, improve the liveability of the city, and promote government, academia, and citizens' engagement.

Geographically speaking, continents such as Europe and Asia have the highest amount of reported smart city implementations, followed by America, Oceania, and Africa. High-income countries such as United States and China presented a high number of smart city deployments at different cites. Although other continents and cities present fewer smart cities, it is only a matter of time for more to arise, as they follow the steps of their predecessors [28]. Several applications of sensors for smart cities were identified and described within this work. To summarize, most of the applications involved the sensing and sharing of data to offer on-demand services (medical records and check-ups, urban transportation, water, and energy consumption), while others are oriented to improve the liveability of the city (citizens' security, green spaces management, water quality, waste collection, public lighting). Among the main challenges of smart city implementations, each sector has its own; however, common factors such as the improvement of sensors, massive data analytics implementations (big data), and citizens' distrust in data sharing can be identified.

Although in future smart cities, the security of the society and community is to be ensured by digitalization and inter-institutional cooperation, human security, generally speaking, is guaranteed by the individual's behavior. It should not be forgotten that safety cannot be forced; it can only be educated, and there is a need to form an internal motive for safe and ethical behavior by creating and fostering a culture of safety in such a new digital environment. Finally, it is also important to consider that in order to implement the proposed smart city solutions, collaboration, and partnership with government agencies is imperative [3]. Deep understanding of each context of implementation and key interconnections between sectors (e.g., transport–energy, energy–water–food, resource efficiency and recovery, etc.), along with meaningful community engagement and involvement in the planning and use of new technologies in the urban infrastructure is essential to enhance political feasibility, transparency, equity, and financial sustainability.

As societies around the world begin to better understand how technological progress can improve quality of life and foster clean economic development, smarter communities will be driving the future of cities towards a more liveable, inclusive, net-zero carbon and sustainable future by mid-century [192].

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