frontiers | Frontiers in Climate

TYPE Review
PUBLISHED 19 February 2025
DOI 10.3389/fclim.2025.1436616

Check for updates

OPEN ACCESS

EDITED BY
Rasa Zalakeviciute,
University of the Americas, Ecuador

REVIEWED BY
Alix Post,
Geoscience Australia, Australia
Oscar Chimborazo,
Howard University, United States
Nancy Betancourt-Mendoza,
Universidad de las Fuerzas Armadas—ESPE, Ecuador

*CORRESPONDENCE
Freddy Escobar-Teran
✉ fescobarteran@hotmail.com

RECEIVED 22 May 2024
ACCEPTED 28 January 2025
PUBLISHED 19 February 2025

CITATION
Escobar-Teran F, Zapata J, Briones F, Rosero M and Portilla J (2025) Use of ICTs to confront climate change: analysis and perspectives.
Front. Clim. 7:1436616.
doi: 10.3389/fclim.2025.1436616

Use of ICTs to confront climate change: analysis and perspectives

Freddy Escobar-Teran*, Jose Zapata, Felipe Briones, Marcelo Rosero and Jorge Portilla

Departamento de Ciencias Exactas, Universidad de las Fuerzas Armadas ESPE, Sangolqui, Ecuador

The effects of climate change, including temperature and precipitation changes, the retreat of ice sheets, and rising sea levels are more evident today. It emphasizes that greenhouse gases are the primary drivers of these changes. In this context, some international organizations such as the United Nations (UN) and others have been making significant efforts to combat these effects and have considered information and communication technologies (ICTs) as an alternative for monitoring and mitigating climate change. However, the role of ICTs in climate change has not been analyzed in detail. Accordingly, this article presents research progress on the role of ICTs in climate change monitoring and evidence that ICTs are effective tools for reducing greenhouse gas emissions from different sectors. Additionally, this article provides a cost-benefit analysis of ICT applications in various sectors, emphasizing the Sustainable Development Goals (SDGs).

KEYWORDS

climate change, GHG emissions reduction, information and communication technologies (ICTs), Internet of Things (IoT), Sustainable Development Goals (SDGs)

1 Introduction

Climate change is one of contemporary society's most complex and pressing global environmental challenges (Nordhaus, 2019; Pörtner et al., 2022). It is characterized by changes in climate patterns, such as long-term trends in temperature and precipitation, the shrinking of global ice caps, and rising sea levels, among other phenomena (Abbass et al., 2022; FitzGerald and Hughes, 2019; Kamal, 2022; Okezie, 2021). Greenhouse gases (GHGs) are identified as the main drivers of this climate crisis, effectively trapping heat within the atmosphere and propelling global warming. Since the 1970s, GHG emissions have increased by over 70%, which has led to noticeable changes in global weather patterns, highlighting the severity of the issue (Lipczynska-Kochany, 2018; Murshed and Dao, 2022; Swain et al., 2021; VijayaVenkataRaman et al., 2012). As a result, it is expected that the worldwide impacts of climate change, coupled with contributing factors such as increased deforestation, will enhance the likelihood of floods, droughts, and erosion. This is due to significant disturbances in atmospheric and oceanic conditions, affecting natural ecosystems and human habitats (Islam and Winkel, 2017).

The main sources of GHG emissions are natural systems and human activities. Natural systems contributing to GHG emissions include phenomena like wetlands, forest fires, earthquakes, and volcanoes (Toulkeridis et al., 2017; Toulkeridis et al., 2019; Toulkeridis and Zach, 2017; Yue and Gao, 2018), while human activities predominantly involve land use changes, and deforestation (Barreto-Álvarez et al., 2020; Cayambe et al., 2023; Heredia-R et al., 2021a; Heredia-R et al., 2022). Furthermore, burning fossil fuels is one of the main causes of GHG emissions. This background sets the stage for examining how Information and Communication Technologies (ICTs) can play a crucial role in monitoring and mitigating climate change's adverse effects, providing a framework for the subsequent discussion.

Several global agreements have supported efforts to monitor GHG emissions over time. The first significant global pact was the Montreal Protocol, signed in 1987, which aimed to protect the ozone layer by curbing substances that lead to its depletion (Chipperfield et al., 2015; Egorova et al., 2013; Goyal et al., 2019; Morgenstern et al., 2008; Velders et al., 2007). The protocol targeted chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which are major contributors to ozone layer depletion (Ibárcena and Scheelje, 2003). The subsequent Kyoto Protocol, adopted in 1997 and enacted in 2005, focused specifically on reducing emissions of five greenhouse gases, including methane (CH_4) and carbon dioxide (CO_2), nitrous oxide (N_2O), and fluorinated gases such as hydrofluorocarbons (HFCs) and sulfur hexafluoride (SF_6) to mitigate climate change (Gerden, 2018; Hussain et al., 2019; Leggett, 2020; Murshed, 2022; Murshed et al., 2020; Sovacool et al., 2021; United Nations Framework Convention on Climate Change, 2009). Most recently, the Paris Agreement, signed in 2015 and ratified by 185 countries to date, aims to maintain global temperature rise this century well below 2 degrees Celsius (Hoegh-Guldberg et al., 2018).

A report published by the United Nations Environment Programme (UNEP) in 2018 highlighted that total global greenhouse gas emissions had reached 55.3 gigatons of equivalent CO_2 (Maertens, 2018) of which 37.5 gigatons were due to CO_2 emissions from fossil fuel combustion and industrial processes. This marked a 2% rise in emissions in 2018 alone, compared to the annual growth rate of 1.5% observed from 2010 to 2018. The increase in emissions was primarily due to higher energy demands. Emissions from land use changes were reported at 3.5 $GtCO_2$ for the same year. Combined, emissions from fossil fuels and land use changes constituted about 74% of all global greenhouse gas emissions in 2018 (United Nations Environment Programme, 2020). Methane emissions increased by 1.7% in 2018, up from the decade's annual growth rate of 1.3%. Nitrous oxide emissions from agriculture and industry grew by 0.8% in 2018, slightly lower than the decade's annual growth rate of 1%. Furthermore, emissions of fluorinated gases saw a significant spike of 6.1% in 2018, compared to a decade-average increase of 4.6% (United Nations Environment Programme, 2020). Global warming is already impacting, necessitating immediate and significant efforts in adaptation, particularly in poorer countries which feel the brunt of the effects more severely due to their lesser capacity to adapt. The socio-economic and environmental context and availability of information and technology significantly influence these countries' ability to respond effectively to climate change (Waisman et al., 2019).

Due to industrialization, climatic variations have been evident which has severe implications for biodiversity (Bellard et al., 2012; Mantyka-pringle et al., 2012; Pawson et al., 2013). A current report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) mentions that the extinction of one million species is threatened in the coming years if important changes are not implemented in land use, environmental protection, and climate change mitigation. This detailed analysis reveals alarming statistics: about 85% of wetlands have already been lost; since the late 19th century, nearly half of all coral reefs have been eradicated; 90% of all livestock breeds have disappeared; between 1980 and 2000, deforestation affected 100 million hectares of tropical forest, with an additional 32 million hectares lost between 2010 and 2015; 23% of the planet's land is now considered ecologically degraded and unusable; the decline of pollinators puts food production worth between $235 billion and $577 billion at risk annually; and the destruction of coastal environments such as mangrove forests endangers the lives of up to 300 million people (Lehikoinen et al., 2019; Oliver and Morecroft, 2014; Thom et al., 2017; Watson et al., 2019).

Technological advancements have significantly increased the use of information and communication technologies (ICTs), accounting for approximately 2–2.5% of global GHG emissions. The hundreds of millions of computers and over a billion televisions that are never turned off at night in homes and offices contribute 40% of the total GHG produced by ICT. In contrast, servers and refrigeration systems contribute 23%, fixed communication lines generate 15%, mobile communications 9%, local area networks, and telecommunications sites 7%, and, lastly, printers 6% (see Figure 1) (Uddin et al., 2017). Despite this, the contribution of ICTs to the gross domestic product (GDP) is much larger than their environmental impact. For instance, in the United States, the ICT sector represents about 8% of the GDP, highlighting that its primary output is information rather than physical goods (Kelly and Adolph, 2008).

The impact of climate change is evident across different sectors including agriculture, health, and infrastructure, necessitating the development of strategies to mitigate these negative effects (Camilloni, 2018; Canaza-Choque, 2019; Hasegawa et al., 2018; Malhi et al., 2020; van Vuuren et al., 2018). For example, droughts and floods can severely impact food production, human health, and infrastructure, while climate change can spread diseases and damage ecosystems. The potential health impacts are profound, including increased mortality, compromised food security, and reduced worker productivity (Carter et al., 2012).

Furthermore, the devastating effects of climate change are prompting cities to develop strategies to lessen these impacts (Clayton, 2020; Leichenko and Silva, 2014; Maldonado et al., 2013). As urban populations grow, so does energy demand, presenting new challenges that add a layer of complexity to sustainability efforts. This dynamic underlines the importance of managing and digitizing data to control natural resources from the individual level to the entire city (Balogun et al., 2020).

The data generated electronically through devices and the transmission, processing, and interpretation of this information constitute the backbone of ICT. The Internet of Things (IoT) facilitates the interconnection of devices and sensors, enhancing the interoperability of systems like big data, cloud computing, edge computing, the semantic web, and data storage. These technologies enable applications in smart healthcare, smart transportation, smart cities, and smart agriculture, among others utilizing databases for real-time monitoring of natural phenomena, employing clean technologies, and disseminating information are all part of this digital innovation (Munang et al., 2013). In this context, ICTs indirectly contribute to controlling greenhouse gases, monitoring environmental changes, managing food resources, preventing deforestation, enhancing energy efficiency, and improving waste management (Lee and Mwebaza, 2022). Global communication networks facilitate timely decision-making for preventing, correcting, and supporting emergency measures before, during, and after environmental crises (Delina, 2020). Moreover, we are in the era of a digital revolution, where big data and data analytics play a pivotal role. The digitization of environmental sciences via ICT products offers a modern framework to tackle the challenges and opportunities associated with climate

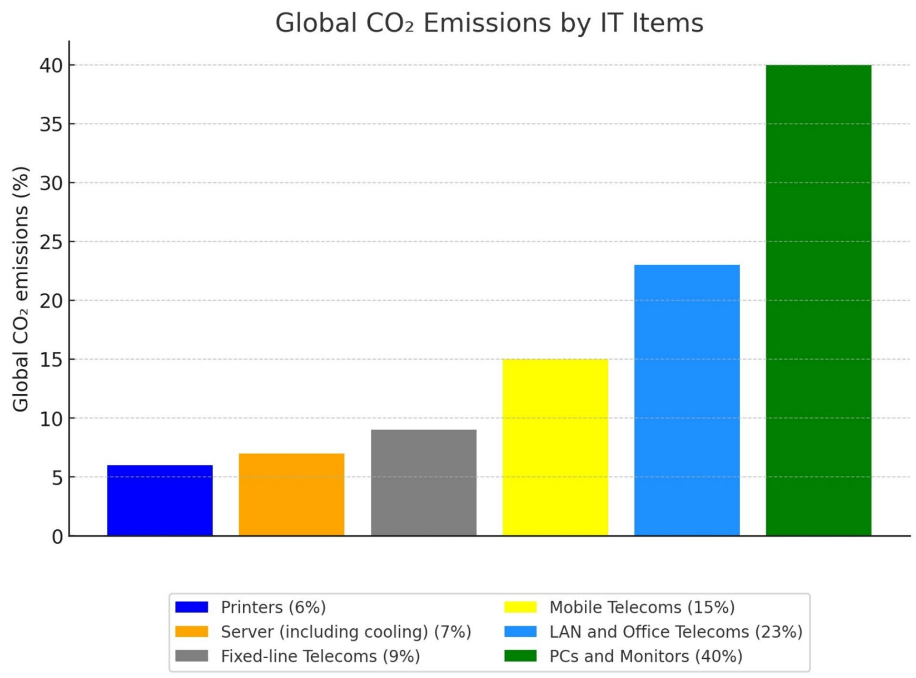

FIGURE 1
Global CO_2 emissions from ICT (Uddin et al., 2017).

change (Ballantyne et al., 2016; Gangopadhyay et al., 2019; Koliouska and Andreopoulou, 2020).

ICTs also play a crucial role in monitoring and predicting climate change, as well as aiding adaptation efforts (Ajwang and Nambiro, 2022). A significant contribution of ICTs in meteorology and the prediction and detection of natural disasters comes through advanced observation systems like those operated by the World Meteorological Organization (WMO), which tracks atmospheric and weather changes (World Meteorological Organization, 2009, 2010, 2019). Over the years, the push for technological tools to mitigate the adverse impacts of climate change has grown, with entities such as the International Telecommunication Union (ITU) utilizing ICTs for monitoring climate change, and in forecasting, detecting, and mitigating the effects of typhoons, earthquakes, tsunamis, and other man-made disasters (Kelly and Adolph, 2008).

The role of ICT in climate and weather monitoring is exemplified by the structure of the World Meteorological Organization's (WMO) World Weather Watch (WWW) program. This program consists of three integral layers utilizing various ICT components and applications: (Zemp et al., 2021).

- The Global Observing System (GOS) captures observations of the Earth's atmosphere and surface, including ocean surfaces, from locations worldwide and outer space. The GOS serves primarily as a hub for relaying data from remote sensing devices mounted on satellites, aircraft, radiosondes, and weather radars, both on land and at sea (see Figure 2) (Moltmann et al., 2019; World Meteorological Organization, 2010; Tanhua et al., 2019). In fact, GOS plays a crucial role in supporting informed decision-making across multiple sectors by providing comprehensive, accurate, real-time data on Earth systems. It combines observations of land, ocean, atmosphere and space to provide useful information for environmental monitoring, disaster response and sustainable development (Zemp et al., 2021).
- The Global Telecommunication System (GTS) integrates radio and telecommunications equipment to facilitate real-time data exchanges of vast volumes of meteorological data and related information among national and international meteorological and hydrological centers (World Meteorological Organization, 2009).
- The Global Data Processing System (GDPS) relies on an extensive network of mini, micro, and supercomputers to process large volumes of weather observation data, producing vital outputs such as weather analyses, warnings, and forecasts (World Meteorological Organization, 2019).

On the other hand, the role of ICTs extends beyond surveillance; they also contribute significantly to the reduction of carbon dioxide emissions by diminishing or replacing the need for travel. The ICT sector provides a range of tools and services that can substitute for travel, especially in the context of business. These range from basic technologies such as email, phone calls, and text messaging to more advanced solutions like high-speed video conferencing (Obringer et al., 2021). As a result, the ICT industry plays a pivotal role in reducing the carbon footprint, a key metric for quantifying the total greenhouse gases emitted—either directly or indirectly—by an individual, organization, or product over a specific period.

Regarding the urban population, a report published by the United Nations in 2028 indicates that two-thirds of the world's population will soon reside in urban areas due to the continued growth of the urban population (United Nations, 2018). In such environments, ICT tools are crucial for the intelligent management

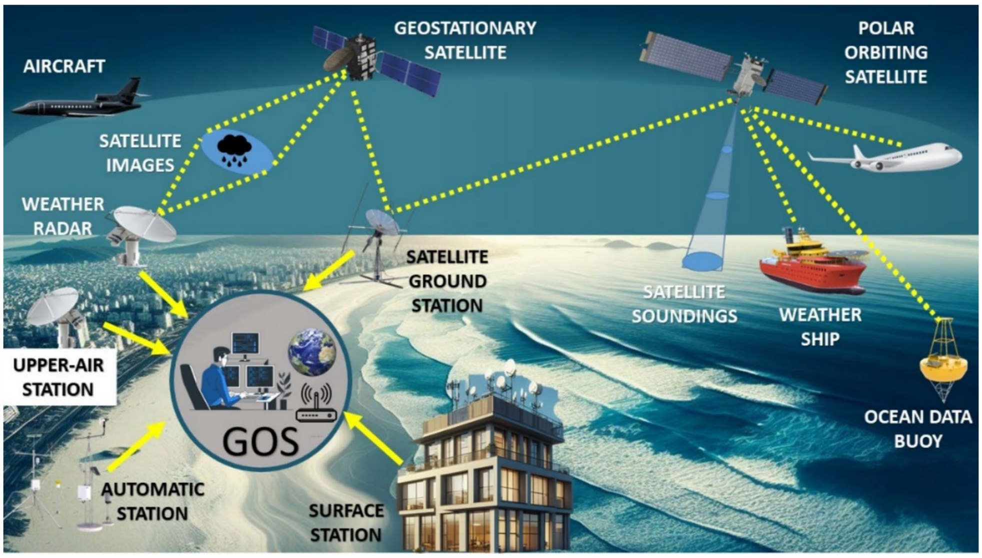

FIGURE 2
Image showing the Global Observing System. Source: Authors.

of essential services, including street and home lighting, waste collection, crime prevention, the maintenance of urban facilities and parks, as well as mobility and transportation of goods, unmanned vehicles, and public parking. The integration of the Internet of Things (IoT) within the urban landscape, through sensors and electronic devices interacting with existing communication infrastructures, facilitates the gathering and analysis of vast amounts of data. This data collection and analysis help in generating projections and identifying patterns that can optimize the use of available resources (Ahmad and Zhang, 2021; Cheng et al., 2022).

In conclusion, ICT tools appear to offer viable alternatives for monitoring and mitigating climate change. Nevertheless, it is crucial to conduct further reviews of existing literature on ICT applications in climate change monitoring and their role in reducing GHG emissions in future scenarios. This research aims to provide a comprehensive overview of both current and potential future applications of ICTs in adapting to and mitigating climate change.

2 Materials and methods

A literature review was conducted using the analytical-synthetic method as a general approach. The data collection relied on compiling a range of bibliographic documents, including major and minor works, references, and study materials. Through guides or repertoires of information sources, it was possible to systematize the conceptual and normative bases giving a better analysis of the information consulted (Valencia et al., 2017). Furthermore, the study examined theoretical-scientific data through units of analysis such as documents, scientific journals, books, texts, and presentations at congresses to conceptualize some terms such as climate change, GHG, information and communication technologies (ICTs), flooding, droughts, glacier melt, ocean acidification, deforestation, and smart systems such as smart city, smart building, smart energy, smart agriculture, smart services, and smart work (teleworking). The methodological process was systematically approached in two stages:

Phase 1. Collection of information: it consisted of searching the database of two international indexers, Scopus and Web of Science, as well as Google Scholar. Likewise, study of the reports of organizations of regional and international significance was unavoidable, such as the Intergovernmental Conference on Climate Change (IPCC), the United Nations Environment Programme (UNEP), the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the World Glacier Monitoring Service (WCMS) and the Global e-Sustainability Initiative (GeSI).

Phase 2. Analysis and interpretation: the study required an investigation, systematization, review, and bibliographic analysis of at least 300 texts of scientific and academic literature, to draw a logical inference about the study. The compilation of theoretical foundations, conclusions, and results found by the various authors allowed us to identify relevant approaches for our research topic.

The search of articles was carried out as follows: a repertory of articles from 2008 to 2023 was collected categorizing the use of ICTs in climate change monitoring and as well as the use of ICTs in CO_2 emissions reduction. For instance, the role of ICTs in monitoring floods, droughts, glacier melt, deforestation, etc., and the role of ICTs (smart city, smart building, smart transport, smart agriculture, etc.,) in CO_2 emissions reduction. The articles were selected by type of article (research article) and subject area (environmental science). A sample of 100 and 520 corresponding to two categories was obtained. Then, in the second category, it was necessary to cluster smart cities, smart buildings, smart energy, and smart transportation into a single sector because these sectors are closely related. Moreover, this allowed us to remove duplicated information from the database and obtain a more reliable sample. After removing duplicated information, a sample of 300 was obtained. Finally, the selection criteria were refined by selecting the most recent articles and the number of citations achieving a sample of 200. The total sample obtained was 300 including the two categories.

3 Results and discussions

3.1 Use of ICTs to monitoring climate change

This part presents results and analyses of scientific reports on ICT applications in climate change monitoring/adaptation. The analyses are restricted to the role of ICTs in flooding, droughts, glacier melting, ocean acidification, and deforestation.

3.1.1 Flooding

Torrential rainfall has become heavier and more frequent in the last few years. This is because climate change leads to warmer natural conditions resulting in increased evaporation and transpiration by vegetation. Thus the concentration of water vapor in the atmosphere tends to be higher (Gärdborn and Xia, 2018). A consequence of the rainstorms is flooding, a high flow or inundation of water that causes damage (Adams, 2016). The environment and human society are both affected by flooding. In this context, ICT tools have been proposed as an alternative for predicting and warning of disaster situations, together with emergency decision-making.

For example, the National Aeronautics and Space Administration (NASA) has developed an app simulator demonstrating what could happen to 293 coastal cities worldwide (Larour et al., 2017). This app shows climatic aspects and possible floods in the next 100 years. NASA researchers have warned for years that rising ocean levels will cause increasingly catastrophic flooding in many parts of the world and that within a few decades, these regions could be entirely underwater. The data for this simulation was derived from an advanced mathematical property of adjunct systems that determines the exact gradient of sea-level fingerprints concerning local variations in ice thickness from all the world's ice drainage systems. This conventional method is based on the following Equation (1) (Larour et al., 2017):

$$\Delta S_{\mathrm{local}}(t) = \int_{\mathrm{ice}} \frac{\mathrm{d}S}{\mathrm{d}H}\Big|_{\mathrm{local}}(\theta,\lambda)\cdot\Delta H(\theta,\lambda,t)\,\mathrm{d}A + \delta S_{\mathrm{local}}(t) \qquad (1)$$

where "local" refers to the location of the port city of interest, "ice" refers to glacial changes, (θ, λ) represents the geographic coordinates on the surface of Earth, t is the time, $\mathrm{d}A$ is an elementary integration area on the globe, and $\Delta S_{\mathrm{local}}(t)$ is the quantity coastal planners wish to assess, given a set of observations or projections about variations in ice thickness, ΔH, around the world. In this equation, $\mathrm{d}S/\mathrm{d}H|_{\mathrm{local}}$ corresponds to the value of the Jacobian at a specific location, also referred to as the gradient of the sea-level fingerprint.

By comprehensively mapping these fingerprint gradients, a diagnostic tool, called gradient fingerprint mapping (GFM), can be created to easily assess future coastal flooding or emergencies (Larour et al., 2017; Stammer et al., 2013). Figure 3 shows some approaches for New York. The gradient [$\mathrm{d}S_{\mathrm{NY}}/\mathrm{d}H$ (in 10^{-3} μm per km^2) of sea level in New York (S_{NY}) with respect to (H) changes in glaciated areas] has been processed for all glaciated regions in the world. According to researchers, the cause of concern in New York is the ice sheets that extend across its northern and eastern parts.

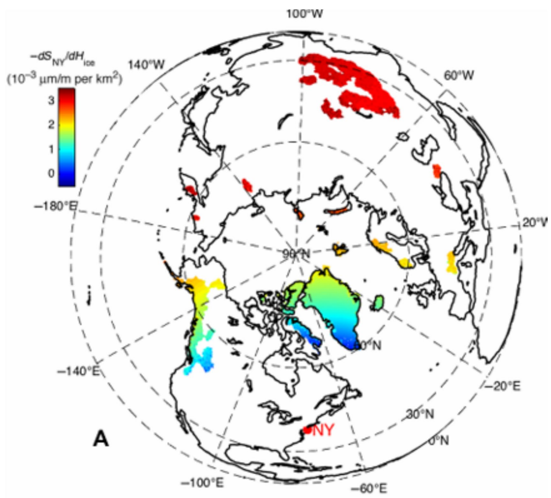

FIGURE 3
Sensitivity of sea-level rise (SLR) to worldwide variations in ice thickness (Larour et al., 2017).

Another example of using ICTs to predict and warn of flood disasters is the European Flood Awareness System (EFAS). It is designed to provide early warnings of potential floods across Europe using advanced ICT systems and predictive modeling tools (McCormick and Salamon, 2023).

In July 2021, heavy rainfall caused severe floods in Germany and Belgium and the EFAS system played an important role in warning and predicting the disaster. The system predicted the potential flooding days before the event, and authorities were alerted. Although the flooding was devastating, the early warnings helped reduce the potential loss of life by enabling timely evacuations and response efforts (Thieken et al., 2023).

3.1.2 Droughts

According to the United Nations, droughts are among the most feared natural phenomena and often impact people, the economy, and ecosystems. Droughts reduce food production and water availability due to a lack of rainfall/surface or groundwater. Droughts also destroy livelihoods and lead to untold human suffering and loss of life (Crossman, 2018).

Several ICT technologies may be used to detect upcoming droughts, as well as to mitigate the consequences of drought. The concept of mitigation in this case does not have to do so much with stopping the drought from happening but rather with preparing society in such a way that it can deal with droughts (Hussain et al., 2005). Predicting and monitoring potential droughts can draw upon Remote Sensing (RS), which is usually satellite or aircraft-based, and detects changes from a distance through "optical, acoustical or microwave" signals (Schowengerdt, 2006). The Global Positioning System (GPS) and Wireless Sensor-Based Networks (WSN) are also used. RS, GPS, and WSN could benefit from further improvements in network technologies such as 5G due to potentially shorter latency and higher bandwidth, making it easier to supply larger amounts of data for analysis (Gärdborn and Xia, 2018; Hussain et al., 2005; Schowengerdt, 2006).

Remote sensing technologies, particularly satellite-based systems, are extensively used to assess the health of vegetation and crops in drought-prone areas. Sensors on satellites like Sentinel-2 (by the European Space Agency) capture multi-spectral images of the Earth's surface, which are analyzed to determine vegetation health through indices such as the Normalized Difference Vegetation Index (NDVI).

ICTs, especially through Geographic Information Systems (GIS) and satellite data, provide geospatial analysis of drought-affected areas. By overlaying drought data (soil moisture, precipitation anomalies) with population maps, ICT tools can help authorities assess which regions and populations are most vulnerable to drought conditions.

- This analysis enables better resource allocation (e.g., water distribution or food aid), prioritizing areas most in need of support. For instance, drought conditions can be mapped against human population density, agricultural activity, or infrastructure, providing a clear picture of where interventions are most urgent.
- Remote sensing data combined with climate models can also predict future drought patterns, helping long-term planning for water management and agricultural policy adjustments.

Drought forecasting is a potential adaptation role that ICTs can play in droughts. Likewise, the role of ICTs is to analyze what happens to society when a drought occurs and to take measures to prepare from the beginning with adequate adaptation strategies. However, people at risk of drought and other natural disasters should be informed in advance to be prepared for possible consequences.

3.1.3 Glacier melting

The enhanced greenhouse effect is the main cause of glacier melt. It is particularly due to changes in heat or high temperatures which affect the melting of the glacier (Glick, 2004; Zillman, 2009). In this context, ICT can provide a powerful tool for transmitting hydro-meteorological information to predict, prepare, and adapt to such events. However, in remote regions, such as mountains, the poles, and islands, preventive and adaptive measures are often limited by data availability and lack of data networks (de Jong, 2013).

ICT tools have been used for glacier monitoring. For example, tracking of the movement of the ice sheets of the Trift Glacier, Switzerland between 2004 and 2005 was carried out using sensors based on ICT equipment (telemetry). In addition, the World Glacier Monitoring Service (WGMS) (WGMS, 2021) uses a multi-tiered, integrated approach to documenting glacier variation, which involves bringing together satellite and GPS remote sensing data with aerial photography, *in situ* measurements, and ice mass balance computer models (Garza and Hidalgo, 2017).

According to the IPCC (Hock et al., 2019), the duration of snow cover has decreased in almost all areas, particularly at lower elevations, by approximately 5 days per decade on average, within a probable range of 0 to 10 days per decade. Additionally, the depth and extent of snow at lower elevations have decreased, though there is significant annual variability. Mass change of glaciers in all mountain regions (excluding the Canadian and Russian Arctic, Svalbard, Greenland, and Antarctica) was very likely −490 ± 100 kg m^{-2} $year^{-1}$ (−123 ± 24 Gt $year^{-1}$) in 2006–2015.

Alterations in snow and glaciers are modifying the volume and timing of runoff in regions dependent on snow and glacier-fed river basins, which is affecting local water resources and agriculture. In the polar areas, there is a significant loss of ice and rapid changes in the oceans. These shifts in the polar regions have global implications, influencing diverse aspects such as climate-related changes in Arctic hydrology, wildfires, and sudden thaws, which affect vegetation, water availability, and food security. Additionally, there has been a reduction in snow and lake ice cover, with June snow cover decreasing by 13.4 ± 5.4% per decade from 1967 to 2018. Runoff into the Arctic Ocean from Eurasian and North American rivers has increased by 3.3 ± 1.6% and 2.0 ± 1.8%, respectively, from 1976 to 2017. The future of the polar regions will be markedly different from today, with the extent and nature of these changes heavily dependent on the pace and scale of global climate change (Meredith et al., 2019). Scientists using increasingly detailed field surveys and remotely sensed data are rapidly improving the understanding of glacier melt. However, assessing the effect this has on water resources and poverty is still fraught with difficulties.

3.1.4 Ocean acidification

Ocean acidification, driven by carbon dioxide (CO_2) absorption from the atmosphere, represents a significant risk to marine ecosystems and biodiversity. When the ocean absorbs CO_2, it interacts with seawater and forms carbonic acid, causing a reduction in pH, increased acidification, and altering carbonate chemistry (Falkenberg et al., 2020). Oceans comprise about 70% of the earth's surface and are getting acidified because humans emit CO_2 and other gases in different processes, e.g., driving a car (Gattuso and Hansson, 2011). A quarter of the emitted CO_2 ends up in the oceans and the consequences of acidified oceans are reported as follows (Rockstrom, 2010):

- Reduction of important matter for marine species such as the formation of shells and skeletons.
- Some species, e.g., shellfish, corals, and plankton will have difficulties growing and surviving.
- The fish stock could decrease since they have difficulties surviving, therefore the food source may decrease.

Ocean acidification can change the abundance and chemical composition of harmful algal blooms so that the toxicity of shellfish increases, thereby negatively affecting human health (Falkenberg et al., 2020). Furthermore, acidification could cause uncoupling of biological and environmental signals, leading to reproductive failure with significant consequences for population dynamics in marine ecosystems (Padilla-Gamiño et al., 2022).

Regarding the fish stock, ICT applications on smartphones could be useful because they can provide computational knowledge so fishermen can estimate the number of fish they can catch without putting the fish stock at risk (Oviedo and Bursztyn, 2017). In other words, applications can be integrated with databases and monitoring systems that provide real-time data on fish populations, seasonal movements, and reproduction cycles, helping fishermen avoid overfishing certain species or areas.

ICT applications are already used on a large scale for monitoring systems. For example, the European Union (EU) uses the Vessel Monitoring System to track vessels through satellites and communication systems (Lee et al., 2010). Vessel Monitoring Systems (VMS) have been largely used to map the distribution of fishing activities. According to Gerritsen (2023), mapping areas with low levels of fishing activity can be interesting to avoid conflicts between fishing and other uses like offshore renewable energy or to protect relatively pristine ecosystems from increasing fishing pressure. Wada et al. (2013) mention that in Indonesia, the monitoring of the production and distribution of fish can be improved through ICT applications. That is throughout the chain from hatching to delivering the product. In the same way, Kimbahune et al. (2013) mention that through smartphone applications, optimal fishing spots can be monitored, and thus the use of diesel fuel can be reduced. Also, Vessel Monitoring Systems (VMS) have revealed increased fishing efficiency following regulatory changes in demersal longline fishery (Watson et al., 2018).

Some case studies are presented in the following: Ji and Li (2021) analyzed lighting fisheries in China based on VMS data transmitted through the BeiDou navigation system, and the research results showed a very significant positive between the Lighting of fishing activities and catch rate. Also in Indonesia, a methodology to compare Vessel Detections (VBD) from the Visible Infrared Imaging Radiometer Array (VIIRS) with Vessel Tracking System (VMS) footprints has been proposed. The process involves predicting the likely location of VMS vessels at the time of each VIIRS data collection with an orbital model. If a VBD record is found within 700 m and 5 s of the predicted location, it is marked as a match. The cross indicates that 96% of matches occur while the boat is fishing (Hsu et al., 2019). To better understand the distribution of fishing efforts across artificial and natural reef types in the Gulf of Mexico, Gardner et al. (2022) linked VMS data from commercial reef fish vessels with high-resolution habitat maps for an iconic species, red snapper (*Lutjanus campechanus*). The findings revealed that approximately 46% of commercial red snapper landings originated from artificial structures. However, exploitation was uneven, with several concentrated hotspots on natural reefs located along the continental shelf break and offshore areas in the Northeast Gulf of Mexico. Regional fishing patterns also varied significantly: in Florida, nearly 91% of landings came from natural reefs, whereas around 75% of landings in the other Gulf of Mexico states were associated with artificial structures. Researchers highlighted that these patterns suggest a potential risk of localized depletion for red snapper populations.

Additionally, Autonomous Underwater Vehicles (AUVs) equipped with sensors and automation technology are used for odometry over coral reefs in Australia. Odometry refers to the process of estimating the position and orientation of the AUVs over time while they navigate the underwater environment, such as coral reefs (Bellavia et al., 2017; Qin et al., 2022). It is a central component of accurate and repeatable monitoring operations. These AUVs play a crucial role in collecting video data and communication, facilitated by ICTs and IT (Dunbabin et al., 2005; Dunbabin and Allen, 2007).

In essence, ICT applications enable monitoring and collection of ocean data on both local and global scales. They also offer a valuable tool for mitigating the impact of climate change on ocean acidification by providing essential feedback on fish stocks.

3.1.5 Deforestation

Deforestation is a significant contemporary environmental issue, spurred by human activities such as land development for construction, agriculture, livestock rearing, and resource extraction like timber and palm oil. While these activities benefit food production and industry, deforestation has detrimental effects on the environment. Forests, especially rainforests, capture greenhouse gases, generate water vapor, and mitigate water pollution. They also harbor diverse ecosystems. The removal of forests can result in climate change, desertification, soil erosion, reduced crop yields, flooding, and snow avalanches, and indirectly contribute to increased greenhouse gas levels in the atmosphere (Farinotti et al., 2020; Gärdborn and Xia, 2018). Furthermore, deforestation affects the ecosystem/environment due to the loss of carbon uptake and storage (Li et al., 2022).

Studies such as Water Resources Research highlight the impact of deforestation, showing that extensive forest removal in snowy regions can double the occurrence of large floods in nearby streams and rivers by accelerating snowmelt through sunlight exposure (Green and Alila, 2012). Another study by Borrelli et al. (2017) underscores the severe consequences of soil erosion from deforestation, leading to land degradation, loss of fertility, and various off-site effects like sedimentation and waterway pollution.

The FAO-led Global Soil Partnership reported a staggering annual soil erosion of 75 billion tonnes from global arable lands, causing an estimated financial loss of US $400 billion (Caon and Vargas, 2017).

Regarding forest fires, they release atmospheric carbon dioxide (CO_2) and are therefore responsible for greatly increasing the pace of climate change (Singh, 2022). Also, larger fires have been associated with greater burn severity, as measured by greater combustion of organic carbon surface, suggesting that they result in greater carbon dioxide (CO_2) emissions per unit area burned and, therefore, have a greater biogeochemical climate warming impact (Zhao et al., 2024).

Understanding land use and land cover (LULC) changes is vital for comprehending the effects of natural and human-induced processes like climate change, deforestation, and urbanization on the Earth's surface (García-Álvarez et al., 2022). LULC change is also important for understanding environmental issues related to surrounding landscapes. Remote sensing data are the primary sources used extensively for LULC analysis. Remote sensing combined with Geographic Information System (GIS) has been used extensively in mapping LULC dynamics (Pandey et al., 2021). For instance, a better understanding of land dynamics requires LULC information to determine changes in natural resources (Heredia-R et al., 2021b), in support of Target 3 of Sustainable Development Goal (SDG) 15. "By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world" (Sims et al., 2017). Regarding forest issues and threats, ICT applications can be useful. ICT applications can be used to map forest resources, monitor forest risks, prevent illegal logging and fires, raise awareness of the need for sustainable forestry practices, improve forest governance as well as linking forest communities to achieve sustainable forest management, increase transparency, public participation, and strengthen land rights (Castrén and Pillai, 2017; Reynolds et al., 2005). In this context, many studies on forest monitoring have been conducted. For instance, a study on mapping deforestation using a mobile phone application was developed by Tuukuo (2018). It combines ICT and handheld devices which enable local communities to monitor their forest efficiently and cost-effectively. The results of this study enabled the determination of different issues related to deforestation like logging, infrastructural development, forest to agriculture land conversion, and unplanned settlement.

Forest monitoring has been carried out thanks to the development of ICTs with emerging technologies such as laser scanners (LIDAR) or unmanned aerial vehicles commonly called drones. LIDAR is generally used to make estimates of the available wood inventory such as the number of trees per hectare, tree height, and trunk diameter (Seleznovs et al., 2019). A more precise knowledge of the terrain, the water flows, and the forest inventory contributes to better planning a harvest (Choudhry and O'Kelly, 2018). Drones are increasingly used in the forestry industry to perform observation and terrain mapping tasks when equipped with the mentioned LIDAR. Furthermore, they can also be equipped with thermal cameras or other devices to detect outbreaks of pests and diseases or give early warnings in the event of fire (Baena et al., 2018).

Based on case studies, it is clear that forest monitoring through ICT applications can contribute to decreasing deforestation in the world. However, the costs of using these techniques can be a limitation.

3.2 Summary of ICT solutions for each indicator of climate change

Table 1 outlines specific climate change indicators to assess the possible contribution of ICTs in climate change monitoring.

3.3 Use of ICTs to decrease greenhouse gas emissions

Multiple studies have pointed out the potential of the ICT sector to lower worldwide greenhouse gas emissions (Ajwang and Nambiro, 2022; Bastida et al., 2019; El-Bawab, 2021; Majeed, 2018; Mickoleit, 2010). For instance, research from the Global e-Sustainability Initiative (GeSI) suggests that ICT applications could help avoid around 20% of annual GHG emissions by 2030 through more intelligent energy usage by businesses and consumers (GeSI, 2015).

Another study highlights that ICTs can cut global greenhouse gas emissions by up to 15% by 2030. This estimate stems from a scenario with high reduction potential, incorporating various ICT solutions across sectors like energy, buildings, transport, and agriculture (see Figure 4). The findings indicate a significant reduction of 10 $GtCO_2$, or approximately 15% of global GHG emissions by 2030 (Malmodin and Bergmark, 2015).

To substantiate these claims, a literature review was conducted to explore the role of ICTs in diverse sectors.

3.3.1 Smart city

A smart city employs an infrastructure primarily reliant on ICTs to enhance efficiencies and enhance the sustainable quality of life for urban residents (Lai et al., 2020). This ICT framework heavily involves intelligent networks comprising interconnected machines and objects that transmit data wirelessly via the cloud. Cloud-based IoT applications play a substantial role in receiving, analyzing, and managing real-time data, aiding municipalities, businesses, and citizens in making informed decisions to enhance overall quality of life (Alam, 2021).

Residents engage with the smart city through various means such as smartphones, mobile devices, connected vehicles, and homes (see Figure 5). Integrating devices and data with the city's physical infrastructure and services can lead to cost savings and sustainability improvements. Through IoT integration, communities can enhance energy distribution, optimize waste management, alleviate traffic congestion, and even enhance air quality (Kramers et al., 2014).

Regarding air quality, smart cities play a pivotal role. A recent study conducted in China affirms that in pilot cities, per capita CO_2 emissions have significantly decreased due to smart city development. In addition, smart cities have considerably enhanced the energy efficiency of cities and accomplished CO_2 emission reductions, principally through energy-saving effects (Guo et al., 2022).

In contrast, building and maintaining smart cities can be costly in terms of materials and cybersecurity. However, these costs underline the importance of planning, with a careful balance between initial investments and long-term maintenance to create a sustainable and efficient smart city.

In short, a smart city is an innovative city that uses ICTs and other means to improve life quality, the efficiency of the operation of urban services, and competitiveness, while ensuring that the needs of present and future generations are met regarding different aspects such as the economy, social and environmental conditions.

3.3.2 Smart transport

Studies on smart transport for reducing CO_2 emissions have been reported in the literature. For instance, Nijkamp and Kourtit (2013) argued that smart transport not only contributes to reducing the ecological footprint, congestion, and accidents but also to sustainability. Furthermore, Contreras and Platania (2019) mentioned that in a holistic smart city initiative aimed at mitigating climate change, the transport sector would be the best beneficiary in terms of CO_2 emission reduction.

Beyond physical infrastructure, smart transportation technologies aim to reduce emissions by minimizing driving times. Numerous global initiatives for smart parking have been deployed to track parking space availability in real-time and guide drivers accordingly. These measures reduce the time drivers spend searching for parking, which in turn decreases traffic congestion and emissions. For instance, a case study in San Francisco documented a notable decrease in the time drivers spent searching for parking, leading to lower emissions and less congestion (Alemi et al., 2018).

Long journeys in electric cars are often stressful due to the difficulties in charging a vehicle, particularly when driving from one country to another (Liu et al., 2015). In this way, the European Union has been developing an ICT network mobility project called NEMO which enables those vehicles to be plugged into charging points in any EU country. The network will make it easy for charge point and grid operators, drivers, and providers of payment, navigation, and other related services (Fanti et al., 2017; Morgan, 2012). Furthermore, it could reduce air pollution from transport since this ICT application will encourage motorists to use electric vehicles.

Additionally, there is research related to the smart use of roads, focusing on the use of ICTs for identification of traffic bottlenecks and the optimization of the use of road capacity, in both cases, helping to the reduction of travel times and for instance the decarbonization of road

TABLE 1 Contribution of ICTs to monitor climate change.

Indicators/trends of climate change	Causes of observed trends	Changes in ecosystems	Prediction of disasters and warning people through ICTs
Changes in precipitation	Alterations in the water cycle due to abrupt shifts in atmospheric temperatures	Elevated precipitation levels can lead to runoff, landslides, soil erosion, alterations in vegetation, and habitat degradation. Conversely, reduced rainfall results in droughts	Record and track seasonal and monthly precipitation data using the Global Telecommunication System (GTS); utilize Geographic Information Systems (GIS) for flood risk assessment; raise awareness among farmers through radio broadcasts and mobile platforms; employ GIS and GPS technologies to pinpoint new freshwater reservoirs. Also, incorporating remote sensing data into (ICTs) can significantly enhance the understanding and management of water resources, flooding, and damage assessment
Glacial melting	Increase in the Earth's surface temperature, commonly referred to as global warming	Flooding, glacial mass depletion, and erosion result in the depletion of soil nutrients. Additionally, many glaciers at the poles end in the ocean, so their retreat can release icebergs that can remove biota from the seafloor and release plumes of sediment into the water column that can smother colonies, particularly affecting filter-feeders	Remote sensing technologies are used to monitor glacier movement and the changes in glacier mass balance, aiding in forecasting floods and runoff events
Sea level rise	Global warming due to the concentration of greenhouse gases leads to sea level rise, driven globally by melting ice sheets and thermal expansion of the ocean (Griggs and Reguero, 2021)	Potential risks associated with coastal areas include coastal flooding, inland floods, shoreline erosion, wetland inundation, intrusion of saltwater into groundwater reserves, displacement of marine ecosystems, and the risk of coastal land submersion	Using satellite altimetry to monitor and record the rise in sea levels, ensuring that any irregularities are documented, which enhances the prediction of disasters to prevent loss of life and property
Soil erosion	Deforestation	Decrease in soil protection, limited nutrient access, and loss of vegetation	Remote Sensing and GIS techniques are regularly used for monitoring and assessing environmental changes including soil erosion
Forest fires	Climate change increases fire-friendly weather in forests (Jones et al., 2024)	Destruction of habitats, endangered species risk, diminished plant coverage, and emissions of particles	Keep and manage satellite images (GIS, GPS), as well as emergency communication through mobile technology
Ocean acidification	Human-caused carbon dioxide (CO_2) emissions are absorbed by the oceans, causing them to acidify	Reduction of important matters for marine species such as the formation of shells and skeletons	AUVs controlled by ICTs and IT are regularly used as observation platforms in the ocean

transport (Ahjum, 2020; Džupka and Horvath, 2021). For instance, a study performed in an experimental area in China shows that after using a big data intelligent traffic signal dynamic timing optimization control platform, the travel time was reduced by 15%. Furthermore, the travel time was reduced by 10% during the off-peak period (Wang et al., 2019).

Another study, performed in the UK by innovITS (Pearson, 2013), comes to a similar conclusion. ITS (Intelligent Transport Systems) measures related to fleet operations and management were found to improve travel time by 2–15%. Interestingly, this study showed a reduction in vehicle emissions of 5–20%.

3.3.3 Smart energy systems

A fundamental component of smart city infrastructure is the implementation of smart energy systems (Hayat, 2016). These systems not only offer real-time monitoring but also incorporate a smart grid that supports both centralized and decentralized power systems. Moreover, smart energy systems play a role in combating climate change. For example, According to Hunter et al. (2018) the increased efficiency of ICT-enabled smart energy systems, along with their capability to deliver detailed consumption data, is expected to decrease energy usage and subsequently reduce carbon emissions. Parks (2019) noticed that smart grids could help increase the integration of renewable energy sources, as well as enhance efficiency. Lastly, Ceglia et al. (2022) mentioned that increasing energy SC (self-consumption) would have greater benefits both from the economic and the environmental perspective since it would reduce the purchase of electricity from the grid and thus mitigate GHG emissions related to non-renewable-based energy systems.

Another advantage of smart energy systems is their resilience against disasters like hurricanes or heatwaves, which can adversely affect electricity generation technologies. Recent studies indicate that the decentralized aspect of smart energy systems enhances their resilience by enabling local electricity generation when centralized

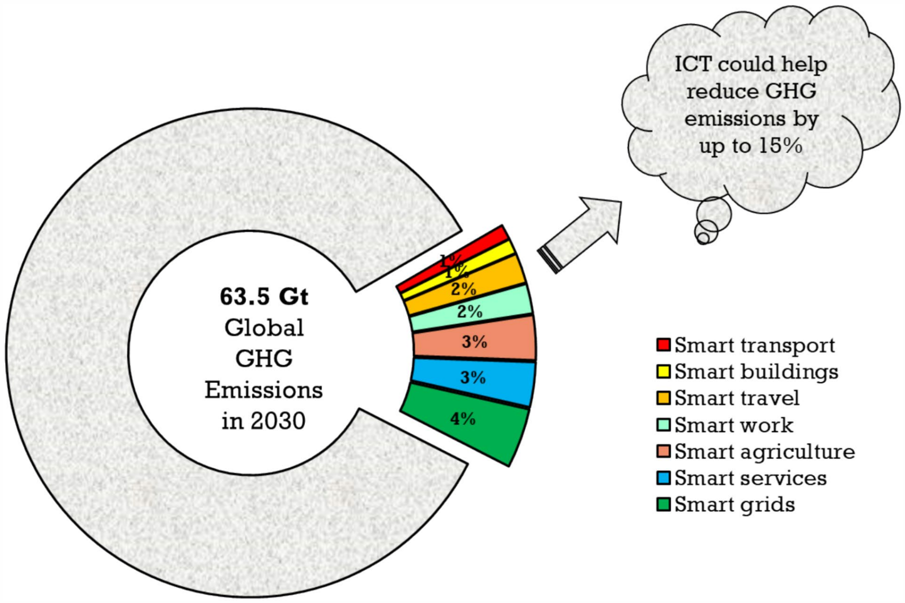

FIGURE 4
A high reduction potential scenario for 2030 per the ICT solution category (Malmodin and Bergmark, 2015).

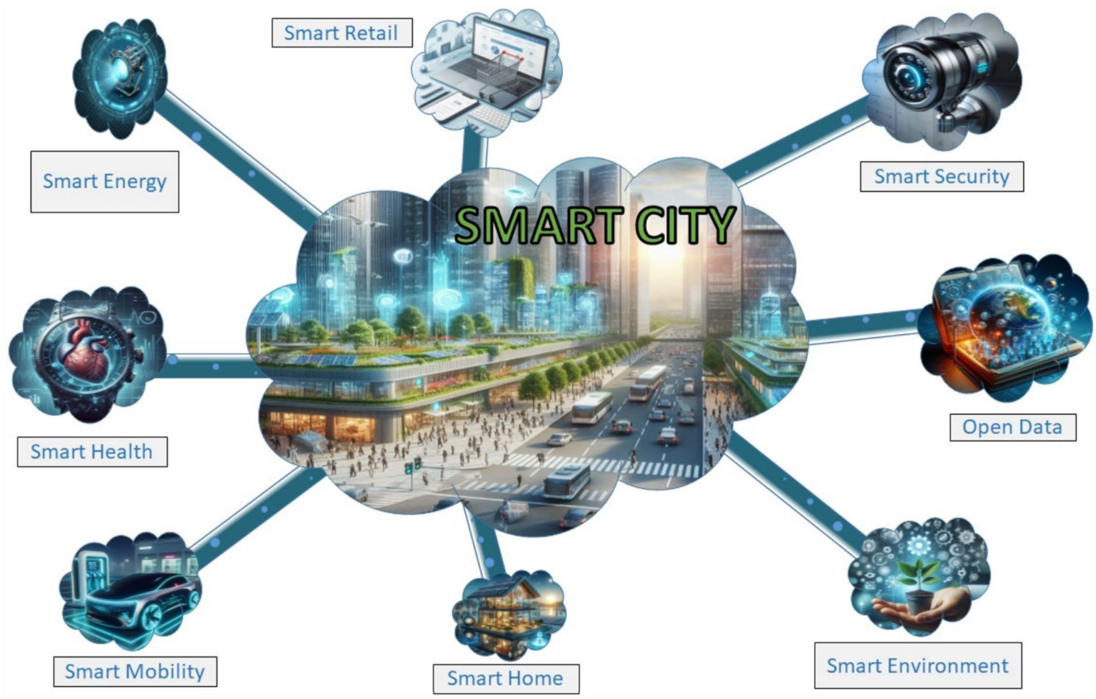

FIGURE 5
Image showing some benefits of a smart city. Source: Authors.

power facilities are compromised by disasters such as hurricanes or storms (Hayat, 2016).

Since climate change can lead to more frequent disasters, such as heat waves (Dosio et al., 2018), a crucial component of adaptation is decreasing the impact on electricity generation technology. These studies reveal the potential role of smart energy systems within smart city applications to help in climate change adaptation and mitigation (Obringer and Nateghi, 2021).

In short, smart energy systems remain a viable option to reduce carbon emissions because of their efficiency in terms of energy optimization and because they play a potential role in climate-related disasters.

3.3.4 Smart houses/buildings

One of the greatest technological advances that benefit the environment is the creation of smart houses, buildings, and even residential developments on a greater scale. It should be noted that homes and offices are the two places with the highest energy consumption and significant carbon emissions. In this way, smart homes (Kim and Baek, 2019) have become a great technological goal since they allow the reduction of costs and pollution thanks to interconnected devices that adjust the devices to operate only when needed (see Figure 6) (Froufe et al., 2020; Rawte, 2017).

3.3.5 Smart agriculture

A significant contributor to global warming is the emission of greenhouse gases (GHGs) from agricultural activities (Lynch et al., 2021). In this way, smart agriculture aims to enhance agricultural efficiency by employing geographic mapping, sensor technology, machine-to-machine connectivity, data analysis, and intelligent information platforms (see Figure 7). The goal is to improve productivity and sustainability in farming practices, leveraging ICTs to ensure food security and resource conservation on a larger scale (Canton, 2021).

ICTs in agriculture, such as e-agriculture, create a collaborative platform involving various stakeholders, particularly farmers, facilitating access to timely information, sharing experiences, and exchanging resources related to agriculture. This approach leverages ICT tools like mobile phones, radio, and television for effective information dissemination, promoting integration with multimedia, knowledge, and cultural sectors (FAO, 2017; Singh et al., 2015).

Digital transformation in agriculture generates valuable data managed through ICT applications and innovations. Technologies like Radio Frequency Identification (RFID) and blockchain enhance data collection, and circulation, and improve traceability in agri-food production, elevating product quality (Braun et al., 2018; Kamilaris et al., 2016; Singh et al., 2015; Tian, 2016; Wolfert et al., 2017).

E-agriculture platforms are still actively used today and continue to evolve, playing an increasingly important role in improving agricultural productivity, sustainability, and food security around the world. FAO e-agriculture Community and Agri-tech Startups are some examples of active e-agriculture.

A study performed by the FAO found that farmers using e-agriculture platforms experienced yield increases of up to 30% compared to those who relied on traditional methods (Food and Agriculture Organization of the United Nations and International Telecommunication Union, 2022). Also, e-agriculture tools that use AI to detect crop diseases have helped farmers take early action, cutting crop losses by 30–40% (Islam et al., 2024).

On the other hand, the environmental benefits of smart agriculture are evident. For example, studies like Maraseni's et al. (2021) work in Australia demonstrate that optimizing land and water resources can reduce GHG emissions by 45% and increase profitability by over 50% while maintaining emissions 15% lower than the baseline level.

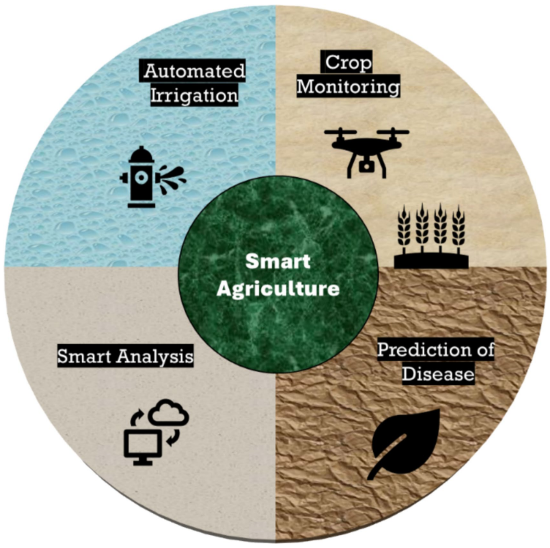

FIGURE 7
Image showing some benefits of smart agriculture. Source: Authors.

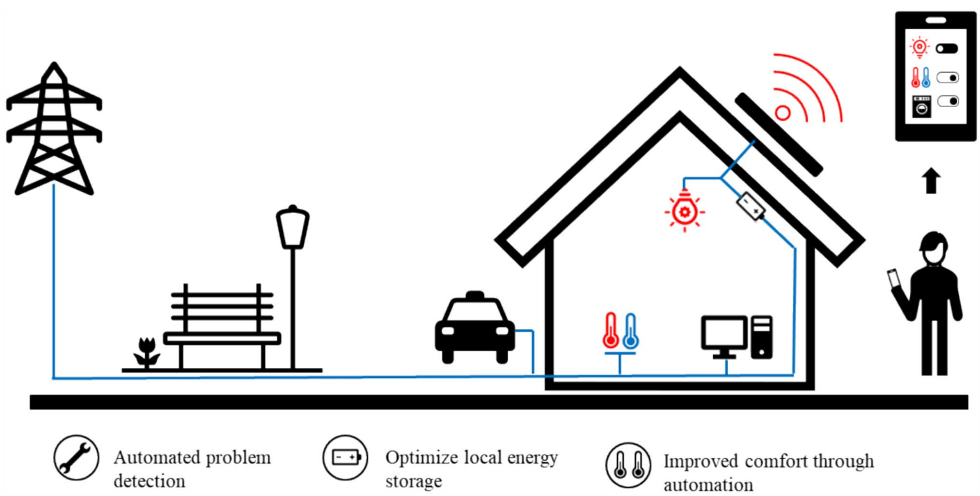

FIGURE 6
Image showing some benefits of a smart house. Source: Authors.

FIGURE 8
Images showing three aspects of the Svalna App: an overall display of the user's greenhouse gas emissions is on the left, a detailed breakdown of emissions across various categories is in the center, and recommendations along with goal-setting options for reducing emissions are on the right (Barendregt et al., 2020), open access.

TABLE 2 Use of ICTs in smart agriculture.

ICT application	Benefit	Economic and productive impacts
Farming data	The farm produces large amounts of data that can be stored in a cloud platform. This data provides farmers with valuable insights into their operations, enabling them to make informed decisions and potentially modify their practices (Wolfert et al., 2017). This is in line with SDG 2 Zero Hunger, "By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers"	Based on research conducted by Norris and Bland (2015) in Britain, farming data can serve as digital proof, leading to reduced time spent on grant applications and farm inspections. This efficiency could result in an average savings of £5,000 per farm
Smart tractors	Smart tractors equipped with GPS-guided steering and efficient route planning help minimize soil erosion (Mat et al., 2018). This is in line with SDG 15 Life on Land, "By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world"	Smart tractors have the potential to reduce fuel consumption by 15% and boost crop yields by 10–20% (Norris and Bland, 2015)
Agricultural robots	Robotics and IoT technology offer sophisticated agricultural assistance to farmers, enabling them to achieve maximum yields in food production (Bhimanpallewar and Narasingarao, 2020). Specialized agricultural robots can perform tasks such as planting, weeding, fertilizing, and harvesting crops (Norris and Bland, 2015) This is in line with SDG 2 Zero Hunger, to "end hunger, achieve food security and improved nutrition, and promote sustainable agriculture." This is also in line with SDG 12 "Responsible Consumption and Production" which strengthens the importance of sustainable practices in both consumption and production sides (Yuan, 2019)	Robots that can apply microdot fertilizers significantly cut down fertilizer expenses by 99.9% (Norris and Bland, 2015). In essence, these robots enhance farming precision and enhance crop yields (Yuan, 2019)
Field monitoring	Aerial drones are used to monitor fields, providing valuable data for mapping weeds, assessing yield, and identifying soil variations. Essentially, drones alleviate the farmer's responsibility of manually monitoring their fields regularly (Raj et al., 2021)	As per a study conducted in Britain by Norris and Bland (2015), the accurate monitoring of fields allows for the targeted application of inputs, resulting in a £70 increase in wheat yields per hectare
Automatic irrigation	Automated irrigation is crucial for effective water management as it ensures crops receive the appropriate amount of water at the optimal times (Limbo et al., 2021). This is in line with SDG 6 "By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate"	Implementing an automated irrigation system leads to savings in both time and money, as it minimizes water wastage due to runoff and evaporation compared to traditional watering methods
Disease prediction system	A disease forecasting system empowers farmers to swiftly and effortlessly detect plant diseases (Bala Murugan et al., 2021)	Utilizing a precise plant disease prediction system enables farmers to enhance the efficiency of chemical spraying, resulting in cost savings and environmental protection (Mäyrä et al., 2018)

In conclusion, ICTs empower farmers to enhance resource efficiency, productivity, and resilience, thereby reducing food waste in the supply chain and contributing significantly to GHG emissions reduction efforts.

3.3.6 Smart services

In today's market, a variety of products offering intelligent services are branded with names like smart TVs, smartphones, smart homes, smart energy, and more. These intelligent services are constantly advancing in productivity, compliance, sustainability, and quality, among other aspects, and are evolving alongside various sectors such as government, healthcare, education, finance, hospitality, communications, energy, utilities, and transportation. This evolution is made possible by analytical and cognitive systems like sensing, big data, computation, and automation, enabling smart services to adapt to dynamic environments to benefit customers and suppliers (Lim and Maglio, 2018; Marquardt, 2017).

In Ecuador's healthcare system, ICT and smart systems have been employed as supportive tools for managing, educating, and preventing trauma (Ordóñez Ríos et al., 2017). Similarly, such systems and applications have been utilized to monitor CO_2 emissions from individuals. For example, the carbon tracking application developed by Svalna App calculates the CO_2 footprint resulting from daily activities. This application offers users information and advice on maintaining acceptable carbon emission levels at work or home,

TABLE 3 Use of ICTs in smart cities.

ICT application	Benefit	Economic and productive impacts
Smart mobility	ICTs incorporated into contemporary transportation technologies enhance urban traffic management by utilizing modern tools like remote tracking and video surveillance (Karimi et al., 2021; Saqib et al., 2022)	Such technologies have the potential to decrease costs, save time, and minimize emissions (Orlowski and Romanowska, 2019)
Smart environment	A smart environment comprises different technologies towards an innovative monitoring system that can be used to collect data from utility services (e.g., energy, air, water and waste management). It provides a more efficient service, improves the quality of life and contributes to achieving environmental sustainability (Kaluarachchi, 2022). This is in line with SDG 11 Sustainable Cities and Communities, "By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management"	Water management prevents large losses through controlled consumption. Energy management can also save money. For instance, LED lights will be available in Singapore and Copenhagen cities throughout the city's street lighting, reducing annual consumption by 60% (Palomo, 2021b)
Smart people	Knowledgeable individuals foster creativity and contribute to the development and adoption of innovative technologies that benefit their cities and nations (Attaran et al., 2022; Saqib et al., 2022). This is in line with SDG 9, to "Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending"	A proactive citizen leverages the human and social assets within the city. Additionally, employing smart methods to produce items like clothing and food can enhance both the quality of life and the economy of the nation (Attaran et al., 2022)
Smart living	Smart living offers solutions that aid individuals in enhancing their quality of life across various aspects such as consumption, lifestyle, security, health, cultural amenities, and diversity (Aldegheishem, 2019). Overall, the objective of this approach is to encourage and achieve a joyful and healthy way of life (Saqib et al., 2022) This is in line with SDG 4, "By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development"	These initiatives would reduce health problems and save money Efforts like the Healthy Living program in Singapore aim to combat sedentary lifestyles effectively. Encouraging shared bike paths and advocating for healthy eating involve measures like eliminating high-sugar and high-fat foods commonly found in vending machines (Palomo, 2021a). Such initiatives not only address health issues but also lead to cost savings in the long run
Smart economy	The concept of a smart economy offers economic solutions focused on streamlined production processes and a versatile labor market This is in line with SDG 8, to "Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services"	A smart economy stimulates the expansion of businesses, the generation of employment opportunities, enhancements in staff qualifications, and increased efficiency gains (Stübinger and Schneider, 2020)
Smart government	The smart government utilizes digital automation, open data, and citizen engagement to enhance the efficiency of administrative units and optimize their functions (Moura and de Abreu e Silva, 2019) This is in line with SDG 16, to "Ensure public access to information and protect fundamental freedoms, in accordance with national legislation and international agreements"	Open data contributes to a 1% higher annual GDP compared to closed government practices (Molina and Balsas, 2018). Several cities already leverage this resource, exemplified by the 1798 data sources accessible through the Government of Singapore, significantly more than the approximately 700 available in the London Datastore, 462 in Barcelona, and 452 in Madrid (Palomo, 2021a)

allowing them to set monthly and annual emission targets (Andersson, 2020; Barendregt et al., 2020). Features of the Svalna App are shown in Figure 8.

3.3.7 Smart work/telecommuting

Over the past 30 years, telecommuting has seen a rise, largely due to the integration of ICTs into home and work environments (Barrett, 2001; McCarthy, 2022; OECD, 2019; Standen, 1997). Moreover, the COVID-19 pandemic further accelerated the adoption of telecommuting, resulting in both positive and negative effects on policies, individuals, and the environment (OECD, 2020, 2021; Criscuolo et al., 2021; Manhertz and Lee, 2022; Milasi et al., 2021). The reduction in vehicle usage during lockdown periods led to a decrease in CO_2 emissions (Krasilnikova and Levin-Keitel, 2022). However, the shift to working from home and increased use of electronic devices contributed to a higher carbon footprint. Nevertheless, adopting eco-friendly practices such as unplugging mobile device chargers, maintaining clean email inboxes, and minimizing camera use in video conferences can help reduce the carbon footprint associated with telecommuting. Smart work solutions like video and teleconferencing outside traditional office settings are seen as environmentally sound practices (Obringer et al., 2021; Arnfalk et al., 2020).

Telecommuting also offers various benefits for employees. For instance, it allows for flexible work schedules that can enhance job performance and reduce stress. Additionally, it eliminates the need for parking spaces and office real estate.

In conclusion, telecommuting brings about more positive than negative impacts, and numerous studies view it as a socially, economically, and environmentally beneficial practice for the future.

3.4 Summary of ICT contributions in different sectors

Tables 2–5 provide an overview of how ICT is utilized across various sectors, outlining the benefits and economic/productive outcomes. Additionally, the ICT applications outlined in the tables are analyzed according to the Sustainable Development Goals (SDGs) (Figure 9).

Previous literature has highlighted that key sectors contributing to economic and environmental productivity include smart energy, smart city/building, and smart agriculture. Furthermore, these sectors are analyzed according to Sustainable Development Goals (SDGs) 7, 11, and 12. Here's a breakdown:

TABLE 4 Use of ICTs in smart buildings.

ICT application	Benefit	Economic and productive impacts
Smart building technologies	Predictive analytics: Intelligent software utilizes data from IoT devices to predict the performance of the building and its various systems over time (Himeur et al., 2022; Schneider Electric, 2020 2020). App-based building services: The mobile phone serves as the central hub for smart building operations. This allows occupants to manage their environment, schedule services, and receive guidance, all through a mobile application (Schneider Electric, 2020)	As per Castro Miranda et al. (2022) predictive analytics could assist stakeholders in enhancing the accuracy of cost forecasting within the construction industry, facilitating proactive budget management for project owners
Smart asset	- Smart materials: Utilizing nanotechnology, smart materials can enhance the strength and energy efficiency of buildings. For example, electrochromic windows or smart glass reduce glare and heat transfer while maintaining visible light transmission through windows (Hoy, 2016) - Sustainable buildings: Through meticulous monitoring of electricity and water usage, buildings optimize the performance of their various systems, resulting in high energy efficiency (Al Dakheel et al., 2020; Schneider Electric, 2020). This is in line with SDG 11, to "Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials" - Actionable intelligence: Advanced software monitors the performance of devices in each building, identifying issues, scheduling maintenance, and maintaining optimal performance levels (Frank et al., 2019; Schneider Electric, 2020) - Smart security: Utilizing technologies like video analytics and advanced access controls, buildings ensure the safety of occupants (Schneider Electric, 2020; Zhang et al., 2019). These systems often incorporate surveillance cameras, motion sensors, lighting controls, alarm systems, sensors on doors and windows, and a central hub for communication with these devices (Rafiq et al., 2017)	- Regarding smart materials, electrochromic windows can cut air conditioning expenses by 50% in large buildings (Hoy, 2016). Additionally, efficient building materials can lower heating and cooling costs - Sustainable buildings typically experience reduced annual expenditures on energy, water, and maintenance/repairs (Parashar and Parashar, 2012). According to SMARTer2030 (GeSI, 2015), these savings amount to 5 billion MWh of energy and 300 billion liters of water, resulting in cost savings of $360 billion - Smart security: According to Deamer (2018), smart cameras can lead to significant cost reductions. For instance, eliminating just two false positives from a remote site per night can result in savings exceeding £29,000 in the first year, with total savings nearing £150,000 over 5 years
Smart workplace	Workplace data: Data on workspace occupancy is collected through networks of sensors and cameras, allowing building managers to pinpoint areas requiring intervention. Additionally, sensor data enables managers to monitor current and historical usage and predict future utilization trends (Hoy, 2016)	As per JLL/Technologies (2022), this technology can propose modifications to the office arrangement, achieving an optimal density and service balance. This results in a 50% reduction in testing time, a 33% decrease in decision-making time, and a 40% cost reduction

SDG 7 (smart energy): This sector focuses on enhancing energy efficiency and accessibility and promoting renewable energy in the energy mix. Its target is to save over 1.3 billion MWh by 2030.

SDG 11 (smart city and smart buildings): Emphasizes the role of smart buildings and transportation in cities, aiming to reduce CO_2 emissions by 5% by 2030, while also improving resource utilization, energy efficiency, and reducing air pollution.

SDG 12 (smart agriculture): This sector aims to optimize production and consumption patterns, transitioning towards a circular economy model, and targeting a 20% reduction in food waste by 2030.

4 Critical analysis

It has been confirmed that ICT applications play an important role in addressing climate change by improving resource efficiency, supporting informed decision-making, and fostering sustainable practices. However, despite its considerable potential, its implementation brings benefits and challenges that require to be analyzed in detail. In this context, some benefits and limitations are shown in Tables 6, 7.

5 General discussions

Climate change is one of humanity's greatest threats due to its tremendous effects on the planet. It emphasizes that greenhouse gases are the primary cause of this climate crisis. In this way, some international organizations such as the United Nations (UN) and others have been making significant efforts to combat these effects and have considered ICTs as an alternative for monitoring and mitigating climate change. Many studies have pointed out the potential of the ICT sector to lower greenhouse gas emissions worldwide. For instance, a study from the Global e-Sustainability Initiative (GeSI) suggests that ICT

TABLE 5 Use of ICTs in smart transportation.

ICT application	Benefit	Economic and productive impacts
Internet of Things (IoT)	The evolution of smart transportation is driven by the integration of IoT technology and communication networks. Billions of interconnected smart devices contribute to this network. This connectivity extends to smart vehicles like cars, buses, trains, and airplanes, ensuring continuous Internet access for individuals (Sadiku et al., 2016; Sadiku et al., 2017)	Due to the connectivity of vehicles with diverse devices, Brlek et al. (2019) explored the cost-effectiveness of IoT in transportation within the EU. Their study indicates that connecting 30 million cars each year could lead to equipment costs up to €3 billion annually. However, this investment could result in a significant decrease in accident rates (approximately 5% per year), leading to annual savings of €3.5 billion by 2030
Wireless technologies	Numerous wireless technologies have been suggested for smart transportation. For instance, the US and UK are pioneers in implementing smart wireless digital traffic signs on roads. This innovation eliminates the necessity for drivers to constantly watch for signs while driving, enabling them to focus on the road ahead. Additionally, it relieves drivers from the responsibility of remembering all traffic signs (Toh et al., 2020). Furthermore, the utilization of wireless internet technology and GPS systems can reroute traffic to bypass congestion (Pearson, 2013)	Smart wireless digital traffic signs are cost-effective (Toh et al., 2020), especially when considering the fuel savings they enable (International Energy Agency, 2009)
Smart roads	Electric vehicles need recharging when their battery capacity is depleted, which can be challenging when driving in rural areas with limited access to nearby charging stations To address this issue, some countries are working on developing roads that can automatically charge vehicles (Toh et al., 2020). For instance, in Sweden, approximately 1.2 miles of road near Stockholm have been transformed into an "electrified road" that recharges the batteries of cars and trucks as they drive along it (The Guardian, 2018). This is in line with SDG 7, "By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency, and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology"	As stated by the Swedish government (The Guardian, 2018), the cost of constructing an electrified road is €1 million per kilometer, significantly lower compared to the expense of building an urban tram line, which is 50 times higher. This initiative has the potential to significantly boost the number of electric vehicles with charged batteries. On the other hand, electrified road can be more expensive than installing charging stations in rural areas, but it is an innovative technology and a study from "the Swedish government shows that E-roads stretching 155–186 miles (155–300 km) could reduce the CO_2 emissions of trucks by more than 200,000 tons" (Climate Adaptation Platform, 2024)
Smart traffic surveillance/ monitoring	Smart traffic monitoring utilizes on-road traffic cameras as video surveillance tools to monitor roads and assess real-time traffic conditions. This allows authorities to make traffic management decisions based on current road conditions, such as redirecting traffic through alternative routes. These new routes are then communicated to drivers (Olusanya et al., 2020). This is in line with SDG 11 "By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons"	According to SMARTer2030 (GeSI, 2015), approximately $6 billion can be saved by mitigating traffic congestion and meeting mobility demands

FIGURE 9
The Sustainable Development Goals (SDGs) (Setó-Pamies and Papaoikonomou, 2020), open access.

TABLE 6 Benefits of ICT applications in climate change.

Benefit	Example	Evaluation
1. Monitoring and data collection		
ICT provides real-time monitoring through IoT devices and collects data on GHG emissions, climate patterns, etc	The European Operational Satellite Agency (EUMETSAT) and NASA's Earth Observing System (EOS). Researchers from the Université libre de Bruxelles, Belgium, performed a case study. They studied a decade's global ammonia emissions data from EUMETSAT's Metop polar-orbiting satellites. They found 248 hotspots associated with either a single point source or a cluster of agriculture and industrial point sources (Van Damme et al., 2018)	It provides critical data for climate modeling, policy formulation, and early warning systems for natural disasters
2. Data analysis and climate modeling		
Advanced ICT tools, such as artificial intelligence (AI) and machine learning (ML) are used to process large amounts of climate data and improve predictive capabilities and scenario planning	Supercomputers model future climate scenarios to assist policymakers in developing mitigation and adaptation plans. For example, researchers from the California Institute of Technology modeled global vegetation gross primary productivity, transpiration, and hyperspectral canopy radiative simultaneously using a Next Generation Land Surface Model—CliMA (Climate Modeling Alliance) Land (Wang et al., 2023)	Improves accuracy and supports evidence-based decision-making
3. Energy efficiency and smart grids		
ICTs can improve energy efficiency through smart grids. This optimizes electricity distribution and reduces waste	Smart meters enable consumers to monitor and lower their energy usage. For example, a study performed in China revealed that by applying a smart grid in China's manufacturing industry, carbon emissions could be reduced by 27.51% in the optimistic scenario (Fu et al., 2021)	Reduces carbon emissions and improves the sustainability of energy systems

applications could help avoid around 20% of annual GHG emissions by 2030 through more intelligent energy usage by businesses and consumers (GeSI, 2015). Another study confirms that ICTs can cut global greenhouse gas emissions by up to 15% (10 $GtCO_2$) by 2030 (Malmodin and Bergmark, 2015). However, the environmental impact of ICTs has not been analyzed in detail. According to Freitag et al. (2021) there are huge trends that can significantly increase the carbon footprint of ICTs, including in AI, IoT, and blockchain. Yu et al. (2024) also analyzed the carbon emissions from 79 prominent AI systems released between 2020 and 2024 and projected that the total carbon footprint from the AI systems in the top 20 carbon emissions could reach up to 102.6 Mt. of CO_2 equivalent per year. In this context, an emissions cap is essential for encouraging industries to adopt greener practices and technologies, paving the way for a more sustainable future for AI.

ICT applications aid in monitoring, forecasting, and managing environmental, ecosystem, and human activities. They offer crucial support to nations in adapting, preparing, and formulating policies for the energy and agricultural sectors, sustainable development, and

TABLE 7 Limitations of ICT applications in climate change.

Limitation	Example	Evaluation
1. Energy consumption and E-waste		
ICT consumes substantial energy, especially through data centers and blockchain technologies. Furthermore, the manufacturing and disposal of electronic devices generate e-waste and deplete natural resources	Data centers are believed to account for approximately 1% of global energy consumption, which is expected to increase (Kamiya and Bertoldi, 2024)	Although ICT contributes to mitigating climate change, its environmental impact must be carefully managed
2. Digital divide		
Unequal access to ICT tools and infrastructure leaves many underserved populations without the benefits of technology	Rural areas and low-income countries frequently lack access to tools such as SMS-based disaster alert systems or satellite-driven climate monitoring technologies. For example, during the catastrophic floods of 2022, communities lacking access to real-time digital alerts were caught off guard, resulting in preventable tragedies. Families were displaced from their homes, children were forced out of schools, and entire communities suffered significant economic losses, making recovery an overwhelming challenge (Cooper, 2023). A 2021 report by the World Bank revealed that only 10% of rural areas in developing countries have access to dependable ICT infrastructure, in contrast to 80% in urban areas (World Bank, 2021)	Increased vulnerability to climate-related disasters and prolonged recovery times in underserved areas
3. Implementation costs		
Developing and implementing advanced ICT solutions for climate change can be costly, limiting their implementation in low-income regions	The significant expenses associated with implementing IoT sensors or AI-based climate models	Demands financial frameworks and global cooperation to guarantee fair implementation

climate change impacts. Notably, the high energy consumption in urban areas underscores the importance of ICTs in mitigating climate challenges. Energy efficiency in cities is central to the smart city concept and the Internet of Things, leveraging data and interconnected devices via ICT infrastructure (Silva et al., 2018). However, these benefits are counterbalanced by challenges like energy consumption (Kamiya and Bertoldi, 2024), the digital divide (Cooper, 2023), and implementation costs (Freitag et al., 2021). To fully harness the potential of ICTs, efforts should prioritize minimizing its environmental footprint, closing accessibility gaps, and incorporating traditional and community-driven methods. By overcoming these challenges, ICTs can be a more powerful tool in the global effort to combat climate change.

6 Conclusions and perspectives

In recent years, the clear impacts of climate change have been observed through extreme weather conditions, posing threats to public health, infrastructure, and water resources. Nevertheless, integrating Information and Communication Technologies (ICTs) with robust legal frameworks can catalyze the essential changes needed to address global climate challenges. Our literature review has corroborated this, highlighting the pivotal role of ICTs in enabling earth observations and facilitating the exchange of information crucial for decision-making, early warnings, climate tracking, predicting climate changes, managing disasters, and implementing other measures for climate mitigation and adaptation. Consequently, it is recommended that the global community implement specific measures, including ICTs, to tackle climate change and fulfill the Sustainable Development Goals effectively.

Regarding environmental pollution, it is mentioned that ICTs can contribute to reducing at least 20% of global GHG emissions by 2030 from different sectors of the economy (GeSI, 2015). For this, it is recommended that the international community use ICTs in a coordinated, intelligent way to increase productivity and save time and money while reducing the carbon footprint. In other words, using ICTs in a coordinated and intelligent way would require seamless integration of data, collaboration between governments, organizations, and the private sector, standardization of systems, and leveraging cutting-edge technologies such as artificial intelligence, machine learning, and cloud computing. Making this vision possible would involve multilateral cooperation, capacity building in developing countries, and a commitment to secure, open, and sustainable technological deployment.

Concerning ICTs in agriculture (smart agriculture), the digital revolution could drastically transform the face of farms in the coming years. Automation of agricultural activities reduces environmental impact, and production costs and improves animal welfare and food quality.

In the same way, implementing smart cities and energy not only reduces environmental impact and energy consumption but also improves the quality of life and education of residents/populations.

Telecommuting is also shown as a socially, economically, and environmentally beneficial practice for the future because it allows flexible work schedules and consequently improves work performance and reduces stress.

In summary, the evidence shows that ICTs are effective tools for monitoring climate change and provide an alternative to reduce GHG emissions from different sectors in the coming years. Furthermore, it has been proven that ICTs can increase productivity and reduce costs.

Author contributions

FE-T: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. JZ: Writing – review & editing. FB: Software, Writing – review & editing. MR: Methodology, Writing – review & editing. JP: Conceptualization, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

We thank the reviewers for their valuable comments which have allowed us to improve the quality of the article. Additionally, with the help of ChatGPT (Mar 14 version) (large language model), we enhance the quality of some figures and the syntax in the text.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer N-BM declared a shared affiliation with the authors to the handling editor at the time of review.

Publisher's note

References

Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., and Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environ. Sci. Pollut. Res.* 29, 42539–42559. doi: 10.1007/s11356-022-19718-6

Adams, T. III (2016). "Flood forecasting in the United States NOAA/National Weather Service" in Flood forecasting: a global perspective (London: Elsevier), 249–310.

Ahjum, F. (2020). SADC e-mobility outlook: accelerating low carbon transport futures. Johannesburg: South African Institute of International Affairs.

Ahmad, T., and Zhang, D. (2021). Using the Internet of Things in smart energy systems and networks. *Sustain. Cities Soc.* 68:102783. doi: 10.1016/j.scs.2021.102783

Ajwang, S. O., and Nambiro, A. W. (2022). Climate change adaptation and mitigation using information and communication technology. *Int. J. Comput. Sci. Res.* 6, 1046–1063. doi: 10.25147/ijcsr.2017.001.1.101

Al Dakheel, J., Del Pero, C., Aste, N., and Leonforte, F. (2020). Smart buildings features and key performance indicators: a review. *Sustain. Cities Soc.* 61:102328. doi: 10.1016/j.scs.2020.102328

Alam, T. (2021). Cloud-based IoT applications and their roles in smart cities. *Smart Cities* 4, 1196–1219. doi: 10.3390/smartcities4030064

Aldegheishem, A. (2019). Success factors of smart cities: a systematic review of literature from 2000–2018. *J. Land Use Mobil. Environ.* 12, 53–64. doi: 10.6092/1970-9870/5893

Alemi, F., Circella, G., Mokhtarian, P., and Handy, S. (2018). Exploring the latent constructs behind the use of ridehailing in California. *J. Choice Model.* 29, 47–62. doi: 10.1016/j.jocm.2018.08.003

Andersson, D. (2020). A novel approach to calculate individuals' carbon footprints using financial transaction data—app development and design. *J. Clean. Prod.* 256:120396. doi: 10.1016/j.jclepro.2020.120396

Arnfalk, P., Chudnikova, V., and Löfgren, M. (2020). DigiNord: virtual meetings and climate smart collaboration in the nordic countries. Examples of good practice and promotion. Borlänge: Swedish Transport Administration.

Attaran, H., Kheibari, N., and Bahrepour, D. (2022). Toward integrated smart city: a new model for implementation and design challenges. *GeoJournal* 87, 511–526. doi: 10.1007/s10708-021-10560-w

Baena, S., Boyd, D. S., and Moat, J. (2018). UAVs in pursuit of plant conservation—real world experiences. *Eco. Inform.* 47, 2–9. doi: 10.1016/j.ecoinf.2017.11.001

Bala Murugan, M. S., Rajagopal, M. K., and Roy, D. (2021). IoT based smart agriculture and plant disease prediction. *J. Phys.: Conf. Ser.* 2115:012017. doi: 10.1088/1742-6596/2115/1/012017

Ballantyne, A. G., Wibeck, V., and Neset, T.-S. (2016). Images of climate change—a pilot study of young people's perceptions of ICT-based climate visualization. *Clim. Change* 134, 73–85. doi: 10.1007/s10584-015-1533-9

Balogun, A.-L., Marks, D., Sharma, R., Shekhar, H., Balmes, C., Maheng, D., et al. (2020). Assessing the potentials of digitalization as a tool for climate change adaptation and sustainable development in urban centres. *Sustain. Cities Soc.* 53:101888. doi: 10.1016/j.scs.2019.101888

Barendregt, W., Biørn-Hansen, A., and Andersson, D. (2020). Users' experiences with the use of transaction data to estimate consumption-based emissions in a carbon calculator. *Sustainability* 12:7777. doi: 10.3390/su12187777

Barreto-Álvarez, D. E., Heredia-Rengifo, M. G., Padilla-Almeida, O., and Toulkeridis, T. (2020). Multitemporal evaluation of the recent land use change in Santa Cruz Island, Galapagos, Ecuador. Conference on Information and Communication Technologies of Ecuador. 519–534

Barrett, M. (2001). K Daniels, DA Lamond and P Standen managing telework: perspectives from human resource management and work psychology business press (Thomson learning). *J. Austral. N. Z. Acad. Manage.* 7:63. doi: 10.5172/jmo.2001.7.1.63a

Bastida, L., Cohen, J. J., Kollmann, A., Moya, A., and Reichl, J. (2019). Exploring the role of ICT on household behavioural energy efficiency to mitigate global warming. *Renew. Sustain. Energy Rev.* 103, 455–462. doi: 10.1016/j.rser.2019.01.004

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., and Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecol. Lett.* 15, 365–377. doi: 10.1111/j.1461-0248.2011.01736.x

Bellavia, F., Fanfani, M., and Colombo, C. (2017). Selective visual odometry for accurate AUV localization. *Auton. Robot.* 41, 133–143. doi: 10.1007/s10514-015-9541-1

Bhimanpallewar, R. N., and Narasingarao, M. R. (2020). AgriRobot: implementation and evaluation of an automatic robot for seeding and fertiliser microdosing in precision agriculture. *Int. J. Agric. Resour. Gov. Ecol.* 16, 33–50. doi: 10.1504/IJARGE.2020.107064

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nat. Commun.* 8:2013. doi: 10.1038/s41467-017-02142-7

Braun, A.-T., Colangelo, E., and Steckel, T. (2018). Farming in the era of Industrie 4.0. *Procedia CIRP* 72, 979–984. doi: 10.1016/j.procir.2018.03.176

Brlek, P., Cvitković, I., and Globočnik-Žunac, A. (2019). Costs and benefits of deploying cooperative intelligent transport systems in the European Union. ZIRP 2019: Next Generation Transport Industry Innovations

Camilloni, I. A. (2018). Argentina and climate change. *Argent. Assoc. Adv. Sci.* 68, 5–10.

Canaza-Choque, F. A. (2019). De la educación ambiental al desarrollo sostenible: desafíos y tensiones en los tiempos del cambio climático. *Rev. Cienc. Soc.* 165, 155–172. doi: 10.15517/rcs.v0i165.40070

Canton, H. (2021). “Food and Agriculture Organization of the United Nations—FAO” in The Europa directory of international organizations 2021 (London: Routledge), 297–305.

Caon, L., and Vargas, R. (2017). “Threats to soils: global trends and perspectives. Global soil partnership Food and Agriculture Organization of the United Nations” in A contribution from the intergovernmental technical panel on soils. Global land outlook working paper.

Carter, J., Schmid, K., Waters, K., Betzhold, L., Hadley, B., Mataosky, R., et al. (2012). An introduction to lidar technology, data, and applications. Charleston, SC: NOAA Coastal Services Center.

Castrén, T., and Pillai, M. (2017). Using ICT to improve forest governance. *ICT Agric.* 2017, 371–400. doi: 10.1596/978-1-4648-1002-2_Module14

Castro Miranda, S. L., Del Rey Castillo, E., Gonzalez, V., and Adafin, J. (2022). Predictive analytics for early-stage construction costs estimation. *Buildings* 12:1043. doi: 10.3390/buildings12071043

Cayambe, J., Torres, B., Cabrera, F., Díaz-Ambrona, C. G., Toulkeridis, T., and Heredia-R, M. (2023). Changes of land use and land cover in hotspots within the Western Amazon: the case of the Yasuní biosphere reserve. I + D for Smart Cities and Industry. RITAM 2021

Ceglia, F., Marrasso, E., Pallotta, G., Roselli, C., and Sasso, M. (2022). The state of the art of smart energy communities: a systematic review of strengths and limits. *Energies* 15:3462. doi: 10.3390/en15093462

Cheng, Y. L., Lim, M. H., and Hui, K. H. (2022). Impact of Internet of Things paradigm towards energy consumption prediction: a systematic literature review. *Sustain. Cities Soc.* 78:103624. doi: 10.1016/j.scs.2021.103624

Chipperfield, M. P., Dhomse, S. S., Feng, W., McKenzie, R., Velders, G. J., and Pyle, J. A. (2015). Quantifying the ozone and ultraviolet benefits already achieved by the Montreal protocol. *Nat. Commun.* 6:7233. doi: 10.1038/ncomms8233

Choudhry, H., and O’Kelly, G. (2018). Precision forestry: a revolution in the woods. Chicago, IL: McKinsey & Company.

Clayton, S. (2020). Climate anxiety: psychological responses to climate change. *J. Anxiety Disord.* 74:102263. doi: 10.1016/j.janxdis.2020.102263

Climate Adaptation Platform. (2024). Electrified roads can help boost EV uptake. Available at: https://climateadaptationplatform.com/electrified-roads-can-help-boost-ev-uptake/ (Accessed February 6, 2025).

Contreras, G., and Platania, F. (2019). Economic and policy uncertainty in climate change mitigation: the London Smart City case scenario. *Technol. Forecast. Soc. Change* 142, 384–393. doi: 10.1016/j.techfore.2018.07.018

Cooper, L. (2023). How the digital divide worsens the human impacts of climate change. Available at: https://www.human-i-t.org/digital-divide-climate-change/?srsltid=AfmBOopaFujzYzSbdJFHVWxMKvWR1i_I5yU6gSIQoeiViNrTwMTR59Ny

Criscuolo, C., Gal, P., Leidecker, T., Losma, F., and Nicoletti, G. (2021). “The role of telework for productivity during and post-COVID-19: results from an OECD survey among managers and workers” in OECD Productivity Working Papers (Paris: OECD Publishing).

Crossman, N. D. (2018). Drought resilience, adaptation and management policy (DRAMP) framework. Bonn: UNCCD, 20.

de Jong, C. (2013). Linking ICT and society in early warning and adaptation to hydrological extremes in mountains. *Nat. Hazards Earth Syst. Sci.* 13, 2253–2270. doi: 10.5194/nhess-13-2253-2013

Deamer, L. (2018). The economics of smart security cameras. Available at: https://www.electronicspecifier.com/products/cyber-security/the-economics-of-smart-security-cameras (Accessed February 6, 2025).

Delina, L. L. (2020). ICTs for delivering climate-development strategies: an informational governance framework for local climate-development organizations. *Clim. Dev.* 12, 626–635. doi: 10.1080/17565529.2019.1671784

Dosio, A., Mentaschi, L., Fischer, E. M., and Wyser, K. (2018). Extreme heat waves under 1.5°C and 2°C global warming. *Environ. Res. Lett.* 13:054006. doi: 10.1088/1748-9326/aab827

Dunbabin, M. D., and Allen, S. S. (2007). Large-scale habitat mapping using vision-based AUVs: experiences, challenges & vehicle design. OCEANS 2007-Europe

Dunbabin, M., Roberts, J., Usher, K., Winstanley, G., and Corke, P. (2005). A hybrid AUV design for shallow water reef navigation. Proceedings of the 2005 IEEE International Conference on Robotics and Automation

Džupka, P., and Horvath, M. (2021). “Urban smart-mobility projects evaluation: a literature review” in Theoretical and empirical researches in urban management (Bucharest: Research Centre in Public Administration and Public Services), 55–76.

Egorova, T., Rozanov, E., Gröbner, J., Hauser, M., and Schmutz, W. (2013). Montreal protocol benefits simulated with CCM SOCOL. *Atmos. Chem. Phys.* 13, 3811–3823. doi: 10.5194/acp-13-3811-2013

El-Bawab, T. S. (2021). Network engineering versus climate change. *IEEE Commun. Mag.* 59, 6–7. doi: 10.1109/MCOM.2021.9422338

Falkenberg, L. J., Bellerby, R. G. J., Connell, S. D., Fleming, L. E., Maycock, B., Russell, B. D., et al. (2020). Ocean acidification and human health. *Int. J. Environ. Res. Public Health* 17:4563. doi: 10.3390/ijerph17124563

Fanti, M. P., Pedroncelli, G., Roccotelli, M., Mininel, S., Stecco, G., and Ukovich, W. (2017). Actors interactions and needs in the European electromobility network. 2017 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI)

FAO (2017). E-agriculture in action. Rome: Food and Agriculture Organization of the United Nations and International Telecommunication Union, 372.

Farinotti, D., Immerzeel, W. W., de Kok, R. J., Quincey, D. J., and Dehecq, A. (2020). Manifestations and mechanisms of the Karakoram glacier anomaly. *Nat. Geosci.* 13, 8–16. doi: 10.1038/s41561-019-0513-5

FitzGerald, D. M., and Hughes, Z. (2019). Marsh processes and their response to climate change and sea-level rise. *Annu. Rev. Earth Planet. Sci.* 47, 481–517. doi: 10.1146/annurev-earth-082517-010255

Food and Agriculture Organization of the United Nations and International Telecommunication Union (2022). Status of digital agriculture in 47 sub-Saharan African countries. Rome: Food and Agriculture Organization of the United Nations and International Telecommunication Union.

Frank, S. M., Lin, G., Jin, X., Singla, R., Farthing, A., Zhang, L., et al. (2019). Metrics and methods to assess building fault detection and diagnosis tools. NREL/TP-5500-72801. Golden, CO: National Renewable Energy Laboratory.

Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G. S., and Friday, A. (2021). The real climate and transformative impact of ICT: a critique of estimates, trends, and regulations. *Patterns* 2:100340. doi: 10.1016/j.patter.2021.100340

Froufe, M. M., Chinelli, C. K., Guedes, A. L. A., Haddad, A. N., Hammad, A. W. A., and Soares, C. A. P. (2020). Smart buildings: systems and drivers. *Buildings* 10:153. doi: 10.3390/buildings10090153

Fu, H., Shi, Y., and Zeng, Y. (2021). Estimating smart grid’s carbon emission reduction potential in China’s manufacturing industry based on decomposition analysis. *Front. Energy Res.* 9:681244. doi: 10.3389/fenrg.2021.681244

Gangopadhyay, P. K., Khatri-Chhetri, A., Shirsath, P. B., and Aggarwal, P. K. (2019). Spatial targeting of ICT-based weather and agro-advisory services for climate risk management in agriculture. *Clim. Change* 154, 241–256. doi: 10.1007/s10584-019-02426-5

García-Álvarez, D., Camacho Olmedo, M. T., Paegelow, M., and Mas, J. F. (2022). Land use cover datasets and validation tools: validation practices with QGIS. Cham: Springer.

Gärdborn, Q. L., and Xia, Z. (2018). Information and communication technology solutions role in climate change adaptation. KTH, Stockholm, Sweden.

Gardner, C., Goethel, D. R., Karnauskas, M., Smith, M. W., Perruso, L., and Walter, J. F. (2022). Artificial attraction: linking vessel monitoring system and habitat data to assess commercial exploitation on artificial structures in the Gulf of Mexico. *Front. Mar. Sci.* 9:772992. doi: 10.3389/fmars.2022.772292

Garza, J. C. G., and Hidalgo, Y. G. (2017). Las tecnologías de la información y las comunicaciones y el cambio climático. *Ojeando la Agenda* 47:5.

Gattuso, J.-P., and Hansson, L. (2011). Ocean acidification. Oxford: Oxford University Press.

Gerden, T. (2018). The adoption of the Kyoto protocol of the United Nations framework convention on climate change. *Contrib. Contemp. Hist.* 58, 160–189. doi: 10.51663/pnz.58.2.07

Gerritsen, H. D. (2023). Methods to get more information from sparse vessel monitoring systems data. *Front. Mar. Sci.* 10:1223134. doi: 10.3389/fmars.2023.1223134

GeSI (2015). SMARTer2030-ICT solutions for 21st century challenges. Executive summary. Brussels: Global e-Sustainability Initiative (GeSI).

Glick, D. (2004). The big thaw. *Natl. Geogr.* 206, 12–31.

Goyal, R., England, M. H., Gupta, A. S., and Jucker, M. (2019). Reduction in surface climate change achieved by the 1987 Montreal protocol. *Environ. Res. Lett.* 14:124041. doi: 10.1088/1748-9326/ab4874

Green, K. C., and Alila, Y. (2012). A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments. *Water Resour. Res.* 48:W10503. doi: 10.1029/2012WR012449

Griggs, G., and Reguero, B. G. (2021). Coastal adaptation to climate change and sea-level rise. *Water* 13:2151. doi: 10.3390/w13162151

Guo, Q., Wang, Y., and Dong, X. (2022). Effects of smart city construction on energy saving and CO_2 emission reduction: evidence from China. *Appl. Energy* 313:118879. doi: 10.1016/j.apenergy.2022.118879

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B. L., Doelman, J. C., et al. (2018). Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Change* 8, 699–703. doi: 10.1038/s41558-018-0230-x

Hayat, P. (2016). Smart cities: a global perspective. *India Q.* 72, 177–191. doi: 10.1177/0974928416637930

Heredia-R, M., Cayambe, J., Schorsch, C., Toulkeridis, T., Barreto, D., Poma, P., et al. (2021a). Multitemporal analysis as a non-invasive technology indicates a rapid change in land use in the Amazon: the case of the ITT oil block. *Environments* 8:139. doi: 10.3390/environments8120139

Heredia-R, M., Torres, B., Cabrera-Torres, F., Torres, E., Díaz-Ambrona, C. G. H., and Pappalardo, S. E. (2021b). Land use and land cover changes in the diversity and life zone for uncontacted indigenous people: deforestation hotspots in the Yasuní biosphere reserve, Ecuadorian Amazon. *Forests* 12:1539. doi: 10.3390/f12111539

Heredia-R, M., Torres, B., Cabrera-Torres, F., Vasco, E., Díaz-Ambrona, C. G., and Toulkeridis, T. (2022). Free data processing applied to detect changes in land use coverage at biodiversity hotspots of the Amazon. Doctoral Symposium on Information and Communication Technologies-DSICT

Himeur, Y., Elnour, M., Fadli, F., Meskin, N., Petri, I., Rezgui, Y., et al. (2022). AI-big data analytics for building automation and management systems: a survey, actual challenges and future perspectives. *Artif. Intell. Rev.* 56, 4929–5021. doi: 10.1007/s10462-022-10286-2

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., et al. (2019). "High mountain areas" in IPCC special report on the ocean and cryosphere in a changing climate. eds. H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K., et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 131–202.

Hoegh-Guldberg, O., Jacob, D., Bindi, M., Brown, S., Camilloni, I., and Diedhiou, A. (2018). "Impacts of 1.5ºC global warming on natural and human systems" in Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. eds. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A., et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 175–135.

Hoy, M. B. (2016). Smart buildings: An introduction to the library of the future. *Med. Ref. Serv. Q.* 35, 326–331. doi: 10.1080/02763869.2016.1189787

Hsu, F.-C., Elvidge, C. D., Baugh, K., Zhizhin, M., Ghosh, T., Kroodsma, D., et al. (2019). Cross-matching VIIRS boat detections with vessel monitoring system tracks in Indonesia. *Remote Sens.* 11:995. doi: 10.3390/rs11090995

Hunter, G. W., Vettorato, D., and Sagoe, G. (2018). Creating smart energy cities for sustainability through project implementation: a case study of Bolzano, Italy. *Sustainability* 10:2167. doi: 10.3390/su10072167

Hussain, M., Arsalan, M. H., Siddiqi, K., Naseem, B., and Rabab, U.. (2005). Emerging geo-information technologies (GIT) for natural disaster management in Pakistan: an overview. Proceedings of 2nd International Conference on Recent Advances in Space Technologies

Hussain, M., Butt, A. R., Uzma, F., Ahmed, R., Irshad, S., Rehman, A., et al. (2019). A comprehensive review of climate change impacts, adaptation, and mitigation on environmental and natural calamities in Pakistan. *Environ. Monit. Assess.* 192:48. doi: 10.1007/s10661-019-7956-4

Ibárcena, M., and Scheelje, J. (2003). El cambio climático principales causantes, consecuencias y compromisos de los países involucrados. Quebec, Canada: Food and Agriculture Organization of the United Nations.

International Energy Agency (2009). Transport Energy and CO_2: moving towards sustainability. Paris: International Energy Agency.

Islam, S. N., Marwaha, S., Deb, C. K., and Haque, M. A. (2024). "Role of ICT and artificial intelligence in disease diagnosis, forecast, and management" in Diseases of Field crops: Diagnostics and management. eds. V. K. Singh, J. Akhtar and K. P. Singh (Singapore: Springer), 399–418.

Islam, N., and Winkel, J. (2017). Climate change and social inequality. New York, NY: United Nations, Department of Economics and Social Affairs.

Ji, J., and Li, Y. (2021). The development of China's fishery informatization and its impact on fishery economic efficiency. *Mar. Policy* 133:104711. doi: 10.1016/j.marpol.2021.104711

JLL/Technologies. (2022). Intelligent buildings, smart business. Available at: https://www.jllt.com/intelligent-buildings-smart-business/

Jones, M. W., Veraverbeke, S., Andela, N., Doerr, S. H., Kolden, C., Mataveli, G., et al. (2024). Global rise in forest fire emissions linked to climate change in the extratropics. *Science* 386:eadl5889. doi: 10.1126/science.adl5889

Kaluarachchi, Y. (2022). Implementing data-driven smart city applications for future cities. *Smart Cities* 5, 455–474. doi: 10.3390/smartcities5020025

Kamal, S. A. (2022). The effects of global warming: the case study of Karachi's heat waves & its implication. *Int. J. Policy Stud.* 2. Available at: https://www.ijpstudies.com/index.php/ijps/article/view/22

Kamilaris, A., Gao, F., Prenafeta-Boldu, F. X., and Ali, M. I. (2016). Agri-IoT: a semantic framework for Internet of Things-enabled smart farming applications. 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT)

Kamiya, G., and Bertoldi, P. (2024). Energy consumption in data centres and broadband communication networks in the EU. Luxembourg: Publications Office of the European Union.

Karimi, R., Farahzadi, L., Sepasgozar, S., Sargolzaei, S., Sepasgozar, S. M. E., Zareian, M., et al. (2021). Advances and technologies in building construction and structural analysis. London: IntechOpen.

Kelly, T., and Adolph, M. (2008). ITU-T initiatives on climate change. *IEEE Commun. Mag.* 46, 108–114. doi: 10.1109/MCOM.2008.4644127

Kim, S., and Baek, J. S. (2019). Definitions and attributes of smart home appliances. Proceedings of the Design Society International Conference on Engineering

Kimbahune, S., Singh, V. V., Pande, A., Singh, D., and Chandel, P. A. (2013). ICT for fisheries—environment friendly way: pilot experience in Raigadh. 2013 Annual IEEE India Conference (INDICON)

Koliouska, C., and Andreopoulou, Z. (2020). A multicriteria approach for assessing the impact of ICT on EU sustainable regional policy. *Sustainability* 12:4869. doi: 10.3390/su12124869

Kramers, A., Höjer, M., Lövehagen, N., and Wangel, J. (2014). Smart sustainable cities—exploring ICT solutions for reduced energy use in cities. *Environ. Model Softw.* 56, 52–62. doi: 10.1016/j.envsoft.2013.12.019

Krasilnikova, N., and Levin-Keitel, M. (2022). Telework as a game-changer for sustainability? Transitions in work, workplace and socio-spatial arrangements. *Sustainability* 14:6765. doi: 10.3390/su14116765

Lai, C. S., Jia, Y., Dong, Z., Wang, D., Tao, Y., Lai, Q. H., et al. (2020). A review of technical standards for smart cities. *Clean Technol.* 2, 290–310. doi: 10.3390/cleantechnol2030019

Larour, E., Ivins, E. R., and Adhikari, S. (2017). Should coastal planners have concern over where land ice is melting? *Sci. Adv.* 3:e1700537. doi: 10.1126/sciadv.1700537

Lee, W.-J., and Mwebaza, R. (2022). Digitalization to achieve technology innovation in climate technology transfer. *Sustainability* 14:63. doi: 10.3390/su14010063

Lee, J., South, A. B., and Jennings, S. (2010). Developing reliable, repeatable, and accessible methods to provide high-resolution estimates of fishing-effort distributions from vessel monitoring system (VMS) data. *ICES J. Mar. Sci.* 67, 1260–1271. doi: 10.1093/icesjms/fsq010

Leggett, J. A. (2020). The United Nations framework convention on climate change, the Kyoto protocol, and the Paris agreement: a summary. New York: UNFCC, 2.

Lehikoinen, P., Santangeli, A., Jaatinen, K., Rajasärkkä, A., and Lehikoinen, A. (2019). Protected areas act as a buffer against detrimental effects of climate change—evidence from large-scale, long-term abundance data. *Glob. Change Biol.* 25, 304–313. doi: 10.1111/gcb.14461

Leichenko, R., and Silva, J. A. (2014). Climate change and poverty: vulnerability, impacts, and alleviation strategies. *Wiley Interdiscip. Rev. Clim. Change* 5, 539–556. doi: 10.1002/wcc.287

Li, Y., Brando, P. M., Morton, D. C., Lawrence, D. M., Yang, H., and Randerson, J. T. (2022). Deforestation-induced climate change reduces carbon storage in remaining tropical forests. *Nat. Commun.* 13:1964. doi: 10.1038/s41467-022-29601-0

Lim, C., and Maglio, P. P. (2018). Data-driven understanding of smart service systems through text mining. *Serv. Sci.* 10, 154–180. doi: 10.1287/serv.2018.0208

Limbo, A., Suresh, N., Ndakolute, S.-S., Hashiyana, V., Haiduwa, T., and Ujakpa, M. M. (2021). "Smart irrigation system for crop farmers in Namibia" in Transforming the Internet of Things for next-generation smart systems (Hershey, PA: IGI Global), 120–131.

Lipczynska-Kochany, E. (2018). Effect of climate change on humic substances and associated impacts on the quality of surface water and groundwater: A review. *Sci. Total Environ.* 640-641, 1548–1565. doi: 10.1016/j.scitotenv.2018.05.376

Liu, P., Ross, R., and Newman, A. (2015). Long-range, low-cost electric vehicles enabled by robust energy storage. *MRS Energy Sustain.* 2:12. doi: 10.1557/mre.2015.13

Lynch, J., Cain, M., Frame, D., and Pierrehumbert, R. (2021). Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO_2-emitting sectors. *Front. Sustain. Food Systems* 4:518039. doi: 10.3389/fsufs.2020.518039

Maertens, L. (2018). Depoliticisation as a securitising move: the case of the United Nations Environment Programme. *Eur. J. Int. Secur.* 3, 344–363. doi: 10.1017/eis.2018.5

Majeed, M. T. (2018). Information and communication technology (ICT) and environmental sustainability in developed and developing countries. *Pak. J. Commer. Soc. Sci.* 12, 758–783. Available at: https://www.econstor.eu/bitstream/10419/193446/1/4314.pdf

Maldonado, J. K., Shearer, C., Bronen, R., Peterson, K., and Lazrus, H. (2013). "The impact of climate change on tribal communities in the US: displacement, relocation, and human rights" in Climate change and indigenous peoples in the United States (Cham: Springer), 93–106.

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M. G., Field, C. B., et al. (2020). Climate change and ecosystems: threats, opportunities and solutions. *Phil. Trans. R. Soc. B* 375:20190104. doi: 10.1098/rstb.2019.0104

Malmodin, J., and Bergmark, P. (2015). Exploring the effect of ICT solutions on GHG emissions in 2030. Proceedings of EnviroInfo and ICT for Sustainability 2015

Manhertz, T., and Lee, A. (2022). Renters at the tipping point of homeownership. *Cityscape* 24, 259–286.

Mantyka-pringle, C. S., Martin, T. G., and Rhodes, J. R. (2012). Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. *Glob. Change Biol.* 18, 1239–1252. doi: 10.1111/j.1365-2486.2011.02593.x

Maraseni, T., An-Vo, D.-A., Mushtaq, S., and Reardon-Smith, K. (2021). Carbon smart agriculture: An integrated regional approach offers significant potential to increase profit and resource use efficiency, and reduce emissions. *J. Clean. Prod.* 282:124555. doi: 10.1016/j.jclepro.2020.124555

Marquardt, K. (2017). Smart services-characteristics, challenges, opportunities and business models. Proceedings of the International Conference on Business Excellence. 789–801

Mat, I., Kassim, M. R. M., Harun, A. N., and Yusoff, I. M. (2018). Smart agriculture using Internet of Things. 2018 IEEE Conference on Open Systems (ICOS)

Mäyrä, O., Ruusunen, M., Jalli, M., Jauhiainen, L., and Leiviskä, K. (2018). Plant disease outbreak-prediction by advanced data analysis. *Simul. Notes Eur.* 28, 113–115. doi: 10.11128/sne.28.sn.10431

McCarthy, H. (2022). Flexible workers: the politics of homework in postindustrial Britain. *J. Br. Stud.* 61, 1–25. doi: 10.1017/jbr.2021.126

McCormick, N., and Salamon, P. (2023). Copernicus emergency management service. Available at: https://extwiki.eodc.eu/gfm_assets/gfm_pum_v20231005_compressed.pdf

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., et al. (2019). "Polar regions" in IPCC special report on the ocean and cryosphere in a changing climate.

Mickoleit, A. (2010). Greener and smarter. Paris: OECD Publishing.

Milasi, S., González-Vázquez, I., and Fernández-Macías, E. (2021). Telework before the COVID-19 pandemic: trends and drivers of differences across the EU. Paris: OECD Publishing.

Molina, J., and Balsas, J. M. M. (2018). Gobierno abierto, transparencia y ética pública. *Revista internacional de transparencia e integridad* 8:8.

Moltmann, T., Turton, J., Zhang, H.-M., Nolan, G., Gouldman, C., Griesbauer, L., et al. (2019). A global ocean observing system (GOOS), delivered through enhanced collaboration across regions, communities, and new technologies. *Front. Mar. Sci.* 6:291. doi: 10.3389/fmars.2019.00291

Morgan, T. (2012). Smart grids and electric vehicles: Made for each other?. doi: 10.1787/5K8ZVV8G70Q5-EN

Morgenstern, O., Braesicke, P., Hurwitz, M. M., O'Connor, F. M., Bushell, A. C., Johnson, C. E., et al. (2008). The world avoided by the Montreal protocol. *Geophys. Res. Lett.* 35:L16811. doi: 10.1029/2008GL034590

Moura, F., and de Abreu e Silva, J. (2019). "Smart cities: definitions, evolution of the concept and examples of initiatives" in Industry, innovation and infrastructure. eds. W. Leal Filho, A. M. Azul, L. Brandli, P. G. Özuyar and T. Wall (Cham: Springer), 1–9.

Munang, R., Nkem, J. N., and Han, Z. (2013). Using data digitalization to inform climate change adaptation policy: informing the future using the present. *Weather Clim. Extrem.* 1, 17–18. doi: 10.1016/j.wace.2013.07.001

Murshed, M. (2022). Pathways to clean cooking fuel transition in low and middle income sub-Saharan African countries: the relevance of improving energy use efficiency. *Sustain. Prod. Consum.* 30, 396–412. doi: 10.1016/j.spc.2021.12.016

Murshed, M., and Dao, N. T. T. (2022). Revisiting the CO_2 emission-induced EKC hypothesis in South Asia: the role of export quality improvement. *GeoJournal* 87, 535–563. doi: 10.1007/s10708-020-10270-9

Murshed, M., Nurmakhanova, M., Elheddad, M., and Ahmed, R. (2020). Value addition in the services sector and its heterogeneous impacts on CO2 emissions: revisiting the EKC hypothesis for the OPEC using panel spatial estimation techniques. *Environ. Sci. Pollut. Res.* 27, 38951–38973. doi: 10.1007/s11356-020-09593-4

Nijkamp, P., and Kourtit, K. (2013). The "new urban Europe": global challenges and local responses in the urban century. *Eur. Plan. Stud.* 21, 291–315. doi: 10.1080/09654313.2012.716243

Nordhaus, W. (2019). Climate change: the ultimate challenge for economics. *Am. Econ. Rev.* 109, 1991–2014. doi: 10.1257/aer.109.6.1991

Norris, J., and Bland, J. (2015). Precision agriculture: almost 20% increase in income possible from smart farming. *Nesta*. Available at: https://www.nesta.org.uk/blog/precision-agriculture-almost-20-increase-in-income-possible-from-smart-farming/

Obringer, R., and Nateghi, R. (2021). What makes a city 'smart' in the Anthropocene? A critical review of smart cities under climate change. *Sustain. Cities Soc.* 75:103278. doi: 10.1016/j.scs.2021.103278

Obringer, R., Rachunok, B., Maia-Silva, D., Arbabzadeh, M., Nateghi, R., and Madani, K. (2021). The overlooked environmental footprint of increasing internet use. *Resour. Conserv. Recycl.* 167:105389. doi: 10.1016/j.resconrec.2020.105389

OECD (2019). How's life in the digital age?: Opportunities and risks of the digital transformation for People's well-being. Paris: OECD Publishing.

OECD (2020). Productivity gains from teleworking in the post COVID-19 era: How can public policies make it happen? Paris: OECD Publishing.

OECD (2021). Teleworking in the COVID-19 pandemic: trends and prospects. Paris: OECD Publishing.

Okezie, O. (2021). Impacts of environmental change on assembled climate. *Am. J. Interdiscip. Innovat. Res.* 3, 15–20. doi: 10.37547/tajiir/Volume03Issue10-03

Oliver, T. H., and Morecroft, M. D. (2014). Interactions between climate change and land use change on biodiversity: attribution problems, risks, and opportunities. *Wiley Interdiscip. Rev. Clim. Change* 5, 317–335. doi: 10.1002/wcc.271

Olusanya, G. S., Eze, M. O., Ebiesuwa, O., and Okunbor, C. (2020). Smart transportation system for solving urban traffic congestion. *Rev. Comput. Eng. Stud.* 7, 55–59. doi: 10.18280/rces.070302

Ordóñez Ríos, M., Robles Bykbaev, V., Ortiz Segarra, J., Palacios Espinoza, E., Pino Andrade, R., Reinoso Naranjo, J., et al. (2017). TIC y sistemas inteligentes: como herramientas de soporte para el manejo, educación y prevención del trauma. Universidad Politécnica Salesiana, Av.

Orlowski, A., and Romanowska, P. (2019). Smart cities concept: smart mobility Indicator. *Cybern. Syst.* 50, 118–131. doi: 10.1080/01969722.2019.1565120

Oviedo, A., and Bursztyn, M. (2017). Community-based monitoring of small-scale fisheries with digital devices in Brazilian Amazon. *Fish. Manag. Ecol.* 24, 320–329. doi: 10.1111/fme.12231

Padilla-Gamiño, J. L., Alma, L., Spencer, L. H., Venkataraman, Y. R., and Wessler, L. (2022). Ocean acidification does not overlook sex: review of understudied effects and implications of low pH on marine invertebrate sexual reproduction. *Front. Mar. Sci.* 9:977754. doi: 10.3389/fmars.2022.977754

Palomo, S. T. (2021a). Aplicación de las TIC en el desarrollo de las ciudades inteligentes sostenibles. *ESIC Market Econ. Bus. J.* 52, 217–246.

Palomo, S. T. (2021b). Application of ICTs in the development of sustainable smart cities. *ESIC Market Econ. Bus. J.* 52, 187–216. doi: 10.7200/esicm.168.0521.4

Pandey, P. C., Koutsias, N., Petropoulos, G. P., Srivastava, P. K., and Ben Dor, E. (2021). Land use/land cover in view of earth observation: data sources, input dimensions, and classifiers—a review of the state of the art. *Geocarto Int.* 36, 957–988. doi: 10.1080/10106049.2019.1629647

Parashar, A. K., and Parashar, R. (2012). Construction of an eco-friendly building using green building approach. *Int. J. Sci. Eng. Res.* 3.

Parks, D. (2019). Energy efficiency left behind? Policy assemblages in Sweden's most climate-smart city. *Eur. Plan. Stud.* 27, 318–335. doi: 10.1080/09654313.2018.1455807

Pawson, S. M., Brin, A., Brockerhoff, E. G., Lamb, D., Payn, T. W., Paquette, A., et al. (2013). Plantation forests, climate change and biodiversity. *Biodivers. Conserv.* 22, 1203–1227. doi: 10.1007/s10531-013-0458-8

Pearson, D. (2013). Impact study on intelligent mobility. A sustainability impact framework and case analysis of energy and environment.

Pörtner, H.-O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., et al. (2022). Climate change 2022: Impacts, adaptation and vulnerability. Cambridge: Cambridge University Press.

Qin, J., Li, M., Li, D., Zhong, J., and Yang, K. (2022). A survey on visual navigation and positioning for autonomous UUVs. *Remote Sens.* 14:3794. doi: 10.3390/rs14153794

Rafiq, N. R., Mohammed, S. F., Pandey, J., and Singh, A. V. (2017), Classic from the outside, smart from the inside: the era of smart buildings. 2017 6th International Conference on Reliability, Infocom Technologies and Optimization (Trends And Future Directions) (ICRITO)

Raj, A. Y., Venkatraman, A., Vinodh, A., and Kumar, H. (2021). Autonomous drone for smart monitoring of an agricultural field. 7th International Engineering Conference Research & Innovation amid Global Pandemic

Rawte, R. (2017). The role of ICT in creating intelligent, energy efficient buildings. *Energy Procedia* 143, 150–153. doi: 10.1016/j.egypro.2017.12.663

Reynolds, K. M., Borges, J. G., Vacik, H., and Lexer, M. J. (2005). "ICT in forest management and conservation" in Information Technology and the Forest Sector. UFRO, Vienna 2005. Available at: https://www.researchgate.net/publication/235349602_ICT_in_Forest_Mana gement_and_Conservation

Rockstrom, J. (2010). Let the environment guide our development.

Sadiku, M., Musa, S. M., and Nelatury, S. (2016). Internet of Things: An introduction. *Int. J. Eng. Res. Adv. Technol.* 2, 39–43.

Sadiku, M., Shadare, A. E., and Musa, S. M. (2017). Smart transportation: a primer. *Int. J. Adv. Res. Comput. Sci. Softw. Eng.* 7, 6–7. doi: 10.23956/ijarcsse/V7I3/01312

Saqib, M., Zarine, R., and Noor, Z. (2022). The smart city imperatives-achieving smart and sustainable future. *J. Sch. Psychol.* 6, 675–684.

Schneider Electric. (2020). Smart working: smart buildings and the future of work. Available at: https://go.schneider-electric.com/WW_202007_Smart-Buildings-and-the-Future-of-Work_EA-LP-EN.html

Schowengerdt, R. A. (2006). Remote sensing: models and methods for image processing. Amsterdam: Elsevier.

Seleznovs, A., Smits, I., and Dubrovskis, D. (2019). Use of the LIDAR combined forest inventory in the estimation of sample trees height. Research for Rural Development 2019: Annual 25th International Scientific Conference

Setó-Pamies, D., and Papaoikonomou, E. (2020). Sustainable development goals: a powerful framework for embedding ethics, CSR, and sustainability in management education. *Sustainability* 12:1762. doi: 10.3390/su12051762

Silva, B. N., Khan, M., and Han, K. (2018). Towards sustainable smart cities: a review of trends, architectures, components, and open challenges in smart cities. *Sustain. Cities Soc.* 38, 697–713. doi: 10.1016/j.scs.2018.01.053

Sims, N., Green, C., Newnham, G., England, J., Held, A., Wulder, M., et al. (2017). Good practice guidance. SDG indicator 15.3.1: proportion of land that is degraded over total land area. Bonn: United Nations Convention to Combat Desertification (UNCCD).

Singh, S. (2022). Forest fire emissions: a contribution to global climate change. *Front. For. Glob. Change* 5. doi: 10.3389/ffgc.2022.925480

Singh, K. M., Kumar, A., and Singh, R. (2015). Role of information and communication technologies in Indian agriculture: an overview. *SSRN Electron. J.* Available at: http://dx.doi.org/10.2139/ssrn.2570710

Sovacool, B. K., Griffiths, S., Kim, J., and Bazilian, M. (2021). Climate change and industrial F-gases: a critical and systematic review of developments, sociotechnical systems and policy options for reducing synthetic greenhouse gas emissions. *Renew. Sustain. Energy Rev.* 141:110759. doi: 10.1016/j.rser.2021.110759

Stammer, D., Cazenave, A., Ponte, R. M., and Tamisiea, M. E. (2013). Causes for contemporary regional sea level changes. *Annu. Rev. Mar. Sci.* 5, 21–46. doi: 10.1146/annurev-marine-121211-172406

Standen, P. (1997). Home, work and management in the information age. *J. Austral. N. Z. Acad. Manage.* 3, 1–14. doi: 10.5172/jmo.1997.3.1.1

Stübinger, J., and Schneider, L. (2020). Understanding smart city—a data-driven literature review. *Sustainability* 12:8460. doi: 10.3390/su12208460

Swain, A., Öjendal, J., Jägerskog, A., Michel, D., Eriksson, M., and Klimes, M. (2021). Handbook of security and the environment. Edward Elgar Publishing.Edward Elgar Publishing.: Cheltenham

Tanhua, T., McCurdy, A., Fischer, A., Appeltans, W., Bax, N., Currie, K., et al. (2019). What we have learned from the framework for ocean observing: evolution of the global ocean observing system. *Front. Mar. Sci.* 6:471. doi: 10.3389/fmars.2019.00471

The Guardian. (2018). World's first electrified road for charging vehicles opens in Sweden Available at: https://www.theguardian.com/environment/2018/apr/12/worlds-first-electrified-road-for-chargingvehicles-opens-in-sweden (Accessed February 6, 2025).

Thieken, A. H., Bubeck, P., Heidenreich, A., von Keyserlingk, J., Dillenardt, L., and Otto, A. (2023). Performance of the flood warning system in Germany in July 2021—insights from affected residents. *Nat. Hazards Earth Syst. Sci.* 23, 973–990. doi: 10.5194/nhess-23-973-2023

Thom, D., Rammer, W., Dirnböck, T., Müller, J., Kobler, J., Katzensteiner, K., et al. (2017). The impacts of climate change and disturbance on spatio-temporal trajectories of biodiversity in a temperate forest landscape. *J. Appl. Ecol.* 54, 28–38. doi: 10.1111/1365-2664.12644

Tian, F. (2016). An agri-food supply chain traceability system for China based on RFID & blockchain technology. 2016 13th International Conference on Service Systems and Service Management (ICSSSM)

Toh, C. K., Sanguesa, J. A., Cano, J. C., and Martinez, F. J. (2020). Advances in smart roads for future smart cities. *Proc. R. Soc. A* 476:20190439. doi: 10.1098/rspa.2019.0439

Toulkeridis, T., Chunga, K., Rentería, W., Rodriguez, F., Mato, F., Nikolaou, S., et al. (2017). Mw7.8 Muisne, Ecuador 4/16/16 earthquake observations: geophysical clustering, intensity mapping, Tsunami. 16th World Conference on Earthquake Engineering

Toulkeridis, T., Porras, L., Tierra, A., Toulkeridis-Estrella, K., Cisneros, D., Luna, M., et al. (2019). Two independent real-time precursors of the 7.8 Mw earthquake in Ecuador based on radioactive and geodetic processes—powerful tools for an early warning system. *J. Geodyn.* 126, 12–22. doi: 10.1016/j.jog.2019.03.003

Toulkeridis, T., and Zach, I. (2017). Wind directions of volcanic ash-charged clouds in Ecuador–implications for the public and flight safety. *Geomat. Nat. Haz. Risk* 8, 242–256. doi: 10.1080/19475705.2016.1199445

Tuukuo, F. (2018). Mapping of deforestation using mobile phone application: a case study of uplands, Kinale and Kereita forests in Kiambu county. Nairobi: University of Nairobi.

Uddin, M., Safiva, O., and Saba, T. (2017). Green ICT framework to reduce carbon footprints in universities. *Advances in Energy Research* 5, 1–12. doi: 10.12989/ERI.2017.5.1.001

United Nations (2018). World urbanization prospects: the 2018 revision. United Nations: New York, NY, 799.

United Nations Environment Programme. (2020). UNEP, UNEP Copenhagen Climate Centre (UNEP-CCC).

United Nations Framework Convention on Climate Change. (2009). Kyoto protocol reference manual on accounting of emissions and assigned amount. Bonn, Germany: Climate Change Secretariat (UNFCCC) Martin-Luther-King-Strasse.

Valencia, J., Rodríguez, J. M., Mendoza, J. J. A., and Castaño, J. M. (2017). Valoración de los servicios ecosistémicos de investigación y educación como insumo para la toma de decisiones desde la perspectiva de la gestión del riesgo y el cambio climático. *Rev. Luna Azul* 45, 11–41. doi: 10.17151/luaz.2017.45.3

Van Damme, M., Clarisse, L., Whitburn, S., Hadji-Lazaro, J., Hurtmans, D., Clerbaux, C., et al. (2018). Industrial and agricultural ammonia point sources exposed. *Nature* 564, 99–103. doi: 10.1038/s41586-018-0747-1

van Vuuren, D. P., Stehfest, E., Gernaat, D. E., van den Berg, M., Bijl, D. L., de Boer, H. S., et al. (2018). Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nat. Clim. Change* 8, 391–397. doi: 10.1038/s41558-018-0119-8

Velders, G. J., Andersen, S. O., Daniel, J. S., Fahey, D. W., and McFarland, M. (2007). The importance of the Montreal protocol in protecting climate. *Proc. Natl. Acad. Sci. U.S.A.* 104, 4814–4819. doi: 10.1073/pnas.0610328104

VijayaVenkataRaman, S., Iniyan, S., and Goic, R. (2012). A review of climate change, mitigation and adaptation. *Renew. Sustain. Energy Rev.* 16, 878–897. doi: 10.1016/j.rser.2011.09.009

Wada, M., Hatanaka, K., Saville, R., Radiarta, I. N., and Sugama, K. (2013). Marine observation framework using ICT for mariculture in Indonesia. 2013 OCEANS-San Diego

Waisman, H., De Coninck, H., and Rogelj, J. (2019). Key technological enablers for ambitious climate goals: insights from the IPCC special report on global warming of 1.5 °C. *Environ. Res. Lett.* 14:111001. doi: 10.1088/1748-9326/ab4c0b

Wang, Y., Braghiere, R. K., Longo, M., Norton, A. J., Köhler, P., Doughty, R., et al. (2023). Modeling global vegetation gross primary productivity, transpiration and hyperspectral canopy radiative transfer simultaneously using a next generation land surface model—CliMA land. *J. Adv. Model. Earth Syst.* 15:e2021MS002964. doi: 10.1029/2021MS002964

Wang, Z., Wang, M., and Bao, W. (2019). Development and application of dynamic timing optimization platform for big data intelligent traffic signals. *E3S Web Conf.* 136:01008. doi: 10.1051/e3sconf/201913601008

Watson, R., Baste, I., Larigauderie, A., Leadley, P., Pascual, U., Baptiste, B., et al. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. Bonn: IPBES Secretariat.

Watson, J. T., Haynie, A. C., Sullivan, P. J., Perruso, L., O'Farrell, S., Sanchirico, J. N., et al. (2018). Vessel monitoring systems (VMS) reveal an increase in fishing efficiency following regulatory changes in a demersal longline fishery. *Fish. Res.* 207, 85–94. doi: 10.1016/j.fishres.2018.06.006

WGMS (2021). Global glacier change bulletin No. 4 (2018–2019). ISC (WDS)/IUGG (IACS)/UNEP/UNESCO/WMO, 278. Switzerland: World Glacier Monitoring Service Department of Geography.

Wolfert, S., Ge, L., Verdouw, C., and Bogaardt, M.-J. (2017). Big data in smart farming—a review. *Agric. Syst.* 153, 69–80. doi: 10.1016/j.agsy.2017.01.023

World Bank (2021). World development report 2021: data for better lives. Washington, DC: World Bank.

World Meteorological Organization (2009). Manual on the global telecommunication system. Geneva: World Meteorological Organization.

World Meteorological Organization (2010). Manual on the global observing system. Geneva: World Meteorological Organization.

World Meteorological Organization (2019). Manual on the global data-processing and forecasting system. Geneva: World Meteorological Organization.

Yu, Y., Wang, J., Liu, Y., Yu, P., Wang, D., Zheng, P., et al. (2024). Revisit the environmental impact of artificial intelligence: the overlooked carbon emission source? *Front. Environ. Sci. Eng.* 18:158. doi: 10.1007/s11783-024-1918-y

Yuan, L. (2019). Sustainability aspects of ICT in agriculture and food systems. Stockholm: KTH Royal Institute of Technology.

Yue, X.-L., and Gao, Q.-X. (2018). Contributions of natural systems and human activity to greenhouse gas emissions. *Adv. Clim. Change Res.* 9, 243–252. doi: 10.1016/j.accre.2018.12.003

Zemp, M., Eggleston, S., Míguez, B. M., Oakley, T., Rea, A., Robbez, M., et al. (2021). The status of the global climate observing system 2021: the GCOS status report.

Zhang, Q., Sun, H., Wu, X., and Zhong, H. (2019). Edge video analytics for public safety: a review. *Proc. IEEE* 107, 1675–1696. doi: 10.1109/JPROC.2019.2925910

Zhao, J., Yue, C., Wang, J., Hantson, S., Wang, X., He, B., et al. (2024). Forest fire size amplifies postfire land surface warming. *Nature* 633, 828–834. doi: 10.1038/s41586-024-07918-8

Zillman, J. W. (2009). A history of climate activities. *WMO Bull.* 58:141.