# Geospatial Data-Driven Approaches for Sustainable Smart Cities

Subjects: Computer Science, Interdisciplinary Applications

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The concept of smart cities has become increasingly important in the pursuit of sustainable development goals. In general, common urban challenges have been addressed through smart-city services, and new perspectives for more sustainable cities have emerged. To realise the full potential of such smart urban environments, geospatial approaches have been used as a focal point, offering a plethora of applications that contribute to a better understanding of urban challenges and innovation potentials.

Keywords: urban planning ; data mining ; OpenStreetMap ; GIS ; dataset ; data science

## 1. Introduction

In recent years, the concept of smart cities has emerged as a pivotal paradigm in urban development, fueled by the global pursuit of sustainable development goals (SDGs) established by the United Nations [1][2]. As urbanization continues to grow at an unprecedented rate, cities are faced with a series of complex challenges, inevitably leading to a growing demand for smart urban services [3]. The concept of smart cities emerges as a response to this adverse scenario, offering a vision of urban environments that are not only intelligent but also ecologically sound and socially inclusive [4].

Sustainability has become a defining principle in the smart-city paradigm. The recognition of environmental stewardship, resource conservation, and the promotion of quality of life as essential components of urban development have fundamentally reshaped the way cities are envisioned and engineered [5][6]. Therefore, the pursuit of SDGs, reinforced by global concerns over climate change and environmental degradation, has placed increasing importance on the transformation of urban centers into smart cities that prioritize the well-being of its inhabitants and surrounding ecosystems [7].

Common urban challenges, encompassing traffic congestion, inadequate infrastructure to reduce pollution, and energy inefficiency, have been considered for optimizations backed by smart-city services [8][9]. Besides the generic idea of "improvement" that has been largely advertised by governments and big companies, smart cities can be a central element to guide the urgent sustainable revolution in our cities. In short, while smart services can optimize the use of resources and reduce waste and pollution, smarter cities will potentially be constructed around a more holistic and harmonious relationship between people and their urban environment [10].

Although the expected benefits of sustainable smart cities have been largely known, an important challenge is to properly understand the dynamics and complexities of the modeled cities. While this concern may seem trivial, the urban dynamics in developed smart-city systems may be neglected or only partially addressed. Among the potential ways to achieve a better understating of this matter, data-driven analyses have emerged as a central element to empower the developed approaches. Recently, the era of Big Data and the proliferation of public and private geospatial information datasets have opened up a realm of possibilities for city planners, researchers, and policymakers. As a result, smart-city services have been increasingly designed to leverage such data in different scales, potentially better adapting to the particularities of the target cities [11][12]. As geospatial data have encompassed location-based information from various sources, data-driven approaches have been better adapted to the posed sustainable development challenges.

Some works have been devoted to surveying the literature to better understand, organize, and classify data-driven geospatial approaches within the smart cities landscape. The work in [11] reviewed data-driven smart-city approaches from a Big Data perspective, particularly focusing on how data mining and artificial intelligence (mostly machine-learning algorithms) can be leveraged to provide deeper knowledge about city data. For the work in [12], a systematic literature review of current data-driven smart applications in urban contexts was performed. Although it focused on data-driven smart cities, it analyzed opportunities and challenges associated with real-time data utilization, emphasizing smart governance and the role of people (citizen participation) in this area. In another systematic literature review, authors in [13] also addressed sustainable smart cities through data science and analytics, particularly focusing on smart urbanism. Finally, the survey in [14] also related data-driven approaches with smart cities, but a broader perspective was adopted when considering urban challenges, with shallow insights about sustainable developments.

## 2. Smart Cities and Sustainability

A smart city is an urban environment that optimizes resource utilization to enhance the quality of life for its residents. This is commonly accomplished through advanced technologies that enable the optimization of city operations and the addressing of various challenges associated with urban living. For that, these cities leverage information and communication technologies to collect and analyze data, facilitating informed decisions to improve efficiency, sustainability, and overall well-being. Moreover, smart cities offer digital solutions across various domains such as transportation, energy, healthcare, governance, and public services, creating an interconnected and intelligent urban ecosystem [15]. Therefore, providing long-term viability for these cities is essential, notably through the integration of sustainability principles, accomplished via innovative data-driven strategies.

In the context of smart cities, sustainability refers to the capability of the urban environment as a whole to “execute” actions and deploy technologies for its ongoing development while preserving and enduring its resources over the long term while not imposing substantial adverse impacts on the environment, society, or economy. It entails meeting present needs without compromising the ability of future generations to fulfill their own demands. The creation and development of sustainable cities and communities align with one of the United Nations’ sustainable development goals (SDG 11). However, the potential for achieving sustainability through smart-city solutions extends beyond this goal. Smart cities can be intricately designed to actively contribute to harmonious coexistence between human activities and the natural world, embracing practices and policies that balance three pillars: environmental conservation, social equity, and economic viability [16][17]. **Table 1** illustrates the 17 SDGs of the United Nations, categorizing the domains they address, which can be directly influenced by smart-city solutions.

**Table 1.** Categorization of the UN Sustainable Development Goals (SDG).

| SDG | Goal | Category | | |
|---|---|---|---|---|
| | | **Environment** | **Economy** | **Social** |
| 1 | No poverty | |  |  |
| 2 | Zero hunger | |  |  |
| 3 | Good health and well-being | | |  |
| 4 | Quality education | | |  |
| 5 | Gender equality | | |  |
| 6 | Clean water and sanitation |  | | |
| 7 | Affordable and clean energy |  |  | |
| 8 | Decent work and economic growth | |  |  |
| 9 | Industry, innovation and infrastructure | |  | |
| 10 | Reduced inequalities | |  |  |

| SDG | Goal | Category | | |
|---|---|---|---|---|
| | | **Environment** | **Economy** | **Social** |
| 11 | Sustainable cities and communities |  |  |  |
| 12 | Responsible consumption and production |  |  | |
| 13 | Climate action |  | | |
| 14 | Life below water |  | | |
| 15 | Life on land |  | | |
| 16 | Peace, justice and strong institutions | | |  |
| 17 | Partnerships for the goals | |  |  |

Therefore, to attain sustainability in smart cities (SDG 11), it is necessary to tackle various challenges that emerge from the complex and dynamic interactions between the urban environment and its stakeholders. These challenges align with the sustainability pillars, covering a range of issues and aspects that require careful consideration and proactive measures. The discussions in this research delve into some of the most relevant and pressing challenges within each category, elucidating how geospatial data-driven approaches can help to overcome them. Since geospatial data-driven approaches will rely on geospatial data and associated technologies, they may provide valuable insights for the integration and optimization of smart-city solutions, enhancing their expected sustainability outcomes and facilitating the assessment and feedback of the impacts associated with these solutions.

Concerning the environmental challenges faced by sustainable smart cities, a primary consideration is the adoption of alternative energies that can diminish reliance on fossil fuels and lower greenhouse gas emissions. Examples of alternative energies encompass solar, wind, hydro, geothermal, and biomass sources, offering clean and renewable power for a variety of urban applications [18]. However, these sources also pose some challenges, such as high initial costs, intermittency, storage, and grid integration. Smart cities must invest in innovative solutions to surpass these barriers and ensure a reliable and efficient alternative energy supply. For instance, smart grids can use advanced sensors, communication, and control systems to manage the demand and supply of electricity, integrating various distributed energy sources and enabling demand response and load shifting [19]. Geospatial data-driven approaches can support the planning and operation of smart grids by providing spatial and temporal information on the availability and potential of alternative energy resources, the location and characteristics of energy infrastructure and consumers, and the environmental and social impacts of energy production and consumption [20].

Another environmental challenge is the reduction of the use of private motorized vehicles. This can contribute to lower air pollution, noise, congestion, and accidents. Smart cities can promote sustainable mobility by implementing policies and employing technologies that encourage the use of public transportation, cycling, walking, and shared mobility services. These modes of transport can reduce the environmental and social impacts of urban mobility, as well as improve the health and well-being of citizens. Smart cities can also leverage intelligent transportation systems that monitor and optimize traffic flows, provide real-time information and guidance to travelers, and implement dynamic pricing and incentives to influence travel behavior [21][22]. Geospatial data-driven approaches can enable the development and deployment of such intelligent transportation systems by collecting and analyzing data on the location, speed, and direction of vehicles and travelers, the road network and traffic conditions, the availability and accessibility of transport modes and services, and the travel patterns and preferences of citizens.

Sustainable smart cities must also deal with preserving ecosystems in an environmental sphere. Ecosystems provide essential services and benefits for human well-being, such as water purification, climate regulation, biodiversity, and recreation. Smart cities must protect and restore the natural environment within and around the urban area, ensuring the conservation of land, water, and biological resources [23]. Actually, smart cities can use geospatial data and technologies to map and monitor the state and trends of ecosystems, assess their values, functions, and significance for human well-being, and identify causes of changes and external influences that affect them. This can help smart cities design and implement effective strategies and actions to enhance the resilience and sustainability of ecosystems, embracing approaches like green infrastructure, ecosystem-based adaptation, and nature-based solutions [24].

Smart cities also face numerous challenges related to economic aspects in their pursuit of sustainability, especially the substantial upfront cost associated with implementing smart infrastructures. Deploying interconnected systems, such as Internet of Things (IoT) devices, intelligent transportation, and energy-efficient solutions, demands a considerable initial investment [25][26]. Cities must navigate budget constraints and explore financing models to fund these initiatives, striking a balance between short-term financial pressures and long-term sustainability goals—a delicate challenge for city planners and policymakers. However, in addressing these economic complexities, smart cities can leverage geospatial data-driven smart approaches. In general, geospatial data, encompassing information tied to specific geographic locations, becomes a powerful tool for optimizing resource allocation and infrastructure planning. In terms of upfront costs, geospatial data enables cities to conduct precise spatial analyses, identifying optimal locations for the deployment of smart infrastructure. This targeted approach not only helps minimize initial investment by focusing on high-impact areas but also enhances the efficiency and effectiveness of resource utilization, contributing to long-term economic sustainability.

As the deployment cost is an issue in sustainable smart cities, it is equally important to deal with the cost of managing obsolete technologies, which necessitates adaptive strategies, balancing the economic viability of innovation with the imperative for a stable urban ecosystem. Cities must continuously evaluate and strategically plan the integration of emerging technologies and effectively address the environmental impact and costs associated with dealing with outdated systems [27][28]. In this context, collaborative efforts between the public and private sectors become imperative to ensure the economic viability and environmental resilience of smart-city initiatives. Thus, geospatial data are essential to the spatial intelligence necessary to overcome financial challenges posed by obsolete technologies and forge a sustainable urban future. Through continuous updates and real-time integration, cities can adapt their smart infrastructure to evolving technological landscapes, enabling agile and responsive decision-making. Geospatial data-driven strategies help ensure that investments remain relevant by integrating emerging technologies into the urban fabric and promoting a harmonious balance between economic viability and environmental sustainability.

The economic sustainability of smart cities is intricately associated with issues of inclusiveness and accessibility. The deployment of cutting-edge technologies, if not implemented thoughtfully, may inadvertently exacerbate existing social and economic disparities [29]. Factors such as income inequality or technological literacy can limit access to digital services like smart transportation or e-governance platforms for certain demographic groups. Achieving economic and social sustainability in smart cities requires proactive measures to ensure equitable distribution of the positive impact of technological advancements, fostering an inclusive urban environment where all residents can participate in and benefit from the innovations brought about by smart-city initiatives [30]. In this context, geospatial data can be used to map socio-economic indicators against geographic locations, while city planners can identify areas with limited access to smart services and formulate targeted interventions. Geospatial analysis facilitates the identification of digital divides, ensuring that smart-city initiatives are strategically implemented to bridge these gaps.

Still addressing the social challenges for achieving sustainability in smart cities, an important aspect involves thoroughly analyzing citizens' culture and habits. These aspects significantly influence the acceptance and adoption of smart-city technologies and practices. Culture and habits encompass the norms, values, beliefs, and behaviors that shape how individuals interact with their surroundings and with each other. Since smart cities must comprehend and respect such a diverse and intricate nature, the design of smart-city solutions should also align with and be adaptable to their needs, preferences, and expectations.

Additionally, promoting a culture of innovation and learning among citizens is essential, encouraging them to experiment, explore, and embrace new and improved ways of urban living [31][32][33]. Geospatial data-driven approaches emerge as valuable tools aimed at understanding and influencing the culture and habits of citizens. By capturing and analyzing data on the spatial and temporal distribution and dynamics of urban activities and behaviors, these approaches identify and address the needs and problems of different groups and communities and provide feedback and incentives to motivate and reward positive changes and actions [33][34].

In this social context, ensuring active and meaningful citizen participation in planning, developing, and managing smart-city initiatives is imperative. Such involvement not only enhances the quality and effectiveness of smart-city solutions but also contributes to the satisfaction and well-being of the inhabitants by ensuring that these solutions genuinely address the real needs and issues of the urban community. Smart cities can employ various methods and tools to encourage and support citizen participation, including surveys, workshops, focus groups, crowdsourcing, gamification, and social media [33]. These mechanisms empower individuals to freely express their opinions, ideas, and feedback, as well as to collaborate in the co-design, co-production, and co-evaluation of smart-city solutions. The efficacy of these approaches is significantly augmented when associated with geospatial information, enabling a more comprehensive understanding of the geographical needs of citizens. This enriched understanding, in turn, enables more precise and tailored solutions that align with the specific spatial requirements of the community [35].

In conclusion, the quest to build sustainable smart cities demands a comprehensive understanding and integration of diverse aspects across environmental, economic, and social domains. By aligning with the United Nations' sustainable development goals, smart cities can act as catalysts for positive change, addressing challenges and promoting a symbiotic relationship between human activities and the natural environment. The intricate nature of these challenges necessitates innovative strategies, particularly through data-driven approaches and geospatial insights. These methods should serve as a reference for smart cities, providing the spatial intelligence necessary to overcome economic hurdles and forge a sustainable urban future. In the upcoming sections, the researchers delve into the applications and positive impacts of data-driven urban processing, discussing smart-city approaches that will shape the trajectory of achieving more sustainable smart cities.

An illustrative example of how all the aforementioned sustainability goals can be pursued when developing smart cities can be seen in **Figure 1**. Some common smart-city services are highlighted, as well as the general idea of geospatial data that will support them. Actually, as discussed in this section, the researchers believe that a healthy smart-city scenario will encompass economic sustainability, efficient technology management, social equality, citizen participation, and climate change preparedness.


**Figure 1.** A data-driven smart-city perspective toward sustainability.

## 3. Geospatial Urban Data Processing

To achieve urban sustainability in a broader sense, new smart approaches must be sought and developed. Every aspect of a city can be considered a potential improvement possibility, taking advantage of new technologies available at the time. In this sense, extensive research must be conducted to discover and develop proper approaches to enhance public services in cities and achieve the desirable level of sustainability. However, studying a city is a complex task that cannot be confined to a laboratory or a desk. Such a research object must be translated into a more practical mechanism that can be studied without the hassle of having to go to every corner of the city, revealing a situation in which modeling tools are highly demanded. Using data-driven methodologies, city models can be developed to help understand this complex environment.

A model represents a real system by omitting irrelevant details and retaining only those attributes that are relevant or important to the proposed study or work [36]. In the context of smart cities, features such as roads, response centers, public facilities, rivers, public parks, relief, and slopes, among others, are relevant and can be modeled properly according to the desired perspective. Tools that include maps, geological representations, and 3D objects are examples of models that can be used to represent real research objects, which are valuable in the research and development phases of smart-city initiatives [37].

To model a city and all its complexities at different levels, different tools and data sources are required, depending on the type of smart-city services being pursued. In terms of how data are produced and processed, three approaches stand out: Geographic Information Systems (GIS), Remote Sensing, and IoT-based sensing. All these basic elements are crucial for the production and management of geospatial data, which can support the operation of smart-city applications or be stored as georeferenced datasets.

## 4. Geospatial Datasets and Management of Georeferenced Data

As cities expand and face complex challenges, efficient data management has become increasingly important in the evolving urban landscape. Geospatial datasets play an essential role in this regard, taking advantage of modern geospatial data analysis technologies to improve our ability to comprehend and manage urban environments [38]. Furthermore, leveraging technologies such as the IoT, Big Data, and cloud computing highlights their importance in driving urban innovation [39]. In this context, integrating urban datasets with geospatial information is essential to provide spatially informed analysis that supports disaster management, urban growth management, and sustainable planning [40][41].

## 5. Sustainable Smart-City Applications

In smart cities, geospatial data plays a fundamental role in the design and implementation of urban services focused on sustainability. The application of data-driven approaches in urban management allows for a deeper and more comprehensive understanding of the specific challenges and opportunities in each locality [14]. By integrating geospatial information such as traffic data, air quality, land use, and infrastructure, cities can make informed and strategic decisions to optimize resources, reduce environmental impacts, and improve the quality of life for citizens [42]. Such an approach not only enables more efficient administration but also contributes to the creation of urban environments that are more sustainable, resilient, and adaptable to the dynamic needs of local communities. The intersection between geospatial data and data-driven urban services is, therefore, crucial for cities that prioritize sustainability at their core [3].

Thus, for the development of sustainable smart cities, it is imperative to adhere to a data collection flow through GIS, IoT applications, and remote sensing techniques [43]. The raw data gathered from these sources drives the processing stage, which is based on data-driven approaches using techniques such as machine learning, descriptive statistics, time series analysis, natural language processing, and data visualization [11]. These methods facilitate the generation of valuable information that provides essential insights for more efficient and sustainable urban planning, as illustrated in **Figure 2**.

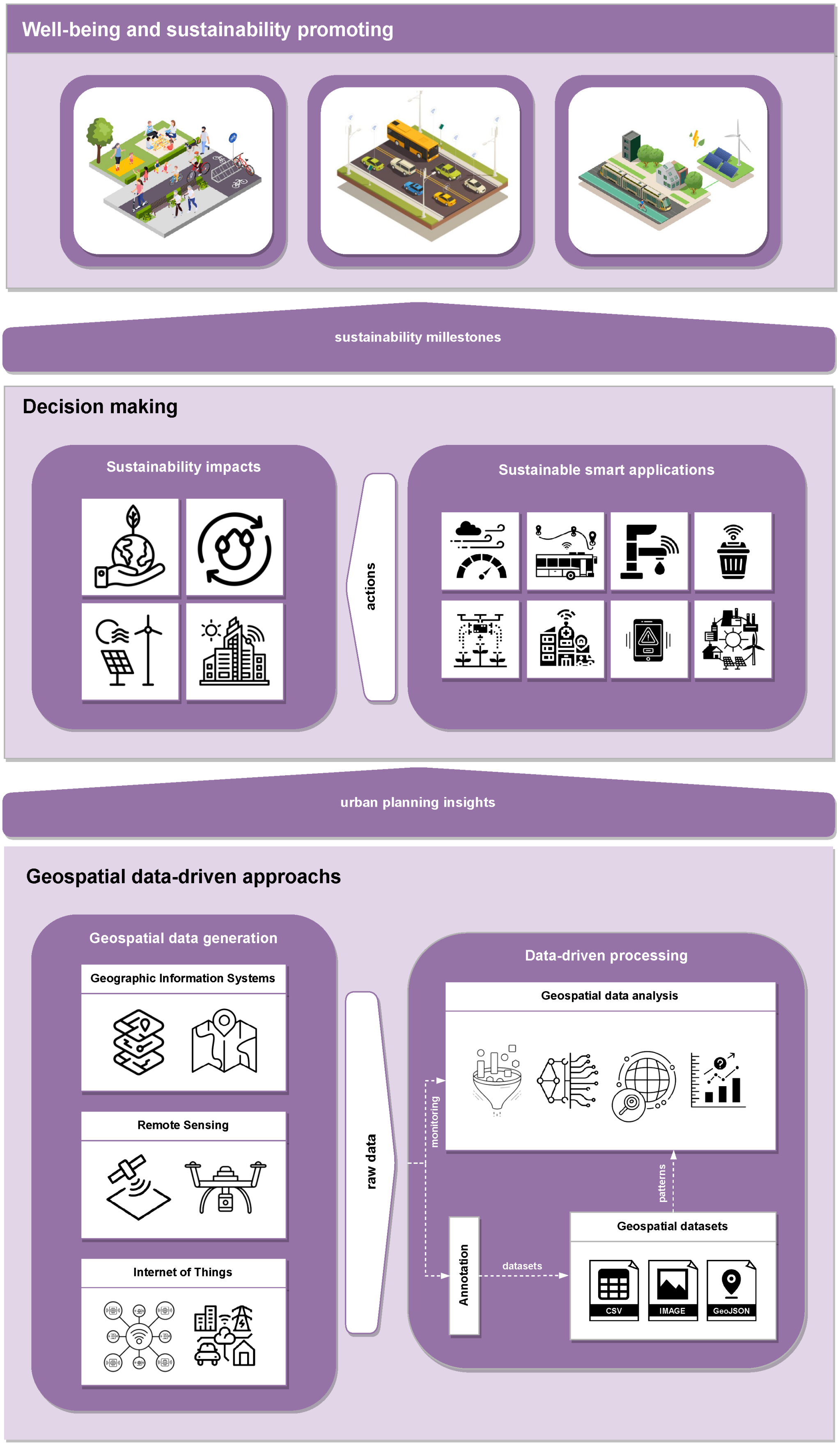


**Figure 2.** A typical processing flow in geospatial data-driven sustainable smart-city applications.

The insights gained from processing geospatial data through data-driven approaches not only enable more effective urban planning but also provide governments with valuable tools for strategic decision-making. As such, this information is critical to the design and implementation of sustainable smart applications, covering various areas related to improving the quality of life in smart cities. Examples of these applications include [3]:

- Pollution monitoring: using data to monitor and reduce air and water pollution and promote healthier urban environments;

- Smart urban mobility: implementing data-driven solutions to optimize traffic, support public transport, and promote sustainable mobility options;
- Efficient water management: using insights to improve water resource management, reduce waste and ensure equitable access to clean water;
- Sustainable waste management: applying technologies to monitor, collect, and sustainably manage waste, therefore contributing to the reduction of environmental impacts;
- Smart urban farming: the use of geospatially enabled agricultural practices to increase efficiency, reduce resource use, and promote sustainable agriculture;
- Smart health: leveraging data to monitor health indicators, prevent disease, and improve the quality of health services in the city;
- Emergency management: integrating policies and technologies to assess, monitor, and respond to disaster risks, therefore increasing urban resilience;
- Smart grids: incorporating advanced technologies to optimize energy distribution, increase efficiency, and promote renewable energy sources.

In summary, smart applications go beyond the mere transformation of the urban landscape; they establish robust milestones for sustainability, with a direct impact on the quality of life of residents and the preservation of the planet, which is in line with the aforementioned UN Sustainable Development Goals numbers 3, 6, 7, 9, 11, 12 and 13 (**Table 1**). These solutions not only promote more efficient, healthy, and resilient urban environments but also consolidate smart cities as protagonists in mitigating environmental damage, thus playing a crucial role in addressing climate challenges, including the growing concern over global warming [44].

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