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# Land, Water, and Climate Issues in Large and Megacities under the Lens of Nuclear Science: An Approach for Achieving Sustainable Development Goal (SDG11)

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**Abstract:** Nuclear science and technology (NST) offers a multitude of applications and tools and has a high level of regulation. However, its contribution to the achievement of global development goals is still incipient. Although its application is directly related to many fields, especially sustainability, the current literature does not relate it to socio-environmental issues, hindering the adoption of public policies based on isotopic and nuclear solutions. In large and megacities, the promotion of human well-being and the conservation of ecosystems are urgent global challenges, especially as a function of the growing expansion of land use modification, water scarcity, and climate change. The relationship between society and NST is addressed in this study, which aims to show how and in what ways the emerging and innovative nuclear and isotopic solutions contribute to the urban dimension of the United Nations 2030 Agenda, expressed by SDG 11 (Sustainable Cities and Communities), and its connection to land, water, and climate change in cities. This gap in knowledge compromises the targeting of resources to improve NST as a development strategy. Demystifying NST and increasing collaboration between ecosystem services and other issues related to sustainability in cities are key to implementing global development policies, especially at the local governance level.

**Keywords:** stable isotopes; ecosystem services; water security; human well-being; 2030 Agenda

## 1. Introduction

Urbanization has transformed people's living environment by concentrating more than half of the population in less than 2% of the total area of the planet, representing a huge water demand which is increasingly difficult to supply [1–3]. This extreme concentration of people has led to the increasing depletion of natural resources, compromising the provisioning of ecosystem services (ES)—which can be defined as the characteristics, functions, or processes that contribute directly or indirectly to human well-being, i.e., the benefits that people obtain from ecosystems [4,5].

Three-quarters of the terrestrial environment and about 66% of the marine environment have been significantly altered by humans. More than one-third of the world's land surface and almost 75% of freshwater resources are devoted to agricultural or livestock production. One-third of marine fish stocks are being harvested at unsustainable levels, and about 60 billion tons of renewable and nonrenewable resources are extracted globally each year—double the estimate for 1980. The dominant factor in all these adverse trends is mankind's increasing need for food, energy, water, and other resources [5–7].

The loss of these services compromises development in its multiple dimensions, which has been addressed in several international agreements. The Paris Agreement, the New Urban Agenda, the Sendai Framework for Disaster Risk Reduction, the Convention on Biological Diversity, the Addis Ababa Action Agenda on financing for development, and the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals constitute the main axis of international development policies, providing recommendations, goals, targets, and indicators.

Promoting human well-being and protecting the environment are the most urgent global challenges, featured in the core ideas of the SDGs, that provide a holistic and multidimensional view of development [8–10]. Environmental sustainability supports the economic and social dimensions of development, as expressed through ecosystem services or, more broadly, nature's contributions to people (NCPs) [4–7,11,12].

The role of water ecosystem services is indispensable for human well-being and sustainable social development [2,13]. Aggravated by the impact of climate change, water availability and supply have become key challenges worldwide [3,14,15], with water security being especially important in large urban agglomerations.

By concentrating the demand of millions of people in small areas, the stress on the restricted supply of freshwater available near urban agglomerations is increased. Despite the increased demand for water resources brought up by urban growth, in global terms, water sources of the world's major cities have only been incipiently evaluated [2,3,13,16].

Large urban agglomerations present problems related to inadequate land use, underdeveloped infrastructure, water scarcity, poor sanitation, air pollution, and traffic congestion [17–19]. Science, technology, and innovation (STI) play a critical role in resolving these challenges and achieving the SDGs [20–22]. However, only few authors have reported the use of NST as contributing directly and indirectly to the 2030 Agenda implementation [23].

Particular uses of nuclear energy have been reported regarding the preservation of cultural heritage. Gamma irradiation processing is a well-established procedure in corrective conservation, capable of stopping biological degradation and, when necessary, it is employed to consolidate more fragile artifacts [24,25]. Another application was found in France, which revealed the use of nuclear energy for electricity production, reducing $CO_2$ emissions [26].

The expansion and enhancement of nuclear energy, as well as renewable energies, has been considered vital to prevent global warming, to mitigate climate change, and to promote economic growth [27,28]. Both Russia and China have invested in nuclear barges to bring cheap energy to remote places, promoting development in these areas [29].

Several studies applying the NST approach have been carried out in different areas of knowledge. However, some of them have highlighted the isotopic tool as an indicator of multiple applications., i.e., they have been used to monitor atmospheric pollution; to assess the eco-physiological status of urban forests; to monitor eutrophication in aquatic systems; to assess food security; to investigate ecological, archeological, paleontological, and geological issues; and to manage water in the face of climate change [30–49]. Although isotopic hydrology has mainly focused on landscapes far from densely urbanized regions, its emphasis in the coming decades will be increasingly important for water supply and dynamics within urban systems [30,50].

Despite the multiplicity of applications, the growing use of isotopic and nuclear tools, and the high level of regulations involved in this area [51], the associations of these contributions to the achievement of global development goals, including the ones related to the environmental sustainability of ecosystems and their services, are still emerging. This constitutes a true information void that compromises resources targeting NST as a development strategy; at the same time, it configures itself as a knowledge gap for the implementation of public policies based on its application, which is crucial to respond to current challenges faced by humanity. This is a gap to be filled, once NST can be considered as a safe, consolidated, well-established, and regulated tool.

Therefore, the relationship between society and NST is addressed in this study, which aims at demonstrating how emerging and innovative nuclear and isotopic solutions may contribute to the urban dimension of the 2030 Agenda expressed by SDG 11, and its connection to land, water, and climate change in cities.

## 2. Literature Review

The world's large and megacities are defined as urban concentrations with a population between 5 and 10 million, and more than 10 million people, respectively, while metacities are those urban agglomerations with populations exceeding 30 million inhabitants. Urbanization refers both to the increase in urban population and changes in land use for the expansion of cities [1].

Globally, more people live in urban than in rural areas, rising from 30% of the world's population in 1950 (741 million) to 53% (3.98 billion) in 2015. Most people inhabit cities with less than 500,000 inhabitants; however, the current concentration of 13% of the world's population living in megacities and 6.8% occupying large cities is extremely relevant for territorial planning [1].

Urbanization and population growth impact the environment, while cities also depend on the benefits obtained from biodiversity and ES [52–54]; however, the lack of understanding of these interconnections limits progress towards achieving SDGs [5–7,11,12,55,56].

Although the city guidelines are directly related to SDG 11, other SDGs are part of the Urban Agenda. Among them, SDGs 6, 13, 14, and 15 stand out. As a highlight of SDG 13, it is emphasized that cities play a crucial role in the climate scenario, while global climate change (GCC) represents both a global and an important local issue [1,9,15].

The 20 warmest years have occurred in the last 22 years, and the years from 2015 to 2021 were the seven warmest ever recorded. In 2021, the global average temperature was about 1.09 °C above the 1850–1900 average. Unless deep reductions in $CO_2$ and other greenhouse gasses (GHG) emissions occur, the average global temperature is projected to exceed 1.5 °C of warming over the next 30 years [57–59].

These disturbances associated with the overexploitation of natural resources are direct results of the conditions of the vulnerability and resilience of each region and ecosystem [15], affecting billions of people worldwide, with a strong impact on the planet's urban areas. Climate change also causes substantial damage and irreversible losses in biodiversity, reducing ecosystem service delivery capacity and decreasing ecosystem resilience [15,60].

While in 1997, the services provided by ecosystems were estimated at USD 33 trillion/year, when considering only the updates in the values of services for 2011, the estimate is that the ESs totaled USD 125 trillion/year. Changes in land use in the same period (1997 to 2011) corresponded to an estimated USD 20 trillion/year of ES loss [61,62]. Thus, it is understood that ecosystems and their services are fundamental for the planning of cities.

Several classifications have been proposed for the services provided by ecosystems [63], and recent evaluations include the concept of nature's contributions to people—NCPs [6,64]. For operational purposes, in this study, ES will be categorized into specific functional lines [4,5]: provision (food, water, fuel); regulation (air and water purification, climate regulation); cultural (education, leisure, inspiration); and support, which maintains all other ecosystem services (such as nutrient cycling, soil formation, primary production).

Even with humanity's growing demand for ecosystem services, an intense degradation of the ecosystems' ability to provide them is clearly observed [5–7]. This perspective of ecosystem services has a strong relationship with SDGs 14 and 15, as they directly involve biodiversity.

Another fundamental aspect for human well-being, especially in cities, is the amount and quality of water. Water security, listed as a particular goal (SDG 6—ensuring the availability and sustainable management of water and sanitation for all), is one of the key elements of the 2030 Agenda [8,9]. At the same time, water security is a constituent element of a series of targets linked to other SDGs related to cities, consumption, health, terrestrial ecosystems, and marine resources [2,3,14].

Many countries make use of NST to contribute to and meet the development goals in areas such as energy, human health, food production, water management, and environmental protection, contributing directly to at least, nine SDGs [23,51]. In Malaysia, for example, NST is used in six technical sectors (medical and health; food and agriculture; industry; water and environment; energy; and security and protection), contributing to national socio-economic growth, with an increasing impact on its gross domestic product (GDP) [65].

Strongly linked to nuclear technology and its applications, the International Atomic Energy Agency (IAEA) was created in 1957, with the "Atoms for Peace" approach, in response to the expectations generated by the discoveries and various uses of nuclear technology. The international regulatory framework for nuclear safety establishes basic requirements for legal, governmental, and regulatory infrastructures for the safety of nuclear facilities and materials, sources of radiation, radioactive waste, and transport. This framework is based on the Convention on Physical Protection of Nuclear Material (CPPNM) and its Amendment; the Code of Conduct on the Safety and Security of Radioactive Sources and its Guidance on the Import and Export of Radioactive Sources; the Safeguards Agreements and their Additional Protocols; the Nuclear Terrorism Convention; and the United Nations Security Council resolutions 1540 and 1373 [51].

Nuclear safeguards, understood as the technical measures applied by the IAEA and incorporated into legally binding agreements, aim to ensure that nuclear materials and other specified items are not diverted from peaceful use [51,66]. Comprehensive agreements with 178 nations have been reached so far [51].

In 1964, the Joint FAO/IAEA Center of Nuclear Techniques in Food and Agriculture was established by the Food and Agriculture Organization of United Nations (FAO), and this was considered a strategic partnership to present to the global community the way in which nuclear applications may add value to solving a number of agricultural issues [51].

Examples of this include irradiation of cross-border animal disease pathogens for application as vaccines and immune inducers. This is becoming an alternative to vaccines that use attenuated or killed pathogens by better triggering the entire host immune system repertoire. In addition, other applications include food irradiation technology to ensure greater quality and safety for technology used in emergency response (including analysis, monitoring, and remediation of radioactive contamination in food and agriculture), and stable isotopes for tracking bird migrations and associations with highly pathogenic avian influenza [51].

Furthermore, in line with its "Atoms for Peace and Development" mandate, the IAEA supports countries in their efforts to achieve the 17 SDGs. As the transition to an inclusive and environmentally sustainable economic development must be based on science, technology, and innovation, it is necessary to both transform the nature of STI and to rearrange it towards meeting the SDGs [20–22].

## 3. Materials and Methods

This review paper sought associations between NST and SDG11 through the evaluation of the scientific literature. For this association, an ES approach was used, since it is strongly related to sustainability in cities.

For the association between ecosystem services, nuclear technologies, and their relationships with the SDGs, a search, analysis, and systematic compilation was conducted in the Web of Science database [67]. The search limited the selection of documents to "article" and "review", published until October 2022.

Using the Web of Science database, records were retrieved with terms selected for the topic option, i.e., when they appear in the title, abstract, or keywords. The following descriptors were employed: (a) "ecosystem service" or "ecosystem services," and (b) "Sustainable Development Goals" or "2030 Agenda."

From this result, an exploratory analysis of the papers was carried out and, when convergent with the study theme, those presenting a relationship between ecosystem services and the 2030 Agenda, at the macro or micro level, exploring the relationship between ecosystem services and SDG 11, were selected for analytical reading.

Based on the conceptual framework of the Millennium Ecosystem Assessment, which also had an ecosystem service approach, as well as on the links between ecosystem services and human well-being, the analysis of the level of dependence of the ecosystem services in relation to water was defined within three levels: (a) ecosystem service in which water or land is the object of the process; (b) ecosystem service that depends on water or land to occur; (c) ecosystem service the potentially depends on water or land.

Subsequently, the search in the Web of Science database using the descriptors "Sustainable Development Goals" or "2030 Agenda" in the topic option was reconducted, with the introduction of descriptors related to the nuclear field: <"Nuclear Application" or "Nuclear Power" or "Nuclear Technology" or "Irradiation" or "Isotope" or "Nuclear Radiation" or "Nuclear Instrumentation" or "Uranium" or "Nuclear Fuel" or "Nuclear Material" or "Nuclear Physics" or "Nuclear Reactor" or "Nuclear Security" or "Nuclear Research">.

From this approach and the design of NST applications to SDG 11, a new search was carried out, searching for the main manuscripts in NST convergent with the targets of this SDG. Subsequently, analytical reading enabled the association between the NST and SDG 11, with the identification of ecosystem services mediated by the use of nuclear science, and the main (and most relevant) references on each aspect are summarized in Table 1.

## 4. Data Analysis and Results

The final search in the Web of Science database resulted in 55.217 publications, 74% of which approached the subject ES, and the remaining 26% discussed the 2030 Agenda. With the introduction of descriptors relating the nuclear field to Agenda 2030, we obtained 35 validated records whose studies had a disciplinary focus on energy generation, energy efficiency, nuclear instrumentation and techniques for the environment, medical and health applications, stable isotopes in environmental studies, and the modification of materials. It is noteworthy that the evidence of synergies between NST and the achievement of SDGs was dispersed in the literature and difficult to identify, which reinforces the need for this study.

We found that anthropic actions cause deep oscillations in natural water supply, especially those concentrated in large and megacities. They also place the dynamic impacts balance of natural ecosystems at risk, contributing to the loss of their benefits and biodiversity [5–7]. This mainly affects water ecosystem services, which support all ecosystem services and are directly related to human well-being and global policies for development [2,3,13,14,16,31,49,68–72]. Figure 1 presents the level of dependence of support, provision, regulation, and cultural ES regarding water ES, as well as the connections between these services and the components of human well-being.

Water scarcity refers to the restriction of water both for human activities and for the maintenance of vital processes in nature, and it is determined by four main factors: (i) a decrease in normal rainfall levels; (ii) natural environmental capacity to store water in the soil, subsoil, and in water bodies (related to the characteristics of coverage, use, and occupation of land and geological and pedological aspects of each region); (iii) the capacity to store rainwater in reservoirs; and (iv) demand, linked to water consumption for different purposes. The relationship and synergy between these factors are the main components of water scarcity in a given region and period of time, making it crucial to incorporate the ecosystem dimension in water crises in large urban settlements around the world [30,68,70].

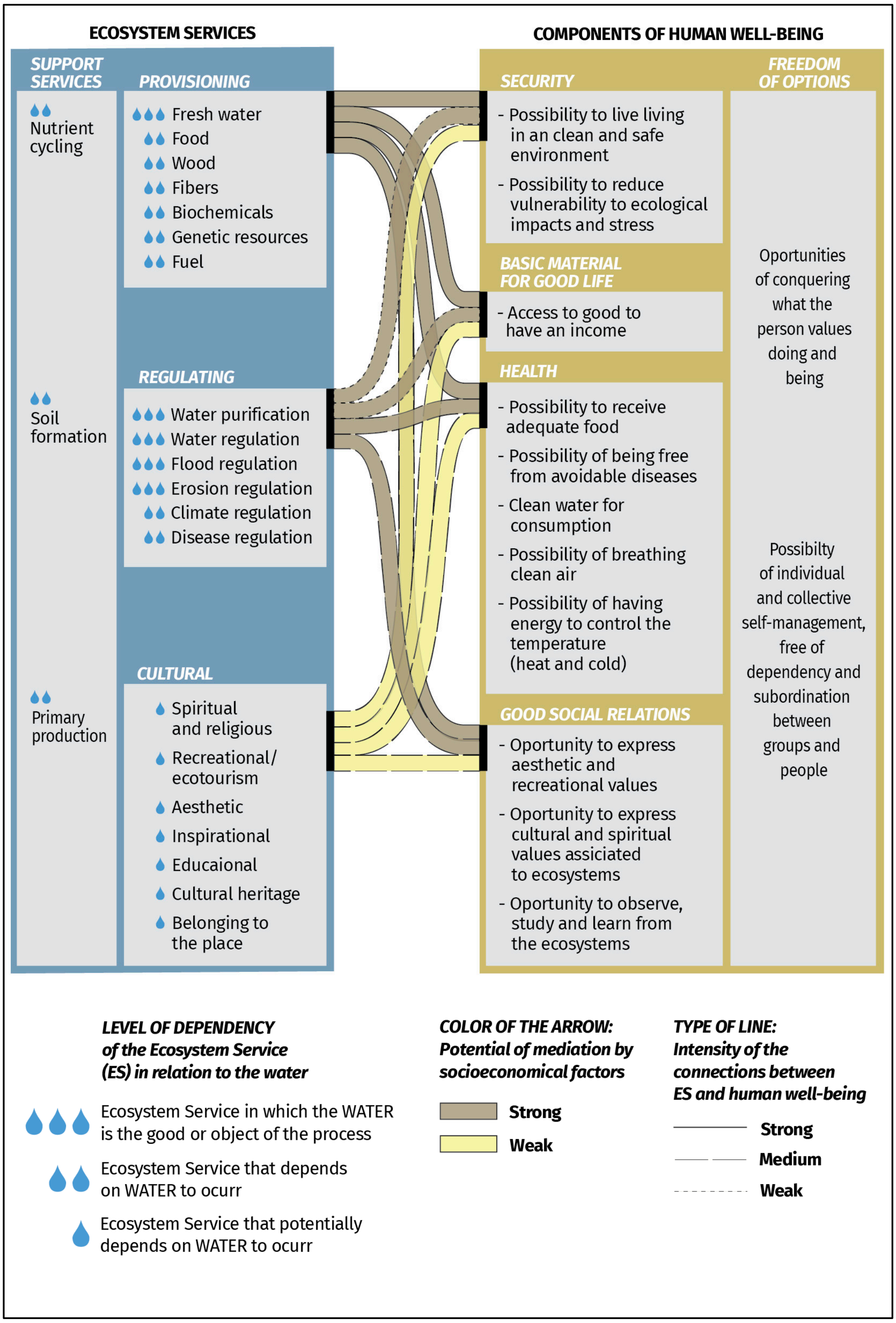


**Figure 1.** Relationship between hydric ecosystem services and the components of human well-being; adapted from: [68]. Copyright © 2003 World Resources Institute.

An analysis of water demand and supply in 12 large cities and megacities has revealed a deficit in 11 of them, which altogether affect up to 178 million inhabitants—Cairo (Egypt); Delhi, Kolkata, and Mumbai (India); Dhaka (Bangladesh); Ho Chi Minh (Vietnam); Jakarta (Indonesia); Lagos (Nigeria); Lahore (Pakistan); Mexico City (Mexico); and Tehran (Iran). With a deficit of 5.27 billion $m^3$/year, and a projected increase of 118% by 2035, if the urban water management sector is not improved, water crises are very likely to occur in these cities; moreover, climate factors may reduce the already vulnerable supply [3].

In this way, stable isotopes have wide applications in urban studies, especially related to water loss. Both deuterium (D) and $\delta^{18}O$ have elucidated issues related to water crises. These isotopes were used in a study of a severe water crisis in a megalopolis located in the western USA, in the city of San Francisco, CA. The authors observed that more than 6% of the water was lost by evaporation during the study period. In addition, it was possible to identify new sources of water that supplied the population during the drought [73].

In a global assessment of the vulnerability of the urban surface water supply, a distinction was made between "vulnerable cities"—those exceeding minimum limits for human, environmental, and storage requirements—and "threatened cities"—those exceeding some, but not all three limits. Vulnerability was assessed both in a baseline condition (2010) and future scenario (2040) for 70 cities in 39 countries with a surface water supply, no diversity of water sources, and more than 750,000 inhabitants. The study pointed out that 35% of the large cities were vulnerable in 2010, with an estimated increase of 45% in 2040. Most of these cities were supplied by rivers with such low flow rates that they had already experienced "chronic water scarcity" [16].

As the impact of local and global climate change should significantly affect water supply services in these large urban centers, a need for water management integrating the trend of current and future impacts and the greater demand for a scarce resource requires innovations and changes to science-based approaches that increase urban resilience and contribute to the 2030 Agenda [14,15,60,74]. A multisectoral approach strengthening ecosystem integrity and function will benefit all SDGs [6,75–78].

A serious problem related to large human settlements and water is the eutrophication of rivers, lakes, or reservoirs. Eutrophic urban aquatic systems have pathogenic microorganisms that are carried by domestic and/or hospital waste, such as viruses, bacteria, and fecal coliforms, or that proliferate under these conditions.

A tool widely employed to monitor such urban impacts are stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), which are good tracers of contamination at the ecosystem scale [79]. The $\delta^{13}C$ stands out for allowing the inference of energy sources, while the $\delta^{15}N$ allows the evaluation of the element along the trophic levels of a system (varying between 2 and 4‰ as the trophic level increases) [80].

However, there are some limitations in the isotopic methodology in eutrophication studies. An example is the cycling of phosphorus, a fundamental element for the maintenance of aquatic systems. Radioisotopes ($^{32}P$ and $^{33}P$) are limited by short half-lives. In this sense, researchers use methods that apply dual isotopes for some more specific evaluations, i.e., in addition to phosphorus, they also use the stable isotope of oxygen present in the phosphate molecule ($PO_4^{-3}$-$\delta^{18}O_{PO4}$). This practice has been applied even when the eutrophication indicator molecules are constituted exclusively by stable isotopes, i.e., nitrate ($\delta^{15}N$-$NO_3$ and $\delta^{18}O$-$NO_3$) and ammonium ($\delta^{15}N$-$NH_4$) ions have been used together to explain sources of pollution in aquatic systems [81,82].

Certainly, eutrophication is not the only problem in the water bodies of large and megacities; however, it is one of the main ones. Therefore, the isotopic tool emerges as a way to monitor and solve urban problems related to water contamination.

The environmental dimension of the 2030 Agenda enables the adoption of integrated actions impacting the economy and social aspects of sustainable development, and vice-versa. This relationship is evidenced in the Agenda's structure, where the notion of sustainability is intertwined with and supports the 17 goals, with 93 of the 244 indicators referring to environmental issues [12,83,84].

Numerous studies show that the use of green spaces brings benefits to physical and mental well-being [85,86]. A very important tool to assess the "health status" of green areas in cities, (i.e., to assess ecological patterns and processes), is by means of stable isotopes [32,33,87]. Carbon isotopes ($\delta^{13}C$) have been widely employed to evaluate ecophysiological processes, especially focusing on the evapotranspiration capacity of trees, which have a high potential to humidify the atmosphere, thus promoting an essential ecosystem service [88]. In addition, some authors have applied nitrogen isotopes ($\delta^{15}N$) as a tool for monitoring air pollution [89], as well as using $\delta^{13}C$ and $\delta^{15}N$ to assess the interference of the vehicular fleet in the canopy of the urban forests in the megacity of São Paulo [32].

In Africa, carbon isotope records in sediment evidence suggest that the primary production in Lake Tanganyika may have declined by about 20%, implying an approximately 30% decrease in fish production, with evidence that the impact of the regional effects of global climate change on aquatic ecosystem functions and services may be greater than that of local anthropogenic activity or overfishing [41].

Regarding the environmental agenda, pollution caused by plastics and microplastics is a growing concern, with about 70% of plastic waste being deposited in the sediments of water bodies, while nearly the entire remaining 30% is deposited in surface waters and in the water column. Microplastics accumulate in sediments and can be ingested by epibenthic and benthic organisms, dispersing through the food chain, with risks of human contamination by consumption of fish and seafood [90,91]. Recycling plastics and rubber can be improved by radiation technologies, and plastic pollution can be mitigated by monitoring techniques and by the evaluation of the impact of microplastics on marine environments [91–94].

The characterization of microplastics can be done using nuclear techniques such as scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS), Fourier-transform infrared (FTIR) spectroscopy, near infrared spectroscopy (NIR), Raman spectroscopy, and nuclear magnetic resonance (NMR) [91]. FTIR using attenuated total reflection (ATR) as an optimization technology has identified various types of microplastics ingested by marine organisms [95] and has been used to identify different microplastics in beach debris and sea surface microlayer and beach sand samples, with confirmation of the polymer type and additional information, such as its origin and behavior [96,97]. NMR spectroscopy can also be employed to identify the concentration of microplastics. Quantitative determination by NMR is based on the fact that the intensity of the signal is proportional to the number of protons supporting a given resonance, and it can achieve high quantitative accuracy—greater than 98%—and detect microplastics of any shape, size, or polymer [91].

However, the use of nuclear and isotopic technologies is not restricted to the recovery and monitoring of ecosystems and their services. As the SDGs are integrated and indivisible, several of these are strongly related to health through their respective goals and indicators. In addition, the social determinants of health (SDH) [98] have a strong influence on human health and the urban environment and directly interfere with the implementation of SDG11. With most of the human population living in urban environments, ambient air pollution is the main cause of preventable premature death and disability in the world [99–101]. An estimated nine million annual deaths are directly attributable to environmental pollution (4.2 million to ambient air pollution and 2.9 million to domestic air pollution) [102].

In an analysis of 47 European cities, a variable load of local mortality due to air pollution was identified, reaching up to 15% of annual premature mortality for particulate matter ($PM_{2.5}$) and 7% for $NO_2$ [99]. Studies also link evidence that polluted air can compromise cognitive ability as people age [103,104]. Acute and chronic exposure to PM air pollution is also associated with an increased risk of death from cardiovascular diseases, in addition to PM being an important endocrine disruptor, contributing to metabolic diseases and diabetes mellitus [101,102]. Hundreds of hundreds of thousands of lung cancer deaths annually worldwide can be attributable to PM air pollution; however, there is still limited epidemiological evidence regarding air pollution and the risks of other cancers (e.g., bladder and breast cancer) and its association with lower levels of cancer survival [100].

In this complex picture, urban health ranges from epigenetics to health inequities in the urban environment, with growing evidence that the underlying causes of disease in the urban context can be found in the physical and socioeconomic environments [105]. Nuclear medicine provides diagnostic, prognostic, predictive, and intermediate biomarkers for use in oncology, cardiology, neurology, and infectious and inflammatory disorders, with diagnostic and therapeutic applications in biophotonics (laser, optical methods of diagnosis and treatment by laser, nanoparticles, brachytherapy, or radiopharmaceuticals) [51,106–108]. The availability of radioisotopes is of continuous and growing importance for nuclear medicine, for both diagnostic and therapeutic applications [107].

Economic development requires a growing, secure, and stable energy matrix, since any interruption in supply can be catastrophic and compromise the conservation of food, products and inputs, production processes, and the transport of goods and materials. With technological and experimental advancement, small and mobile nuclear fusion reactors may emerge as a disruptive technology, providing cheap and clean energy [29]. The closed fuel cycle, with a fast reactor, at the nuclear power plant site presents itself as a technological opportunity for the establishment of an "ecologically correct" nuclear energy system, with a critical role in the implementation of the 2030 Agenda [109].

Nuclear technologies provide competitive, innovative, and unique solutions for fighting hunger and malnutrition [110,111], ensuring animal production and health [112], and providing food security, including techniques for adapting agricultural systems to climate change [113,114] using practices that promote more efficient management of water, soil, nutrients, and other agricultural resources [48,115–117].

The exploitation of genetic and induced diversity is a basic requirement of plant breeding for sustainable food production. The goal of induced mutation is to increase the mutation frequency rate to select appropriate variants for plant breeding. Nuclear technology has offered significant benefits in the genetic improvement of seeds and vegetatively propagated crops worldwide. Radiation-induced mutations have been the most widely used method for developing varieties, accounting for about 90% of the varieties obtained—64% with gamma rays and 22% with X-rays. The types of radiation available for induced mutagenesis applications are ultraviolet radiation (UV) and ionizing radiation (X-rays, gamma-rays, alpha and beta particles, neutrons, and protons) [118].

Examples of the use of NST for agriculture include the extensive use of high-yielding varieties, which has allowed Vietnam to become the world's largest rice exporter, with major achievements attributed to the use of nuclear techniques; more than 55 mutant varieties have been developed, of which most are rice. These varieties have produced significant social and economic effects, contributing to poverty attenuation in some areas. In Japan, around 147 direct-use mutant varieties have been induced by gamma ray irradiation, including Japanese pear cultivars that exhibit disease resistance. In India, several gamma radiation-induced rice mutants have been released as high-yielding varieties, some of which are early maturing varieties [119].

With records dating back to 1950, radiation-induced mutations have been applied in more than 70 countries [119]. When considering the various techniques employed for mutation breeding, 3402 mutant varieties of more than 233 plant species have been recorded worldwide. Among these varieties, we can find cereals (47%), ornamental plants (21%), legumes and vegetables (17%), oilseeds (3%), fodder and forage (3%), fruits (3%), cultivars for fiber (2%), medicinal plants (1%), grasses (1%), cultivars for sugar (0.5%), and tobacco (0.4%) [120]. As most mutant cultivars are rice varieties (815), which is the most important food crop in the world, these results highlight the role of induced mutagenesis as an important strategy to contribute to global food security and sustainable agriculture [51,119,120].

Some mutant varieties are depicted in Figure 2. Binachinabadam-6 (Figure 2A) is a mutant peanut variety for commercial cultivation in the saline areas of Bangladesh. To obtain it, the peanut mutant variety Mut-3 was obtained by irradiating the seeds of the local cultivar Dacca-1 with gamma rays. A plant with different characteristics was obtained in the field and named Mut-6. The seeds of Mut-6 were subsequently irradiated with a 250 Gy gamma ray dose to obtain the Binachinabadam-6 mutant variety [120]. Clemenverd

(Figure 2B) was created by the irradiation of shoots using fast neutrons to generate induced mutations in the Clemenules variety (clementine), along with successive grafting and final selection. This variety was selected for its bud size and late maturity. Binadhan-15 (Figure 2C) is a rice variety developed using carbon ion beams to induce mutations in the Ashfal variety. This mutant variety presents tolerance to high temperatures, is insensitive to the photoperiod, and has a shorter duration than the parent variety.


**Figure 2.** Represented mutant varieties. (**A**) Binachinabadam-6; (**B**) Clemenverd; and (**C**) Binadhan-15; source: [120]. 

In Africa, manioc cultivation using improved methods of nuclear science has tripled the productivity by applying nitrogen isotopes to monitor water and fertilizer use [51].

In addition, it must be considered that most of the population lives in cities, and the issues of food security are alarming in developing countries. With the dependence of urban centers on urban and peri-urban agriculture, food production can be optimized with the application of nuclear technologies [51,118–123] in order to contribute to the resilience of cities.

Regions with fragile economies, i.e., Latin America and Africa, have large carbon reservoirs and can substantially contribute to climate change mitigation. Forest restoration programs can take advantage of irradiation techniques to generate new varieties of seedling crops, thus increasing genetic variability. These issues still need to be better studied, especially in countries on these continents. Botanical collections, used to disseminate the characteristics of flora and mycota of a region, country, or continent, can also benefit from radiation as a method for their conservation [124].

Food security is also directly linked to water security [68], which is a critical issue for megacities and their environmental and economic sustainability, as well as for human development, particularly in face of global population growth [1]. Access to safe and drinkable water is an important factor in maintaining human health and meeting the needs of a growing population. The quality and availability of water resources are also crucial for the sustainable production of energy, industry, and the sustainability of ecosystems and their services.

Nuclear isotopic techniques provide methods for the recovery and conservation of water sources and important information regarding their characterization [30,31,33,49–51,125–127], as well as on the human impact on the climate [51,123,128,129]. As terrestrial pollution, notably from large urban settlements, accounts for about 77% to 100% of marine pollution [130], nuclear and isotopic techniques may mitigate these impacts [51].

To assess the direct contribution of NST to the urban dimension of the 2030 Agenda aiming at developing climate-resilient cities, focusing on water and climate change, we sought to correlate information on the application of NST and its impact on human well-being, using the ecosystem services concept as defined by the Millennium Ecosystem Assessment conceptual framework [4,5]. Based on previous studies [23,71], the use of NST was detailed with a view to achieving SDG1 1 (Inclusive, Safe, Resilient and Sustainable Cities and Communities) (Table 1).

**Table 1.** Nuclear science and technology and its contributions to the Sustainable Development Goal 11—Sustainable Cities and Communities.

| Targets | Contributions of NST to the Targets of SDG 11 | Authors |
|---|---|---|
| 11.1 To ensure access to adequate, safe, and affordable housing and basic services and upgrade slums. | Quality and quantity of water resources; surface and underground. | [30,31,33,42,50,51,73,79,81,82,108,116,125–127,131] |
| | Identification and monitoring of pollutants. | [32,51,79,89,94–97,108,126,132] |
| 11.2 To provide access to safe, affordable, accessible, and sustainable transport systems for all. | Modification of materials aiming at the sustainable development of products for the transport system, with higher quality and elimination of toxic chemical residues (cable insulation, automotive tires, and other products). | [51,91–93,108,133] |
| 11.3 To enhance inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management. | Monitoring and remediation of contaminated areas. | [51,79,108] |
| | Tracing and identifying the origin of air pollutants. | [41,47,51,89,108,132,134] |
| | Transformation of plastic into recyclable material. | [51,91–93,133] |
| 11.4 To strengthen efforts to protect and safeguard the world's cultural and natural heritage | Preservation of cultural heritage, including disinfection, preservation, restoration, and analysis of materials used in artifacts. | [24,25,51,108,124] |
| | Preservation of natural heritage, including identification of contaminants, polluting sources that threaten natural resources, and studies of paleoenvironments. | [30,31,33–38,43,44,51,79,108,124] |
| 11.5 To significantly reduce the number of deaths and the number of people affected by disasters and substantially reduce the direct economic losses caused by them, including water-related disasters. | Control and monitoring of how climate change affects the environment. | [40,41,47,51,89,108,127,134] |
| | Development of climate-resilient crops, climate-smart cultivation methods, food conservation, and animal production. | [45,46,48,51,108,112–114,117–120] |
| | Studies of natural processes that influence the global dissemination of pollutants and their deposition rates on land and sea. | [40,51,108,127,132,134] |
| | Studies of the paleoclimate and development of models to predict changes in the global carbon cycle and climate. | [38,39,51,127] |
| 11.6 To reduce the negative environmental impact per capita of cities, including with special attention to air quality, municipal waste management, and others. | Nuclear medicine and radiation techniques applied in health sciences for diagnostic and therapeutic applications | [51,106–108,110,111] |
| | Identification of isotopes in different contaminants to measure their concentration and trace their origin for the recuperation of contaminated areas. | [51,79,89,94–97,108] |
| | Production of clean and low carbon energy. | [26–29,51,108,109] |
| | Use of radiation for wastewater treatment and cleaning of air contaminants. | [42,47,51,108] |
| | Development of efficient methods of soil management and conservation and urban and peri-urban agricultural production. | [48,51,115–117] |
| | Increased genetic variability of agricultural crops and native species. | [51,118–123] |
| | Monitoring and tracking of building sediments, dredging, or plastics in coastal areas. | [51,94–97,125] |

**Table 1.** *Cont.*

| Targets | Contributions of NST to the Targets of SDG 11 | Authors |
|---|---|---|
| | Modification of plastics and other materials to increase recycling. | [51,91–93,133] |
| | Treatment of nitrogen oxides ($NO_x$) and sulfur oxides ($SO_x$) present in combustion gasses, as well as effluents from industry, and to make sewage sludge suitable for application in agriculture. | [51,108,135] |
| 11.7 To provide universal access to safe, inclusive, and accessible green and public spaces for all. | Assessment of urban green spaces and qualification of ecosystem processes in urban forests. | [32,39,50,51,73,79, 87–89,108,115,116, 127,136,137] |
| | Irradiation techniques to generate new varieties of seedling crops for forest restoration programs. | [51,108,118–123] |
| 11.a To support positive economic, social, and environmental links between urban, peri-urban, and rural areas by strengthening national and regional development planning. | Assessments of ecosystem services provided by peri-urban areas and benefits for urban areas with a view toward regional development. | [30–34,36,37,39,41, 48,50,51,73,79–82,87–89,108,115, 116,127,136,137] |
| 11.b To increase the number of cities and human settlements with integrated policies and plans towards inclusion, resource efficiency, mitigation, and adaptation to climate change, resilience, and holistic disaster risk management at all levels. | Technical cooperation and assistance to local governments to improve agricultural practices, remediate contaminated areas, mitigate climate change, assess freshwater resources, biological systems, atmospheric processes, and ocean ecosystems. | [51,108] |
| 11. c To support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials. | Potential support for large and megacities in least developed countries for the modification of chemical, physical, and biological properties to produce new, more resistant materials to be used in the construction of buildings, as well as in the application of methods of non-destructive testing to assess the property of materials or components without causing damage to the tested object. | [51,108] |

Nuclear science is an area that enables the development of innovative strategies for the 2030 Agenda. The application of isotopic and nuclear techniques directly contributes to the achievement of issues other than water related-SDGs, such as SDGs 2 (zero hunger), 6 (clean water and sanitation), 7 (clean and affordable energy), 9 (industry, innovation, and infrastructure), 13 (climate action), 14 (life below water), and 15 (life on earth), which necessarily depend on the recovery and conservation of ecosystems and their services [23,51].

By generating several technologies that allow the mitigation of negative impacts on urban and peri-urban ecosystems, and also to rehabilitate ecosystems, NST is potentially increasing these ecosystems' capability to provide ecosystem services. NST provides many possibilities to directly improve human well-being and enhance environmental health.

The analysis of the results showed that nuclear techniques and stable isotopes are used to assess biological systems, freshwater resources, ocean ecosystems and atmospheric processes, as well as to study the processes in which pollutants are integrated into biological, geological, and chemical cycles and to assess impacts on the environment, particularly the fingerprints of man-made and natural pollution [51,130].

The framework analyzed points to the importance of NST for building resilient cities, as focused on SDG11. However, global development policies and the 2030 Agenda are intertwined by economic, social, and environmental goals, as an "indivisible whole." As the SDGs depend on each other, actions to minimize trade-offs and mutual reinforcement are needed to implement public policies that reflect the many interactions between the goals and how interventions in one sector can positively or negatively affect another [75].

While countries have made progress in implementing the New Urban Agenda and the urban dimensions of the SDGs, there are still challenges that need to be addressed.

The analyses presented in this study show that the fundamental role of ecosystems and their services are implicit in the global vision articulated by the SDGs. At the same time, the importance of using and applying nuclear science-based tools, especially to address challenges related to ODS 11 and to environmental protection, water availability, and climate change in urban spaces was highlighted.

## 5. Conclusions

As global development policies and ecosystem services have an intrinsic relationship, their approach to the urban context highlights the challenge of achieving a universal commitment to sustainability and resilience for a growing population. This population both influences and is influenced by the concentrated occupation of the territory and by global climate change, whose impacts will increase in the medium and long term.

The depletion of natural resources and its consequences for human well-being expand the range of adversities and commitments for humanity, notably in terms of water shortages and their costs for people and for the maintenance of the ecosystems that sustain life in all of its forms.

In this complex context, NSTs are important tools for the implementation of the SDGs, especially those linked to the urban agenda. This research identified positive correlations between all SDG 11 targets and the use of NST in areas such as energy, human health, food production, cultural and natural heritage, the development of stronger materials, environmental and water resources management, conservation, and recovery.

With the continuing trend of human population growth and its concentration in urban areas, NST is a strategic tool to ensure larger and safer food supplies—either by inducing mutations for plant breeding, or by using isotopic and nuclear techniques to improve the efficiency of crops—protect soil and water resources, or increase organic carbon fixation in the soil.

Human activities degrade and pollute natural environments and create serious consequences for human well-being and the sustainability of the planet, including uncontrolled climate change and massive biodiversity loss. Nuclear science-based tools are playing an important role in protecting, conserving, and restoring the environment.

Noteworthy are initiatives for the circular economy, industrial innovation, reducing dependence on fossil fuels, and the transition to low-carbon energy sources, such as nuclear energy, expected to assume an increasingly important role in the coming decades, along with isotopic hydrology and its role in the dynamics of urban systems and water supply.

The many applications of nuclear and isotopic science include air pollution monitoring, the ecophysiological assessment of urban forests; the monitoring of eutrophication in aquatic systems and water management in face of climate change; food safety assessment; food conservation; archaeological, ecological, geological, and paleontological investigations; and the conservation and protection of cultural and natural heritage artifacts.

Their use for detection and identification of microplastics successfully demonstrates the potential of such techniques to address this global challenge, while radiation technologies can stimulate degradation and enhance the recycling of plastic and rubber, besides promoting the development of industrial and building components with superior properties.

Access to nuclear medicine and radiation technologies applied to health sciences (including the use and implementation of new techniques or processes that use radiation for diagnosis, therapy, and applications) are fundamental for health promotion, especially in an urban context, and requires regulation, research, and innovation.

Overcoming urban environmental problems through stable isotopes, as well as monitoring possible impacts caused by the contemporary lifestyle, is a way to guarantee sustainability towards a development model aligned with environmental and climate agendas. When considering the diversity of NST applications and the potential of its contribution for cities to become inclusive, safe, resilient, and sustainable spaces, the popularization of such technology and its wide transfer becomes crucial.

In addition to the integration between nuclear scientists and researchers in the ecosystem services and urban planning areas, it is necessary to integrate the scientific community and decision makers so that governments of large and megacities can promote supportive environments for the application of science-based tools, especially those using nuclear science and technology. The design and implementation of public policies based on its application, and the continuous improvement, innovation, and regulation of the use of NST in the various sectors, is fundamental to respond to the challenges faced by humanity, just as its reorganization towards the 2030 Agenda is of utmost importance.

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