REVIEW

Innovations in science, technology, engineering, and policy (iSTEP) for addressing environmental issues towards sustainable development

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GRAPHICAL ABSTRACT

PUBLIC SUMMARY

- The evolution of sustainability science and the essence of sustainability and sustainable development are reviewed.
- Climate change, biodiversity loss, land degradation and desertification, and pollution hinder the SDGs achievement.
- iSTEP is addressing key environmental issues towards sustainable development, with its synergies outlined.
- Recommendations and future perspectives on iSTEP for promoting sustainable development are proposed.

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Sustainable development depends on the integration of the economy, society, and environment. Yet, escalating environmental challenges pose threats to both society and the economy. Despite progress in addressing environmental issues to promote sustainability, knowledge gaps in scientific research, technological advancement, engineering practice, and policy development persist. In this review, we aim to narrow these gaps by proposing innovation-based solutions and refining existing paradigms. Reviewing past research and actions, we first elucidate the evolution of sustainability science and the essence of sustainable development and its assessment. Secondly, we summarize current major environmental issues, including global warming and climate change, biodiversity loss, land degradation and desertification, and environmental pollution, as well as their relationships with sustainability and the achievement of Sustainable Development Goals (SDGs). Subsequently, this review critically evaluates the role of innovations in science, technology, engineering, and policy (iSTEP) and their synergies in advancing sustainability and SDGs. While their sequential relationships may vary based on specific contexts or sustainability scenarios within the iSTEP framework, each component reinforces the others, fostering continuous improvement. Finally, this review offers recommendations and future perspectives for formulating sustainability roadmaps. Recommendations include fostering a vision of sustainability, promoting interdisciplinary collaboration, and encouraging transboundary cooperation among stakeholders for future sustainability endeavors.

INTRODUCTION

Sustainable development is based on three pillars: economy, society, and environment.[1-3] Currently, there is growing evidence of their interrelations and recognition that environment-related issues, particularly global warming and climate change, biodiversity loss, land degradation and desertification, and environmental pollution (the focal issues of the upcoming Global Environmental Outlook-7 of the United Nations Environment Programme (UNEP), (https://www.unep.org/geo/ global-environment-outlook-7), pose challenges that threaten to fundamentally undermine global society and economy.[4-7] As we stand at the crossroads of an increasingly interconnected world,[8] it is imperative to reflect on past theoretical frameworks and practical interventions that have shaped the discourse on environmental sustainability.

The achievements and limitations of previous research and practical initiatives have laid the foundation for the current state of sustainability science.[9] Noteworthy advancements have been made, with theoretical frameworks providing conceptual insights and practical solutions emerging in response to pressing environmental concerns. However, amidst these strides, research gaps persist, creating an imperative to explore uncharted territories and refine existing paradigms. One notable example of innovation for sustainable development is found in China's trailblazing efforts in the establishment of Sustainable Development Agenda Innovation Demonstration Zones.[10] These zones serve as living laboratories, integrating scientific research, technological advancements, engineering prowess, and robust policy frameworks, exemplifying a concerted effort to integrate diverse disciplines, test novel strategies, and advance the nation's commitment to sustainability. Despite these commendable efforts, there is limited information sharing by researchers and partners on the latest innovations and methods and their strengths and weaknesses. There is also a lack of clarity about how these can be applied and scaled up to support the monitoring of Sustainable Development Goals (SDGs) globally. There are gaps in understanding the skills and capacities needed to leverage innovation-based solutions for sustainable development.

The present review aims to bridge these gaps through critically examining past and ongoing initiatives, extracting lessons from theoretical underpinnings, and distilling practical experiences to inform future endeavors. The overarching question that motivates this review is to provide a broad critique of the peer-reviewed scientific literature on sustainability and sustainable development and propose innovative science-, technology-, engineering-, and policy-based solutions with the potential to support national, regional, and global sustainable development. This aims to unravel the scientific complexities of multidisciplinary interventions, understand the dynamics of policy implementation, and identify key success factors in technology and engineering that can drive more effective transformative change towards sustainable development.

The review begins by detailing the concepts of sustainability, sustainable development, and SDGs. It analyzes various proposed definitions that have been put forward, followed by a description of the key environmental issues related to sustainability, including climate change, biodiversity loss, land degradation and desertification, and environmental pollution. This review then maps the innovations in science, technology, engineering, and policy (iSTEP) aimed at promoting sustainable development and highlights their strengths and limitations to support national, regional, and global measurement and monitoring of the SDGs. Finally, this review discusses the synergies in iSTEP that facilitate sustainable development, highlighting key insights in terms of policy relevance, science and technology advancement, engineering considerations, finance support, and sustainability policy aspects, followed by concluding comments.

THE EVOLUTION OF SUSTAINABILITY SCIENCE

After the term "sustainable development" first appeared in the International Union for Conservation of Nature's (IUCN) 1980 World Conservation Programme report, it has evolved into a key development framework. It seems likely to continue for the foreseeable future.[11] Sustainable development, in its literal sense, conveys the notion of "development that can be sustained," encapsulating both development and sustainability.[2] Scholars hold different perspectives on the relationship between these two concepts. One perspective asserts that there is no inherent contradiction between development and sustainability.[2] Another view acknowledges the coexistence of the two but recognizes the potential for mutually negative consequences.[12] Some argue that development and sustainability are inseparable, emphasizing that one cannot exist without the other.[13] Hence, a clear understanding of the meaning of sustainability is vital for comprehending sustainable development.

The essence of sustainability

At its core, sustainability implies the capacity to maintain a particular state or process over a prolonged period.[14] Given this broad understanding, the sustainability concept applies to various human activities. Initially, the term sustainability was confined to World Bank documents, referring to the willingness of other entities to continue supporting World Bank loan projects after repaying its loans.[15] However, starting from the 1970s, as environmental concerns gained momentum, sustainability in the World Bank context began to encompass environmental and resource considerations. In reviewing 19th and early 20th-century literature, Kidd[15] identified six foundational research ideas related to the concept of sustainability, viz. ecological carrying capacity theory, resource environment theory, technology criticism theory, biosphere theory, no growth/slow growth theory, and ecological development theory.

Due to the multifaceted nature of the meaning of sustainability, various compound terms have emerged under different research perspectives and contexts, such as "ecological sustainability," "social sustainability," and "economic sustainability".[2,16] In 1999, the U.S. National Research Council (NRC) published a study titled "Our Common Journey: The Transition to Sustainability," introducing the term "sustainability science".[17] Subsequently, Kates et al.[17] published an article in the journal Science entitled "Sustainability Science." Although it is a mere two-page opinion piece, it emphasized that sustainability science revolves around understanding the fundamental characteristics of natural and social interactions across different scales, with a particular emphasis on the intricate evolution of natural-social systems in response to multiple and interconnected pressures. This publication led to the emergence of numerous academic works incorporating "sustainability" in their titles, including the establishment of the journal *Sustainability Science* in 2006.[18]

Martens[19] identified five core elements of sustainability science, encompassing interdisciplinary research, the co-creation of knowledge, a systems perspective emphasizing the co-evolution of complex systems and their environments, "learning by doing" or "learning by using" as crucial experiential foundations, and a focus on institutional innovation. A review by Clark and Harley[20] contends that sustainability science is a practical science defined by the real-world problems it addresses, particularly sustainable development challenges. Recent research in sustainability science has concentrated on the co-evolutionary relationships between natural and social elements in dynamic developmental pathways. These studies consistently emphasize that discussions of ecological, social, or other sustainability-related topics should adopt the holistic and systematic perspective of sustainability science.[20] Hence, the term 'sustainability' should exclusively denote integrated developmental concerns related to the interaction of nature and society, and should not be arbitrarily prefixed, as doing so may lead to misleading or biased outcomes.

The essence of sustainable development

The definition of sustainable development presented by the World Commission on Environment and Development (WCED) in the 1987 report "Our Common Future" is a fundamental reference point for contemporary research and discussion on sustainable development.[1] However, Mebratu[21] highlights that any new concept undergoes a gestation process, and certain pivotal theories, insights, and concepts pave the way for its emergence. Mebratu[21] offers a historical analysis of the concept's development, categorizing it into three stages, viz. a pre-Conference on the Human Environment phase (before 1972), the period spanning the Human Environment Conference to the release of the "Our Common Future" report (1972-1987), and a post-1987 phase up to present day. Zharova and Chechel[22] further denote these stages as the embryonic, formative, and developmental stages of the sustainable development concept, respectively.

In sum, the initiation, development and maturation of the sustainable development concept can be envisaged as following the process outlined in Figure 1. Technological and industrial advancements, coupled with population growth, escalated consumption were acknowledged as posing threats to the availability of natural resources. Scientists and philosophers began contemplating a holistic approach to human development, one that transcended mere economic considerations and raised concerns about environmental degradation, limits to growth, the "tragedy of the commons", and the resilience of social ecosystems, warning against the repercussions of unbridled growth. A consensus gradually emerged within the discourse, initially capturing the attention of non-governmental organizations, international and national government agencies, and eventually businesses and individuals.

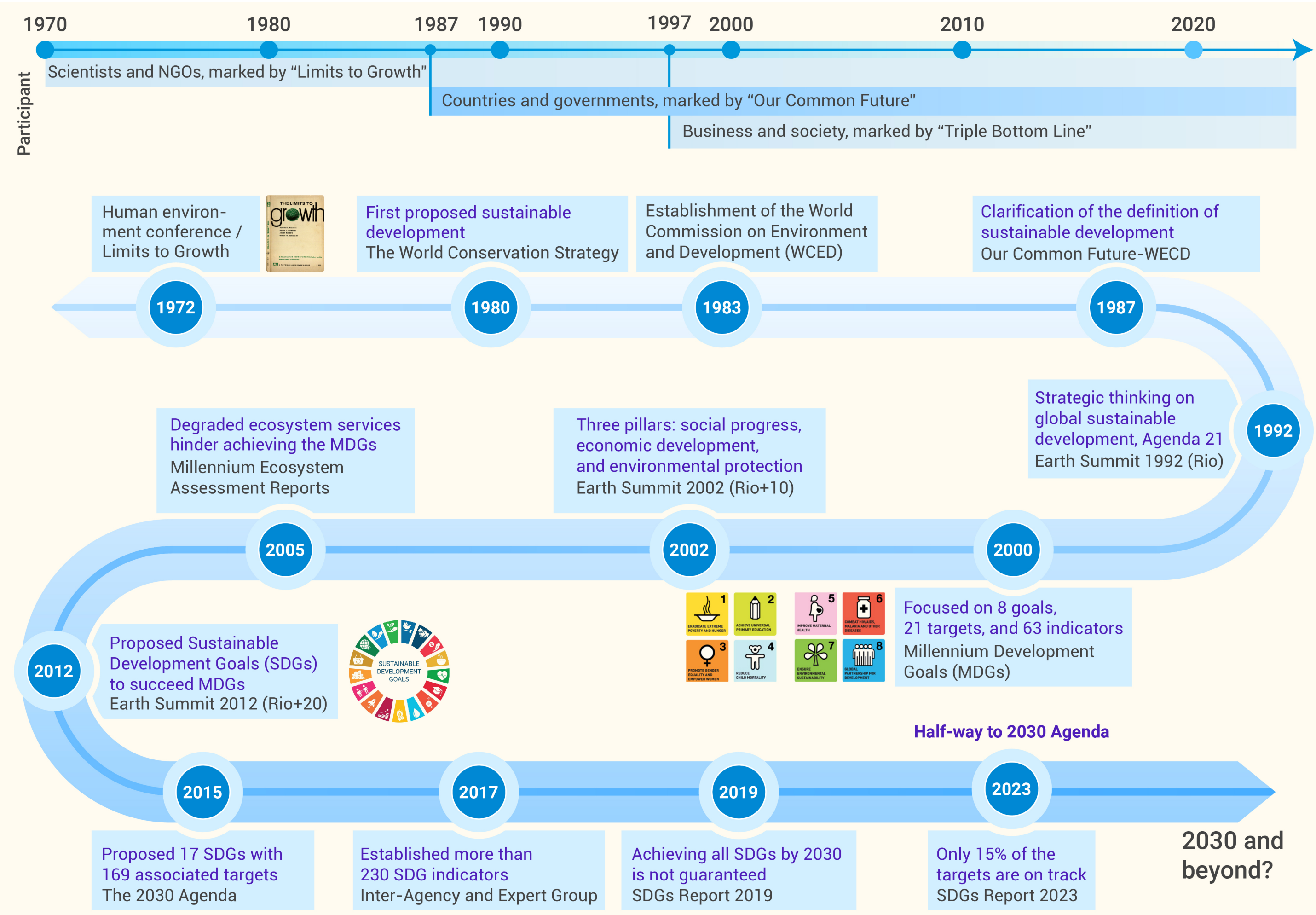

Figure 1. An illustration of the birth and maturation of the concept of sustainable development.

The theoretical foundation of the SDGs is weak,[23,24] and a comprehensive sustainable development theory does not exist. Instead, there are different contested theoretical approaches and definitions.[25–29]

Meanwhile, the "pillars" of sustainable development have been a focal point of scholarly debate.[30] The 2002 World Summit on Sustainable Development held in Johannesburg, South Africa, officially introduced the idea that economic development, social progress, and environmental protection constitute the three pillars of sustainable development, emphasizing their interdependence and mutual reinforcement.[30] This marked the first instance of the three pillars concept being endorsed in a United Nations General Assembly report. However, as early as 1987, Barbier[31] posited that sustainable economic development involves trade-offs between environmental, economic, and social systems, laying the foundation for the three pillars concept. Furthermore, from a corporate responsibility perspective, John Elkington (1997) proposed the "triple bottom line" for enterprises to practice sustainable development, consisting of people, planet, and profit, often referred to as the "3P" principle.[32] This idea also appeared in the 2005 UN Summit report but was subsequently modified to people, planet, and prosperity.[30] In 2015, the 2030 Agenda, the "3P" principle was further expanded into the "5Ps," encompassing people, planet, prosperity, peace, and partnership.[33]

Klarin[16] analyzed important United Nations report documents from 1972 to 2015, revealing a thematic evolution in sustainable development. This evolution was marked by shifts from an early emphasis on resource scarcity and environmental pollution expressed during the 1972 United Nations Conference on the Human Environment, to a more balanced consideration of environment and socioeconomic development as presented at the 1992 United Nations Conference on Environment and Development. Subsequently, poverty alleviation became a priority during the Millennium Summit in 2000 and the World Summit on Sustainable Development in 2002. However, Klarin[16] emphasizes that these thematic transitions do not imply a diminishing focus on environmental protection but rather a growing acknowledgment of the imperative to combat poverty and enhance the well-being of marginalized populations through environmental stewardship. Additionally, the emergence of the COVID-19 pandemic, commencing in December 2019, underscored the importance of factoring in the capacity to respond to major public health crises as a foundation and leveraging opportunities for achieving sustainable development.[34-36] Nevertheless, while the definition and specific objectives of sustainability continue to evolve, the overarching process of striking a balance between social progress, environmental conservation, and economic development persists as the essence of sustainable development.[36,37]

Sustainability assessment indicators

Monitoring and evaluating sustainability using indicators is imperative as a more intuitive understanding of its intricate and complex dimensions, including the determination of whether sustainable development objectives have been attained, an analysis of existing issues, and providing a foundation for decision-making in the formulation of pertinent policies and implementation of actions are all essential.[38,39] The call for countries to develop relevant indicators to facilitate decision-making on sustainable development actions at all levels was initiated by Agenda 21, leading to substantial efforts by various organizations and institutions in creating indicator systems.[16]

Despite numerous sustainable development indicator systems, Kates et al.[40] noted that indicator selection often reflects subjective preferences, causing disparities and conflicts between systems. Historical issues include a lack of specified timeframes for achieving sustainable development, with a tendency to focus on short-term progress. Developing universally acceptable

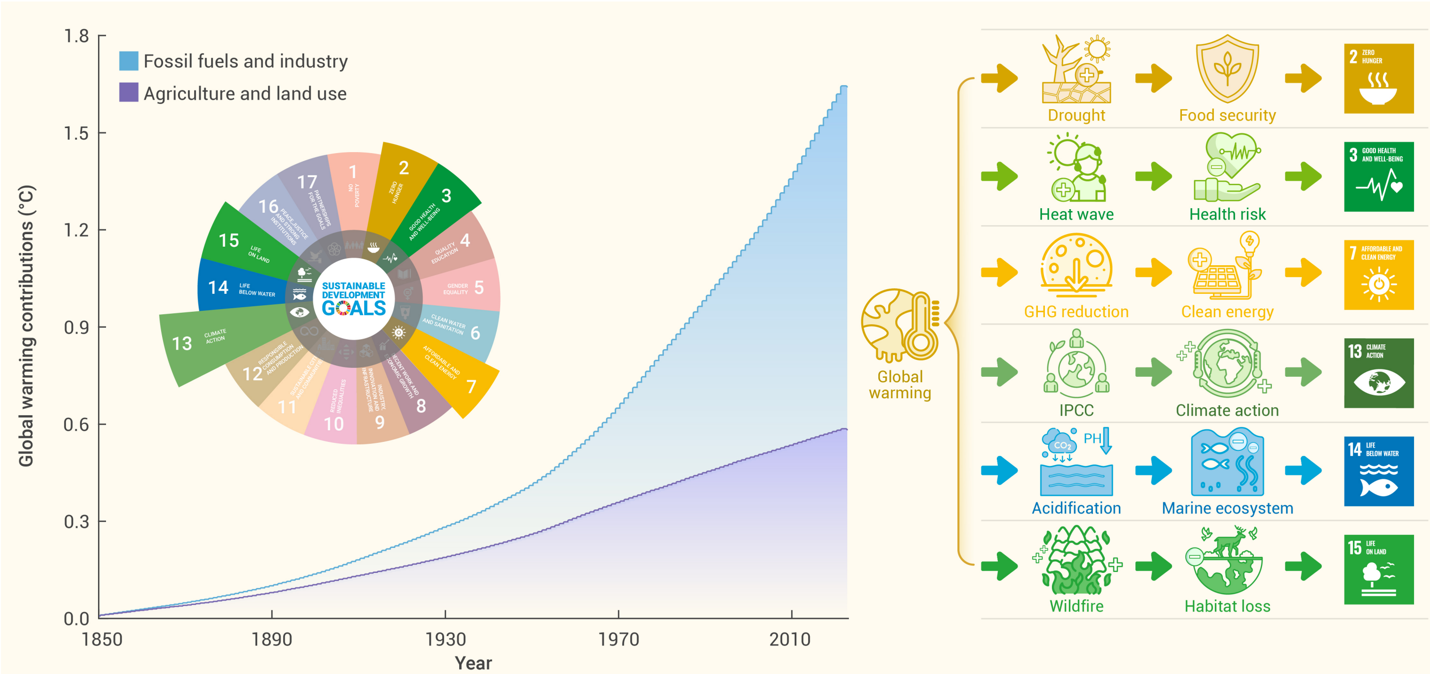

Figure 2. Global warming trends and associated impacts on sustainable development.[78]

indicator systems remains a key challenge.[40] Progress has been made in sustainable development indicator systems, particularly in developing sets and aggregate indices.[41] The Commission on Sustainable Development (CSD) designed 134 indicators based on the "Driving Force–State–Response" framework. Criticisms led to revisions, and the current tendency is to incorporate thematic and sub-thematic structures, departing from generalized social, economic, environmental, and institutional classifications.[41]

Aggregate measures, such as composite indices, play a role in sustainable development assessment. Various methods, including geometric averaging and factor analysis, have produced indices related to social, economic, and environmental properties.[42] Some scholars have explored using different indices to construct evaluation frameworks, emphasizing well-being and sustainability criteria.[43,44] In the realm of environmental issues, it is crucial to highlight the evaluation of sustainability. Indices such as the Ecological Footprint, Environmental Sustainability Index, Human Development Index, Happy Planet Index, and Living Planet Index contribute to assessing environmental dimensions.[45] However, such 'environmental' indices are strongly focused on biophysical elements of SD and largely ignore the other two pillars, and challenges persist in achieving universally acceptable indicator systems, and stakeholder disputes remain.

Notably, the Sustainable Development Goal Index (SDGI), jointly developed by the United Nations Bertelsmann Stiftung & Sustainable Development Solutions Network (BE-SDSN) in 2016, comprehensively incorporates the 17 SDGs. However, it is important to acknowledge that the current SDGs framework has been criticized for a lower emphasis on environmental indicators, reflecting a need for greater balance across social, economic, and environmental dimensions.[46-48]

ENVIRONMENT-RELATED ISSUES AND SUSTAINABLE DEVELOPMENT

Accompanied by the increasing intensification of anthropogenic activities, environmental challenges and their impacts on ecosystems have received incremental attention, especially climate change, biodiversity loss, land degradation and desertification (LDD), and environmental pollution.[49,50] The UNEP Medium-Term Strategy 2022–2025 focuses on tackling these crises in the coming four years. A central concern is the cascading effects driven jointly by climate changes and anthropogenic activities in general. All species living on our planet are subject to the direct and indirect impacts induced by such interactive effects. These interconnected crises pose a great challenge to sustainable development, which requires a systematic analysis from the perspectives of environmental impacts and actions to deal with the integrated challenges.

Climate change

Anthropogenic activities, including fossil fuel usage, industrial and agricultural production, as well as human-induced land-use change, have led to an increase in greenhouse gas (GHG) emissions, resulting in a global temperature rise of 1.8°C since the 19th century,[51] as shown in Figure 2. In addition, anthropogenic emissions of aerosols can affect the climate both directly and indirectly.[52] These aerosol emissions mainly come from industrial production, vehicle exhaust, agricultural activities, etc. The direct effects include scattering and absorption of solar radiation, resulting in a cooling effect as the surface receives less solar energy; while the indirect effects involve the influence of aerosols on the properties of clouds, which may lead to changes in precipitation patterns.[53]

Global warming and climate change are some of the most pressing worldwide issues.[54] It exacerbates weather and climate extremes across the globe, such as heatwaves,[55] droughts,[56,57] and floods,[58,59] leading to losses and damages to nature, human society, and the economy. Over the past two decades, the rising temperature has caused annual heat-related mortality to reach close to 490,000 deaths globally,[60] and heatwave-induced droughts directly led to increased risk globally of water scarcity among more than 933 million people living in urban areas.[61] Meanwhile, rising temperatures have accelerated the regional hydrological cycle and exacerbated flooding risks, placing 1.81 billion people in direct exposure to extreme floods (100-year return period) across the globe.[62] With the continuous acceleration of global warming, climate change-related extreme events increase the threat to human lives and livelihoods, particularly in the low and middle-income regions, accompanied by exacerbated inequality that seriously impacts sustainable development overall.[63-65]

Tackling global warming and climate change is not only a direct target of climate (SDG 13),[66] it also promotes sustainable development from other perspectives, including natural resource access (SDG 7), biodiversity (SDGs 14 and 15), food security (SDG 2), and human well-being (SDG 3).[67-69] Indeed, there is a growing demand for restructuring global systems to mitigate and adapt to these effects while promoting sustainable development. Moreover, it is important to reform current production and consumption systems to reduce GHG emissions and actively promote the capture of carbon dioxide (CO_2) from the atmosphere and crucial to transition away from fossil fuel-based energy sources towards renewable and clean energy alternatives.[70-73] This shift can be achieved through various means such as investing in

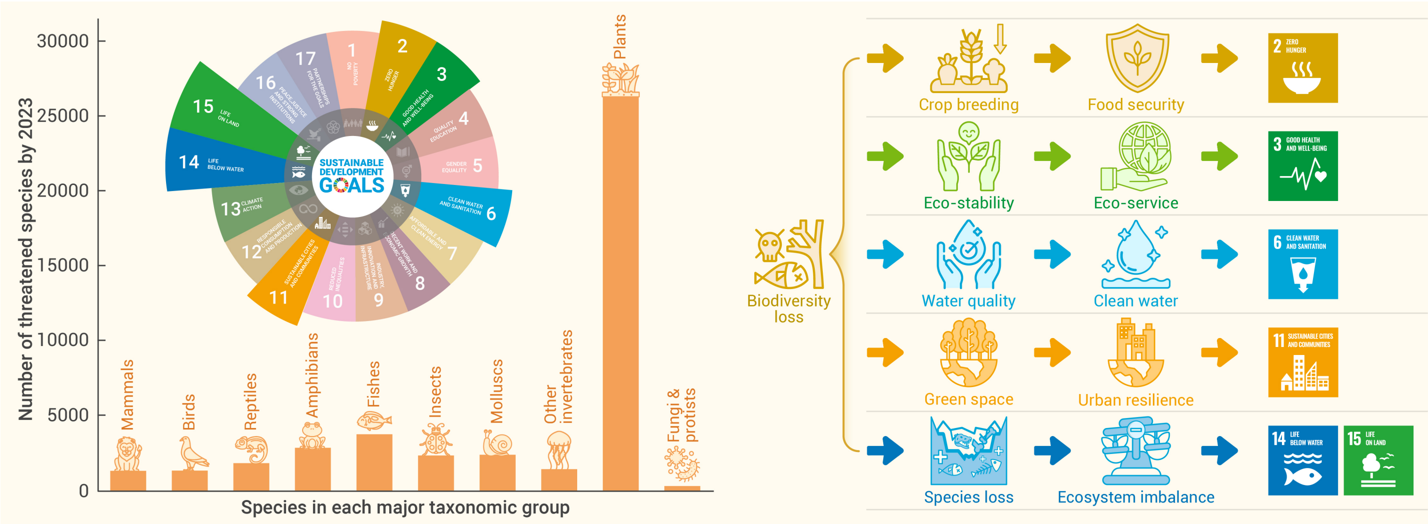

Figure 3. Biodiversity loss across species and associated impacts on sustainable development.[102]

renewable energy technologies like solar, wind, hydroelectric power, and geothermal energy.[74] Additionally, improving energy efficiency in industries, transportation, and buildings can significantly reduce GHG emissions. Another key aspect of promoting sustainability is protecting and restoring natural ecosystems. Forest conservation is vital in mitigating climate change as trees absorb CO_2 from the atmosphere through photosynthesis.[75-77] Therefore, efforts should be made to maintain or increase carbon sequestration by vegetation in general, and forest in particular.

Notably, the transformation of industrial structure and energy consumption patterns may lead to short-term economic decline, affecting public acceptance of the above measures.[79] Hence, policymakers and the public must be made aware of the importance of net-zero emissions, and need to be guided by robust, evidence-based scientific research.[80-85]

Biodiversity loss

The sustainability of humanity on Earth is intricately linked to global ecosystems and biological resources.[86] Genetic, species, and ecosystem diversity play a vital role in maintaining the health and functioning of these ecosystems (SDGs 14 and 15), and hence provide a diverse range of benefits and services for human well-being, such as food, water and air quality, and bioenergy (SDGs 2, 3, and 7).[87-90]

Due to multiple stressors, such as climate change, land use change, agricultural and urban pollution, and invasive species introduction,[91-102] terrestrial biodiversity is facing an unprecedented crisis. It is imperative to recognize that a reduction in biodiversity across species[102] (Figure 3) has profound and detrimental impacts on the functioning and sustainability of terrestrial ecosystems, posing a great challenge to the well-being of humanity. On the one hand, species loss can directly affect the balance of the food chain, jeopardizing the stability of the terrestrial ecosystem (SDG 15) and posing a threat to the human food supply (SDG 2). On the other hand, the decline of plants weakens the capture and adsorption of airborne particulate matter and reduces their transpiration-based climate regulation function, with significant impacts on air quality and threats to human health (SDG 3). In addition, species decline affects the production of biomass energy, which is detrimental to the promotion of sustainable modern energy (SDG 7).

Over the past century, aquatic biodiversity loss has been exacerbated by various anthropogenic activities. More explicitly, hydropower and irrigation projects, such as dams and reservoirs built for hydroelectricity generation and irrigation, have fragmented river ecosystems, altered natural flow regimes, and blocked fish migrations, negatively impacting many native aquatic species.[97,98] Meanwhile, environmental pollution such as high ammonia levels, poses a direct threat to aquatic biodiversity by impairing the physiological functions of invertebrates and fish.[100-103] In addition, climate change is exacerbating hydrological extremes, such as prolonged droughts and severe floods, which can push freshwater communities beyond tolerance thresholds, leading to local extinctions.[91-93] These pressures have negatively impacted many native aquatic species (SDG 14), causing changes in flow, sediment, water quality, food webs, and biotic interactions.[91-97] Under these circumstances, fishery resources are at risk of depletion, threatening human food supplies (SDG 2). Furthermore, the reduction of aquatic species weakens the capacity for water purification and eutrophication prevention, resulting in a decline in water quality and posing a challenge to clean water for humans (SDG 6).

The maintenance of terrestrial and aquatic biodiversity is essential for sustainable development, as it not only directly contributes to SDGs 14 and 15 but also enhances the resilience of natural infrastructures and human settlements in response to climate-related hazards (SDGs 9, 11, and 13).[104] Nature-based solutions present a promising avenue for enhancing terrestrial biodiversity by facilitating the preservation and restoration of landscape-scale habitats, as well as land use management. Regarding aquatic biodiversity loss, conservation and restoration efforts, such as protecting free-flowing rivers, implementing environmental flows for regulated rivers, installing fish passes at dams, reducing watershed pollution, and controlling invasive species introduction, can help maintain and restore aquatic ecosystems.[89] Furthermore, sustainable agriculture practices are essential for maintaining biodiversity and reducing environmental impacts. Implementing agroecological approaches prioritizing soil health, water conservation, and biodiversity conservation can help mitigate climate change while ensuring food security for future generations.

Land degradation and desertification

Land degradation and desertification (LDD) is defined as the progressive deterioration or loss of the productive capacity of soils for the present and future.[105,106] The pervasive occurrence of LDD, particularly prevalent in drylands with limited water resources, exacerbates environmental disparities. Globally, about 25% of the total land area has been degraded, leading to a dramatic decline in the productivity of croplands and rangelands worldwide.[107]

LDD leads to three outcomes that influence sustainable development. Firstly, positive feedback between LDD and environmental changes, including climate variability (SDG 13), exacerbates aridity in water-limited regions. LDD alters surface physical properties, such as increasing surface albedo and evapotranspiration, thereby decreasing water vapor flux and precipitation. More importantly, degraded land can exacerbate climate change by reducing carbon sequestration capacity. Secondly, LDD disrupts the balance of social-ecological systems, particularly affecting agricultural areas and thereby the global food security (SDG 2), and leads to poor nutrition and water scarcity (SDG 6), affecting human health (SDG 3). LDD exerts adverse effects on 10%-20% of global drylands,[108] which account for ~45% of the Earth's land surface and support ~33%, ~44%, and ~50% of the global population, croplands, and livestock, respectively (Figure 4).[109,110] With the increasing demand for livestock products, such as meat, projected to double from 258 million tons in

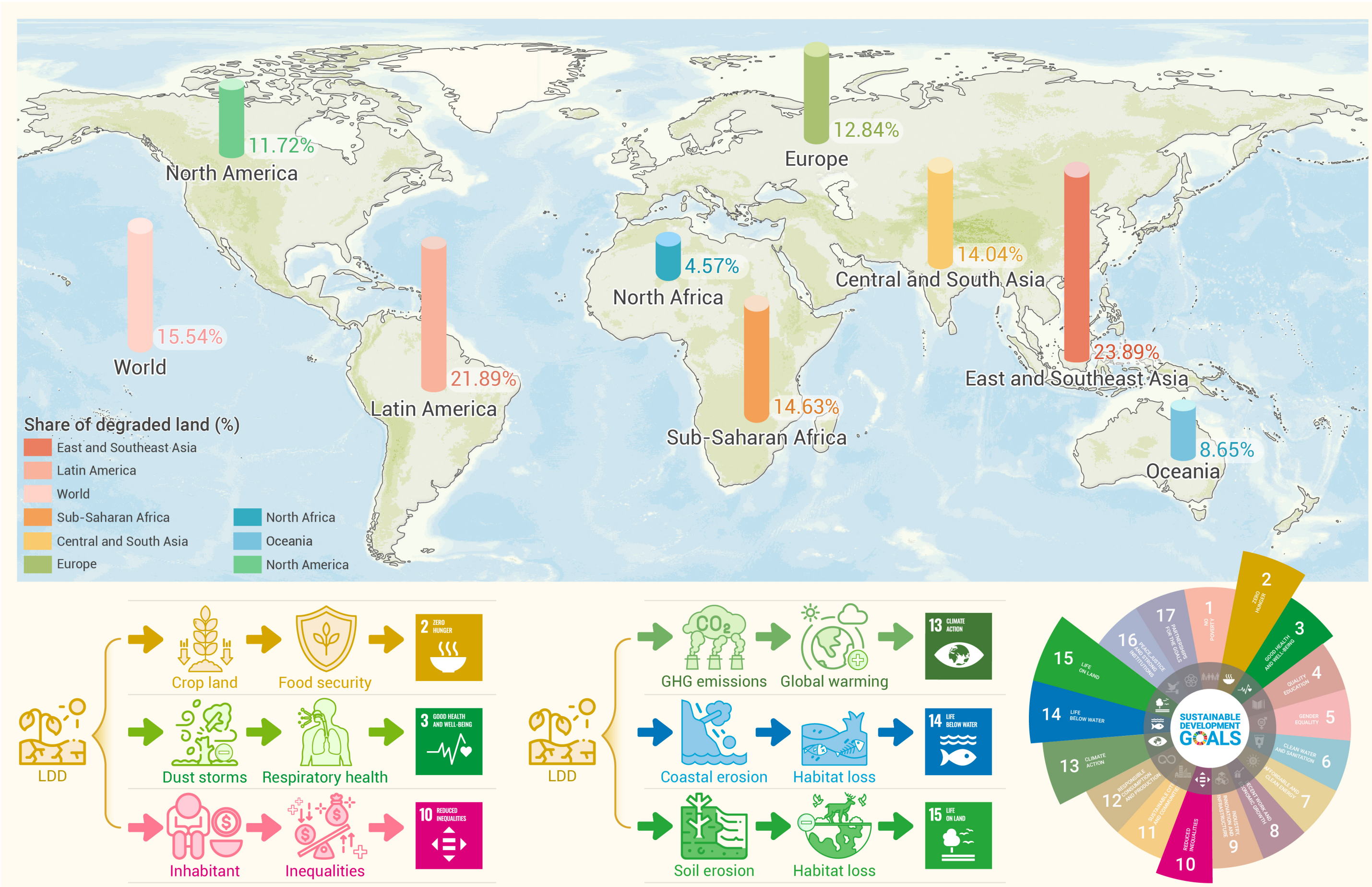

Figure 4. Land degradation across regions and associated impacts on sustainable development.[116]

2006 to 455 million tons by 2050 globally,[111,112] drylands are likely to become more susceptible to LDD. Thirdly, LDD has the potential to decrease the transformation threshold of ecosystems, decreasing their resilience and resistance, which could result in irreversible shifts in ecosystem dynamics (SDG 15).[113] This process can lead to a reduction in available land and encroach upon human habitation space. Drylands are driven by multiple aridity thresholds related to LDD, such as water availability, vegetation productivity, biodiversity, and so on. It is estimated that by 2100, more than 20% of the terrestrial surface will surpass at least one of these thresholds, leading to the abrupt collapse of vegetation and soil.[114,115]

LDD affects vegetation productivity by reducing soil quality such as soil erosion and nutrient loss. Numerous factors related to climate, water, plants, and soil are available to indicate the causes and processes of LDD, which could be utilized to evaluate ecosystem variability. Plant cover is effective for monitoring LDD as it can be easily derived from satellite imagery.[117] However, there are uncertainties regarding the threshold for dryland collapse and its complex interactions with other indicators, such as plant spatial patterns.[118] Freshwaters (streams, lakes, and wetlands) may temporarily or permanently dry out when LDD occurs, with significant implications for the flora and fauna they host, including the disappearance of endemic species.[119-121] Desertification is challenging to reverse once initiated, identifying and selecting the LDD indicators for detecting the onset is a priority necessary to combat desertification.

Perennial plants usually aggregate into patches in a matrix of bare soil, and changes in their spatial patterns have been suggested as potential indicators of degradation in drylands.[122-126] Restoration measures, such as improving soil properties and microclimatic conditions to promote vegetation growth resulting from the positive interactions within plant patches.[127-128] Additionally, optimizing the spatial pattern of carbon source-sink dynamics,[129] introducing biocrusts,[130] planting less water-thirsty crops, implementing drip irrigation, and reducing water use per area are[131] also potential strategies for decreasing the risk of LDD and promoting a sustainable ecosystem. For inland aquatic systems shift to less water-thirsty crops and drip culture as well as restriction in water use per area may help avoid dry outs and devastating salinization effects.[132] Additionally, uncertainties persist regarding the interactions between natural and anthropogenic factors, making it challenging to quantify their contributions to LDD.

Environmental pollution

Anthropogenic activities have spurred widespread environmental pollution issues, including air pollution, aquatic pollution, and soil pollution. These pollution issues have resulted in widespread impacts on various ecosystems, economies, and human well-being,[133,134] severely threatening sustainable development.

Air quality is an essential concern, as it significantly affects human health (SDG 3) and life on land (SDG 15). Since the 1860s, air quality has deteriorated as the Industrial Revolution spread geographically. Various pollutants such as carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), ozone (O_3), heavy metals, and particulate matter ($PM_{2.5}$ and PM_{10}) are emitted into the atmosphere by several natural or anthropogenic activities.[135-138] Moreover, airborne bioaerosols, such as pollen, fungal spores, bacteria, and viruses, can be released and transported through the air,[139-141] posing a serious threat to human health as well as the broader environment.[142] The number of deaths attributed to air pollution (Figure 5) globally in 2015 (3.9 million) was approximately two times higher than in 1990 (2.0 million).[143-145] Among them, the elderly, and those with chronic diseases, especially in low-income groups are most vulnerable to air pollution.[136] In this regard, countries and regions around the globe are endeavoring to address the problem of air pollution[137] as a contribution to human health (SDG 3), and in reducing inequality (SDG 10).

Water pollution is regarded as one of the most worrying issues in sustainable development, as this directly impacts food security (SDG 2) and drinking

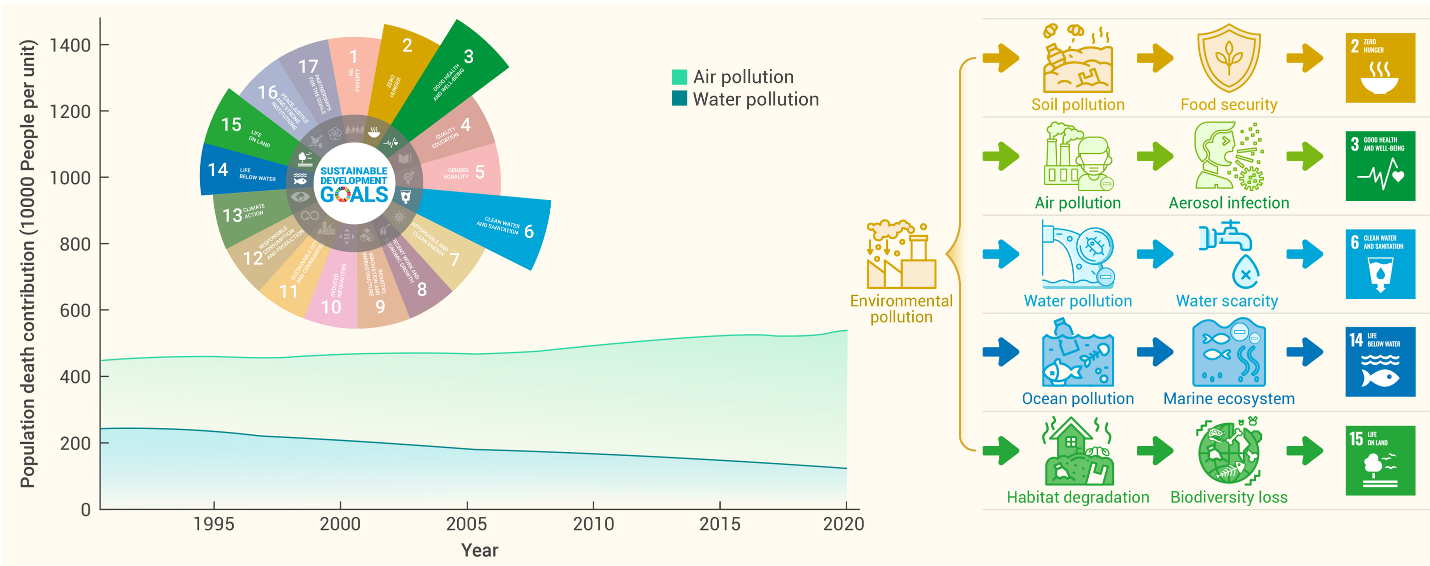

Figure 5. Environmental pollution-induced fatalities and associated impacts on sustainable development.[145]

water safety (SDG 6). A wide range of anthropogenic activities, including urbanization, transport, industry, and pharmaceutical production,[146,147] various pollutants are generated, including organic compounds,[148,149] heavy metals,[150,151] microplastics,[152,153] nutrients, and antibiotics.[151,154] These pollutants are transmitted through sewer systems and eventually enter natural water bodies,[155] causing point source pollution. Meanwhile, agriculture, including crop cultivation and livestock production, instigates the discharge of fertilizer,[156-158] pesticides,[159,160] and animal excrements,[161,162] with excess nitrogen,[137,157] phosphorus,[163,164] and chlorinated toxic compounds,[165,166] which enter water bodies along with rainfall runoff in the form of non-point pollution. One illustrative example is excessive loading of various forms of nitrogen that may have potentially toxic effects on fish,[167] macroinvertebrates,[168] and macrophytes,[169-171] and stimulate the sediment phosphorus release,[172-174] thereby further accelerating eutrophication of aquatic ecosystems. In addition, land-cover transformation, especially deforestation, exacerbates soil erosion surface,[175] increasing sedimentation in water bodies[176] and associated reduction in water quality. Under the impact of hydrological connectivity and geochemical processes,[153,177] pollutants in rivers and lakes ultimately end up in the oceans, which compromises the function of marine ecosystems. As a result, increasing concern has been expressed regarding water pollution as it impacts water security. More than 933 million people currently reside in water-scarce regions,[61] while estimates of annual deaths attributed to unsafe water sources range from 1.2 to 2.5 million (Figure 5).[178] There are inherent risks, not only to human health (SDG 3) due to pollution exposure,[134] but also to regional equality (SDG 10). Deterioration in water quality also results in negative environmental impacts, including eutrophication,[133] hypoxia,[179] cyanobacteria,[63] and fish kills,[180] thereby threatening aquatic ecosystems (SDG 14). Many shallow lakes globally have shifted from macrophyte-dominated to phytoplankton-dominated states due to the eutrophication.[167] Addressing water pollution has therefore become an urgent and pressing challenge.

Healthy soil plays a vital role in sustainable development; it not only sustains global food production systems (SDG 2), but also fundamentally supports life on Earth (SDGs 3 and 15). Soil acts as the foundation of agriculture, serving as the primary resource for cultivating crops and raising livestock and has obvious significance in its contribution to global food security (SDG 2). More than 80% of the calories and 75% of the protein consumed by the global population daily come directly from soil.[181] The global population continues to increase rapidly with a consequent increased food demand but the quality of arable land has significantly deteriorated, resulting in a continuous decline in its capacity to produce high-quality food.[182] Moreover, soil systems have become reservoirs for various environmental pollutants. Soils in the Mediterranean and African regions are subject to heavy pollution from heavy metals,[183] persistent organic pollutants,[184] endocrine disruptors,[185] antibiotics,[186] and microplastics,[187] while the capacity of soil to remove pollutants is limited. Soil pollutants not only hinder plant growth but lead to a decline in the biodiversity of the soil microbiome. Additionally, these pollutants contaminate other elements of the ecosystems, for example via runoff, and may ultimately enter the human body through the food chain. Accordingly, it is essential to preserve soil health to attain sustainable development.

INNOVATIONS IN ADDRESSING ENVIRONMENTAL ISSUES

Addressing environmental issues contributes to sustainable development, which requires collaboration between science and policy communities in terms of both mitigation and adaptation. On one hand, an increasing number of innovative technologies have been adopted to reduce GHG emissions and mitigate compound pollution, such as renewable energy (wind, solar, and hydro),[188] geo-engineering,[189] and bioremediation.[190] On the other hand, various adaptation policies have been implemented regarding resource management,[191] pollution prevention and control,[192] and ecosystem protection.[193] These policies have institutionally facilitated the resolution of environmental issues. However, a gap between science and policy remains because, just as scientific research is time-consuming and replete with inherent complexities and uncertainties, policy decisions are typically required in the short term and are results-oriented.[194] Accordingly, there is a demand for a smooth transition from scientific research to policy implementation. In this regard, the iSTEP framework, which integrates science-based innovations (SBIs), technology-based innovations (TBIs), engineering-based innovations (EBIs), and policy-based innovations (PBIs), offers a promising concept to bridge the gap between scientific and political efforts.

Science-based innovations (SBIs)

Science-based innovations (SBIs) encompass breakthrough advancements and discoveries in existing knowledge and technology aimed at addressing real-world challenges or exploring novel possibilities[195,196] and embrace fundamental research, applied research, technology development, and practical applications. In the realm of environmental science, SBIs incorporate pioneering environmental monitoring technologies, sustainable energy solutions, and ecosystem restoration techniques, among others. At their core, SBIs continually push the boundaries of knowledge to identify more efficient and sustainable ways to manage and safeguard the environment (Figure 6).

The foundation of SBIs lies in the development of novel theoretical frameworks. To address environmental challenges within the context of sustainable development, researchers continuously devise new theories and concepts to gain a deeper understanding of the issues at hand. For instance, the strong/weak sustainability theory introduces the notion of different sustainability types, with strong sustainability emphasizing the non-substitutability between natural and social assets.[197] This theory underscores the critical role of natural resources in human well-being, in contrast to weak sustainability theories that emphasize substitutability. These theoretical

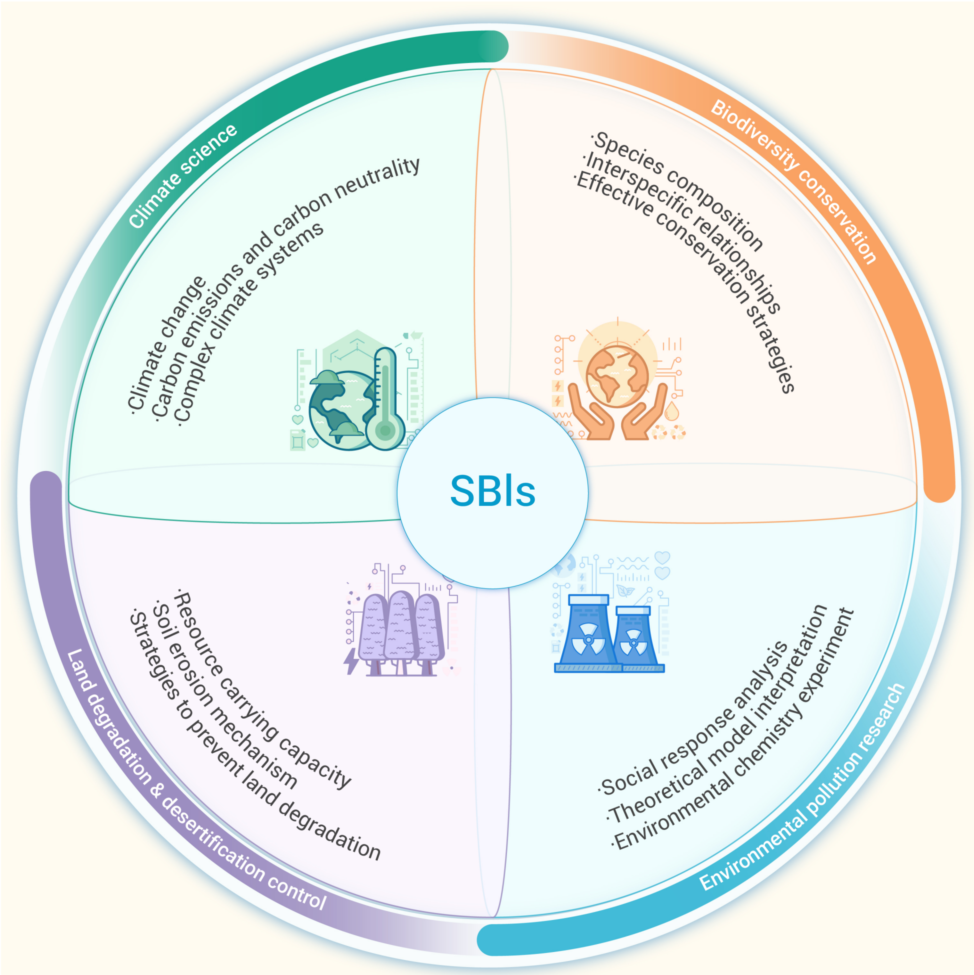

Figure 6. Framework of SBIs for promoting environmental sustainable development.

frameworks provide distinct perspectives, enabling policymakers to better comprehend the nature of environmental issues and formulate more effective policies.

Furthermore, sustainable development, as viewed from a resource and environmental standpoint, seeks to harmonize environmental protection with economic progress and entails using resources at a rate that allows for regeneration while constraining pollutant emissions within acceptable environmental limits.[195] The emergence of new theories that shed light on the complexities inherent in sustainable development typically involve convoluted interactions among various subsystems over extended timeframes.[198,199] New theories are needed that are better equipped to capture this complexity, thereby contributing to improved policy formulation and implementation. Complex science-based research methods, for example, have been instrumental in analyzing ecosystem dynamics and environmental intricacies, offering fresh insights for environmental policymaking.[20]

SBIs serve as a linchpin in addressing pressing environmental challenges, notably in the realms of climate change, biodiversity conservation, land degradation and desertification, and environmental pollution.[200] The development of novel theoretical frameworks in climate science enhances our understanding of complex climate systems and provides essential scientific foundations for global climate policies.[201] Particularly in the realm of renewable energy, innovation propels the development of clean energy, reducing reliance on fossil fuels and mitigating greenhouse gas emissions.

In the context of global biodiversity conservation, research into the ecology, behavior, and genetics of species provides critical information for crafting effective global biodiversity conservation strategies.[202] Concepts such as ecological threshold, island biogeography, and meta-population theory contribute to informed conservation planning.[202] Theoretical advancements also extend to conservation biology, guiding the establishment of protected areas and corridors to preserve biodiversity.

Theoretical contributions to combating land degradation and desertification involve the development of conceptual frameworks in soil science and land management. Soil degradation theories, such as the "cascade model," help elucidate the processes leading to land degradation, guiding the formulation of preventive strategies.[203] Theoretical frameworks in sustainable land management emphasize the importance of integrating ecological, social, and economic considerations to comprehensively address land degradation. Additionally, theoretical advances in agroecology contribute to developing sustainable agricultural practices that promote soil health and resilience.[204] Theoretical contributions from anthropology and human geography shed light on traditional land management practices, offering valuable insights for sustainable land use strategies.[205]

In the realm of environmental pollution, theoretical advancements play a crucial role in shaping our understanding of pollutant behavior, impacts, and societal responses. Theoretical models in environmental chemistry elucidate the fate and transport of pollutants in different ecosystems,[206] while those in environmental ethics contribute to discussions on the moral implications of pollution, influencing policy decisions.[193] Additionally, social theories help analyze the root causes of pollution, considering factors such as economic systems and consumption patterns. Theoretical contributions in environmental justice guide discussions on the equitable distribution of environmental risks and benefits, fostering a theoretical foundation for inclusive pollution mitigation strategies.[24]

While many disciplinary theoretical frameworks such as those discussed above have led to useful insights, interdisciplinary theoretical frameworks are needed to understand and promote sustainable development. Some interdisciplinary frameworks have emerged. For example, the coupled human and natural systems framework focuses on human-nature interactions within a specific place.[207] The telecoupled human and natural systems framework connects human-nature interactions between distant places.[208] The metacoupled human and natural systems framework links human-nature interactions within a specific place, between distant places, and between adjacent places.[209]

In essence, science serves as a crucial source of information and knowledge to guide decision-making and the implementation of sustainable development policies. SBIs aid in comprehending the complexities and challenges of sustainability, such as striking a balance between environmental conservation, resource utilization, and economic development. Scientists employ research and experimentation to obtain data and evidence supporting decisions and practices aligned with sustainable development. Furthermore, science offers technological and innovative solutions for diverse sustainable development issues. Nevertheless, recent analyses indicate that sustainability research has not yet achieved mainstream status in global academic publications.[196] For example, approximately half of the 56 topics most relevant to the eight SDGs accounted for less than 0.1% of the global scientific output between 2011 and 2019.[196] Although the prevalence of sustainability topics is higher in developing countries and smaller scientific communities, the overall number of scientific publications on sustainable solutions remains relatively limited worldwide. Therefore, there is still ample room for improvement in harnessing science's potential to effectively promote sustainable development.

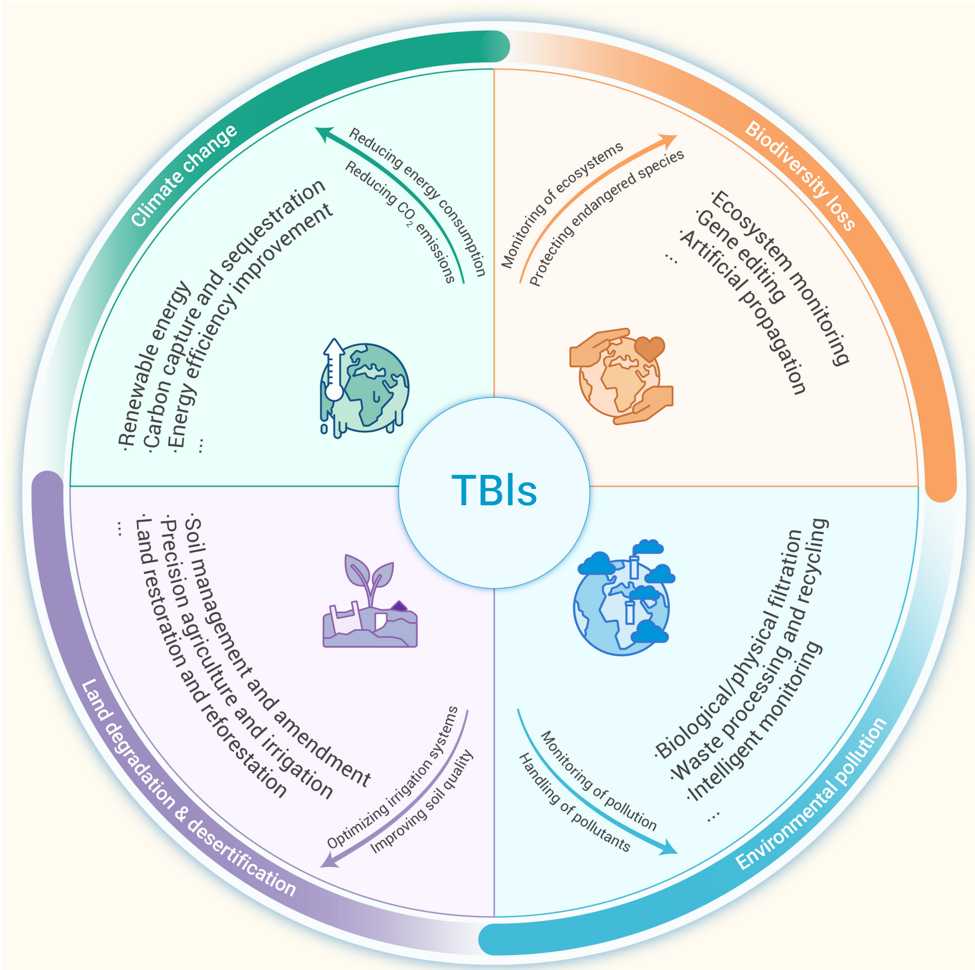

Figure 7. Framework of TBIs for promoting environmental sustainable development.

Technology-based Innovations (TBIs)

Technology refers to the application of scientific knowledge to create tools, systems, or methods capable of solving practical problems, emphasizing the utility of tools and methods and how they can be improved and innovated to meet human needs. Technology-based innovations (TBIs) aim to create new technologies or innovations based on scientific and technological knowledge and the resources they create, including the development of new technologies, or the application of existing technologies for innovation.[210,211] TBIs have been proven to play a crucial role in climate change response and mitigation, biodiversity conservation, land degradation prevention and environmental pollution control (Figure 7).

Climate change is a crucial challenge facing humankind, and global warming is affecting every region globally, through increasing temperatures, sea level rise, and more frequent extreme events.[212-214] A series of innovative technologies have emerged to cope with and mitigate climate change, notably including renewable energy technologies, carbon capture, utilization and sequestration technologies, and technologies that improve energy efficiency. Among them, renewable energy technologies utilize sustainable and continuous energy sources in nature to generate electricity or other forms of energy, which include solar, wind, hydro, biomass, and geothermal energy.[215-217] For example, solar technology converts sunlight into electricity through photovoltaic panels, which can provide heat, cooling, natural light, electricity, and fuel for many applications,[218] and wind technology generates kinetic energy by utilizing large wind turbines located on land or at sea to move air.[219] Carbon Capture, Utilization, and Storage technologies separate carbon dioxide from emission sources and then directly utilize or sequester it to achieve carbon dioxide emission reductions.[220] Energy Efficiency Improvement technologies reduce energy consumption by increasing the efficiency of energy utilization, such as using more efficient lighting and building insulation.[221]

Biodiversity conservation is crucial for maintaining life systems, ecological balance and human well-being, although accelerated urbanization and climate change have led to the continuous destruction and even loss of habitats, posing a great threat to global biodiversity conservation.[222,223] In response, a series of innovative technologies have emerged in this field, mainly including ecosystem monitoring technologies and species conservation technologies. Ecosystem monitoring technology oversees the health change status of forests, grasslands, oceans, wetlands and other types of land cover by using high spatial and temporal resolution and large-scale coverage of remote sensing imagery, and the powerful spatial analysis capability of Geographic Information System technology enables spatial analysis of biodiversity such as the distribution of species, habitat destruction, and the management of nature reserves.[224-227] The development of unmanned aerial vehicles also provides many unique advantages for ecosystem monitoring, for instance the ability to monitor species that are sensitive to human disturbances and difficult to access, as well as higher-resolution image data on a region.[228] In addition, species conservation technologies also play an important role, for example by helping to protect endangered species through gene editing and artificial propagation techniques.[229]

LDD is the process by which land is subjected to natural forces or irrational human exploitation leading to a decline in land quality and productivity.[230] Mismanagement and misuse of land resources threaten the health and continued survival of many species on Earth, including humans themselves. Current major innovations in combating land degradation embrace soil management and improvement technologies, precision agriculture and irrigation technologies, and land restoration and reforestation technologies.[231,232] Soil management and amendment technologies use biodegradable substances and biotechnology to improve soil quality;[233] precision or 'smart' agriculture and irrigation technologies use remote sensing, global navigation satellite system, and drone technology to optimize crop management and reduce water waste through efficient irrigation systems.[233] Land restoration and reforestation technologies combine engineering techniques and ecological principles, such as creating dams and terraces to enhance soil retention and utilizing drones to efficiently sow seeds in vast or inaccessible areas to restore degraded land and increase vegetation cover.[234]

Environmental pollution refers to natural or human-induced damage to the environment due to substance addition that exceeds its self-purifying capacity. Over the past fifty years, the global economy has grown nearly fivefold but at a heavy cost to the global environment.[235] In this regard, the current innovative technologies to prevent and control environmental pollution include biological/physical filtration technologies, waste treatment and recycling technologies, and intelligent monitoring and management technologies. Biological/physical filtration technologies degrade or capture particulate matter and hazardous chemicals in the air, water, and soil environments through specific flora or by using nanomaterials.[236,237] Waste processing and recycling technologies use infrared spectroscopy, X-rays, and machine vision systems to automatically identify and separate recyclable materials, increasing sorting efficiency and recycling rates and reducing labor costs.[238] Intelligent monitoring and management technologies utilize sensor networks to monitor environmental pollution in real time and respond quickly to pollution events.[239]

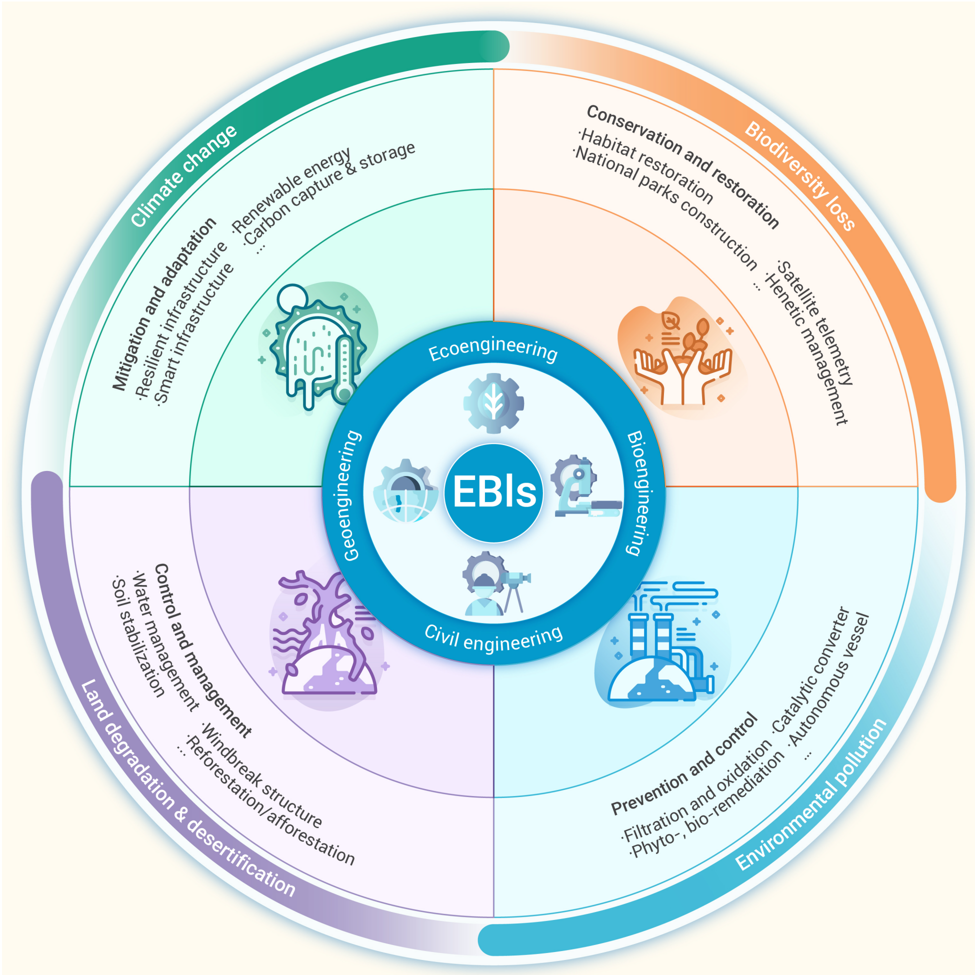

Figure 8. Framework of EBIs for promoting environmental sustainable development.

With the development of information technologies such as artificial intelligence (AI), big data, digital twins, blockchain, etc., there is increasing availability of technologies in the field of environmental sciences. Big data analytics and deep learning technologies enable the definition of ecological reserve boundaries and real-time aboveground biomass estimation, identification and tracking of wildlife populations, and effective identification of biodiversity hotspots on a global scale.[240-242] In addition, remote sensing big data platforms combining digital twins and AI can be used to build an integrated system for land planning and management and to realize the prevention of land degradation and suitability evaluation.[243-246] AI, big data mining, and blockchain technologies can also improve the accuracy and transparency of greenhouse gas emissions monitoring, optimize energy consumption, and promote the fairness and efficiency of the carbon trading market.[247-249] At the same time, the analysis and modeling of massive climate data helps to predict climate change trends more accurately and provide a scientific basis for policy formulation.

TBIs are ushering in a new era, and the use of innovative tools such as intelligent monitoring systems, automated processing technologies, and intelligent management platforms not only improves the efficiency of environmental protection initiatives, but also promotes the sharing and opening up of environmental data, providing a more effective way of monitoring, understanding and protecting the environment, and have become an important part of the promotion of environmentally sustainable development. However, the effectiveness of big data and AI is highly dependent on data quality, while in many cases, environmental data is incomplete, outdated, or biased. Meanwhile, digital twins and certain AI applications are costly, limiting their potential for popularization and application. In this regard, more interdisciplinary technology integration is needed in the future, such as combining AI and remote sensing technologies to improve the efficiency and accuracy of environmental monitoring and management. In addition, through technological advancement and large-scale production, the cost of innovative environmental technologies can be reduced to facilitate their global penetration, especially in resource-limited regions. Overall, despite the challenges, the future of technological innovation in the field of environmental sustainability remains promising. With continued technological advances and increased social awareness, TBIs will be more effective in addressing environmental challenges and promoting global environmental sustainability.

Engineering-based innovations (EBIs)

Engineering-based innovations (EBIs), characterized by their problem-solving approach, serve as an intermediary between scientific theories and technological tools, effectively translating them into practical solutions. This pivotal role is integral in advancing sustainable development initiatives. EBIs have emerged as indispensable agents in realizing sustainable visions and incorporate diverse endeavors such as designing eco-friendly infrastructure for climate change adaptation and mitigation, initiating biodiversity conservation projects, enhancing land degradation management systems, and developing artificial solutions for environmental protection (Figure 8).

The contribution of EBIs to climate change adaptation and mitigation encompass multifaceted approaches. Resilient infrastructure,[155] renewable energy solutions,[250,251] and innovative practices spearheaded by engineers are pivotal in mitigating climate change impacts and navigating evolving environmental challenges. For instance, in achieving SDG 11, smart cities incorporating advanced engineering practices, e.g., Copenhagen's traffic management systems demonstrate increased resilience against environmental pressures.[249] Construction of the Thames Barrier in London highlights the successful implementation of flood-resistant infrastructure in safeguarding vulnerable communities.[253] In deed, climate change mitigation thrives on engineering-driven renewable energy solutions, illustrated in the transition from fossil fuels to sustainable sources, exemplified in SDG 7, that relies on wind and solar power generation initiatives.[254] Additionally, engineering solutions for carbon capture and storage,[255] as seen in the Sleipner project,[256] have a substantial potential in reducing greenhouse gas emissions.

Biodiversity loss emerges as a critical global concern, with ecosystems facing unprecedented threats. Engineering plays a pivotal role across three dimensions – ecosystem, species, and genetic levels – contributing significantly to biodiversity conservation. The range and diversity of adopted EBIs underscores their vital role in addressing the complex challenges confronting the environment. EBIs restore and sustain natural habitats at the ecosystem level,[257,258] as seen in initiatives targeting wetland restoration, such as Florida's Everglades and the Comprehensive Everglades Restoration Plan.[259] These projects employ various engineering strategies to mimic natural processes and revitalize unique ecosystems within SDGs 6, 14, and 15. At the species level, EBIs aid in monitoring and protecting endangered populations;[260] for example, the use of satellite telemetry for sea turtle conservation exemplifies how engineering innovation aids in tracking species movements and identifying critical habitats.[261] At the genetic level, engineering techniques such as genetic management in captive populations,[262] ensure genetic diversity and combat genetic disorders, thereby aiding in species preservation.

Regarding land degradation and desertification, EBIs offer innovative

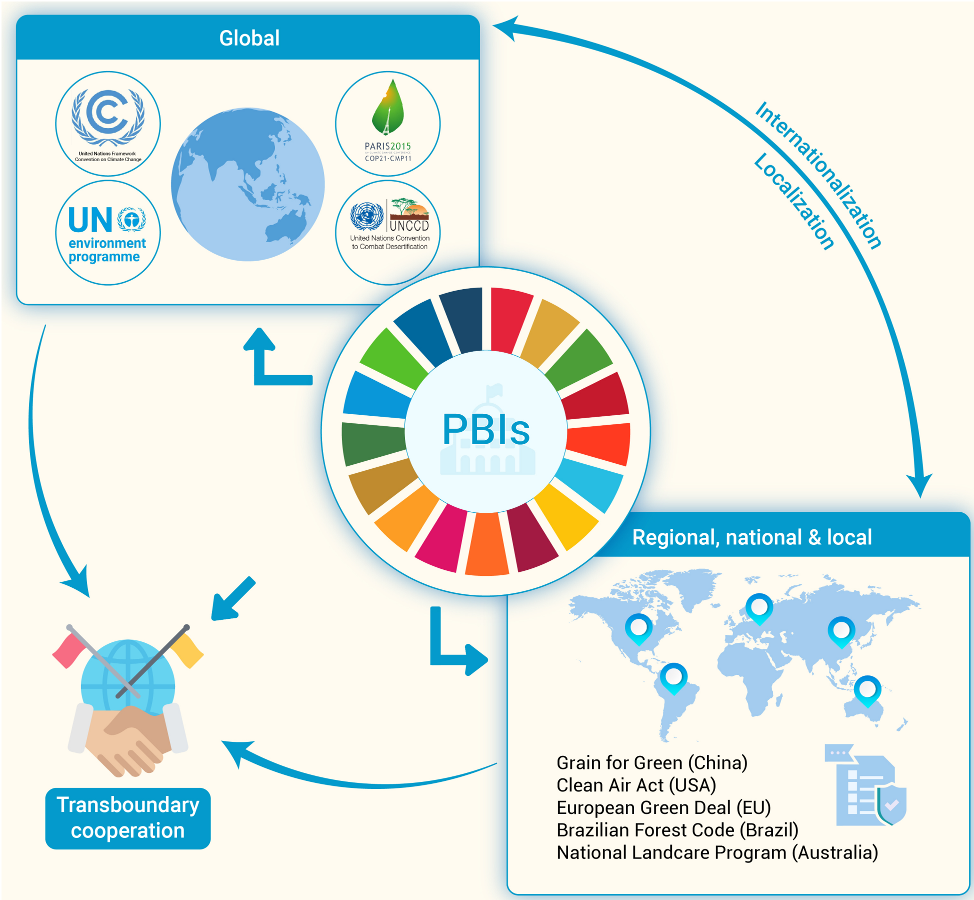

Figure 9. Framework of PBIs for promoting environmental sustainable development.

strategies, such as water management,[263] soil stabilization,[264] windbreak structures,[265] engineered reforestation, and afforestation.[257,266] Soil erosion, a major contributor to land degradation, can be curbed through engineering interventions such as drip irrigation,[267] efficiently delivering water to crops and minimizing water waste and soil erosion. Precision agriculture protects and optimizes water usage, preventing over-irrigation that can lead to salinization and land degradation.[113] Efficient water management strategies and afforestation initiatives, like the Great Green Wall in Africa, combat desertification by restoring degraded landscapes.[268] Additionally, innovative bioengineering solutions combat desertification by introducing plants with enhanced resistance to drought, preventing land degradation.[269] Advanced practices such as satellite-aided monitoring of desertification facilitate targeted engineering interventions.[270] Engineers contribute to ecosystem restoration, biodiversity preservation, and livelihood improvement in vulnerable regions through innovative and sustainable practices.

Environmental issues profoundly impact ecosystems, human health, and Earth's well-being. Engineering has emerged as a critical player in devising sustainable solutions to combat water, soil, air, and marine pollution. Addressing water pollution involves advanced filtration systems and oxidation processes to remove pollutants from wastewater,[271] exemplified by the water-sensitive urban design approach.[272] Soil pollution is addressed through remediation practices that include phytoremediation and bioremediation,[273,274] that help to clean soil contaminated with chemicals, heavy metals, or petroleum products. EBIs innovate and improve emission control devices such as catalytic converters for vehicles and industrial scrubbers[275] that reduce harmful emissions of gases and particulate matter, thereby mitigating air pollution. Marine pollution is addressed through innovative waste management solutions, for example, the Ocean Cleanup Project[276,277] employs autonomous vessels with collection systems to remove plastics and oil spills from oceans and waterways. Sensor-based systems are widely used to monitor quality and detect and assess pollution levels of water, soil, and air.[278,279] These systems can identify the presence, concentration, and movement of pollutants, enabling timely intervention and targeted remediation efforts.

EBIs are pivotal in steering societies toward SDGs by devising engineering practices to address pressing global environmental challenges. However, EBIs face significant hurdles and limitations in fully realizing SDGs. One of the primary challenges is the need to balance technological advancement with environmental protection. While novel engineering developments have improved our lives, their production processes often generate significant carbon footprints.[280] Additionally, implementing sustainable engineering practices faces obstacles related to economic viability and resource availability. Sustainable solutions often require higher initial investments, posing financial constraints, especially in regions with limited resources. Access to technology, education, and adequate infrastructure also plays a crucial role in adopting sustainable engineering practices,[281] highlighting disparities between developed and developing nations. Moreover, integrating sustainability principles across engineering disciplines demands interdisciplinary collaboration and a shift in traditional practices that therefore necessitate a reevaluation of education curricula and professional standards to instill sustainability as a core aspect of engineering education and practice.

Despite these challenges, EBIs are poised for significant advancements that can further drive the achievement of SDGs. Future trends in EBIs particularly related to renewable energy,[250,251] circular economy practices,[282] and smart infrastructure and sustainable urban development.[283,284] Engineers are exploring cutting-edge technologies, e.g., AI,[285] nanotechnologies,[286] and biotechnology,[287] to develop sustainable solutions for energy generation, waste management, and resource utilization. Furthermore, there is a growing emphasis on life cycle assessment and eco-design approaches within engineering processes that entails considering environmental impacts from product inception to disposal, leading to the creation of more eco-friendly and efficient systems.[288] Additionally, advancements in green materials and sustainable manufacturing techniques are revolutionizing industries by reducing their environmental footprint.[289] To overcome limitations, EBIs leverage collaborative partnerships and engage with diverse stakeholders, including governments, industries, academia, and local communities. Such collaborations facilitate data-sharing, resource mobilization, and the development of context-specific sustainable solutions tailored to local needs.

The multifaceted roles of EBIs in addressing environmental challenges underscore their significance in creating a more sustainable future. Technological advancements, sustainable practices, and strategic interventions spearheaded by engineers significantly contribute to global efforts for environmental sustainability. In addressing global challenges that include global warming and climate change, biodiversity loss, land degradation and desertification, and environmental pollution, collaboration among engineers, scientists, policymakers, conservationists, and communities promises innovative strategies for a sustainable future. Although engineering faces challenges in promoting environment-related SDGs, its future development trends show promising avenues for sustainable innovation. Through embracing a holistic approach, integrating sustainable principles, and fostering global collaboration, engineers can indeed be pivotal in driving transformative change toward a more sustainable and equitable future.

Policy-based innovations (PBIs)

Innovative environmental policy is crucial in mobilizing stakeholders from various fields, including scientists, technicians, engineers, and decision-makers, to pool their efforts to address environmental challenges and achieve sustainable development. Throughout history, various policies have been formulated to address a wide range of environmental issues both globally and nationally (Figure 9). However, many policies have failed to yield the expected results, and there remain environmental issues for which effective and innovative policy solutions are still being sought or have yet to be developed.[290] To achieve the highly challenging goals set by the United Nations 2030 Agenda, PBIs have prompted sustainable development governance to shift from palliative interventions to transformative change.[291] The latter emphasizes inclusiveness, broad participation, negotiability, and justice, which means a restructuring of governance power, as well as economic structural changes and shifts in production and consumption patterns.

To address urgent environmental issues such as global warming and climate change, biodiversity loss, land degradation and desertification, and environmental pollution, we need to craft policy-based innovations (PBIs) that account for cross-border interactions between regions. These PBIs should be customized and implemented based on the unique social, economic, and environmental contexts of different regions, effectively addressing their distinct challenges.

There is an urgent need to bolster cooperation among regions and countries to formulate cohesive policies addressing climate change, while the transboundary impacts of global trade cannot be overstated. The current policies to tackle climate change have a notable limitation - they tend to concentrate on reducing GHG emissions within national borders, while often overlooking the transboundary impacts. Globalization has widened the spatial gap between production and consumption sites, leading to a significant displacement of environmental impacts,[292] including those related to climate change. This displacement occurs not only through international trade but also within nations themselves.[293] As a result, improvements in climate change mitigation in one region or country may inadvertently create adverse effects in others due to elaborate trade linkages.[294-296] Comprehensive climate change policy should therefore not only target reducing emissions within any one country or region but should also consider its broader interconnected impact and aim to minimize carbon leakage.[297] Typically, these impacts are transferred from developed to developing nations and from more affluent regions to less affluent ones.[298] For example, manufacturing industries in developing countries, often subject to less stringent environmental regulations than developed countries, are typically significant emitters of GHG emissions.[299] Recent initiatives reflect growing cross-border collaboration aimed at mitigating such environmental impacts. One such example is the Carbon Border Adjustment Mechanism (CBAM) proposed by the European Union, which came into effect in 2023.[300,301] The CBAM is a levy that the European Union plans to impose on the carbon content of certain imported goods. While mechanisms like CBAM are steps in the right direction, there is a pressing need for more initiatives fostering regional cooperation to address environmental sustainability.

Globally, by bringing together stakeholders from various fields, a relatively comprehensive set of policies and regulations for biodiversity protection has been developed. However, policy implementation and localization in different regions are insufficient, and there is a lack of funding.[302] As early as 1987, the United Nations Development Programme began organizing expert groups to explore the possibility of establishing an international convention on biodiversity conservation. In 1992, the Convention on Biological Diversity (CBD) was adopted in Nairobi, Kenya, and subsequently, at the United Nations Conference on Environment and Development held in Rio de Janeiro, Brazil. The Convention was opened for signature to all countries, becoming the international environmental convention with the most signatories worldwide.[303] In 2010, the Tenth Session Conference of the Parties to the CBD was held in Nagoya, Japan, where the Aichi Biodiversity Targets[304] were adopted that represent the first global biodiversity conservation objectives for 10 years (2010-2020) and provide global policy guidelines for biodiversity conservation. The Aichi Biodiversity Targets consist of five strategic goals and 20 action targets, calling on countries to take effective and urgent action to halt biodiversity loss. However, the Aichi Targets ultimately failed as the policy guidelines at national and local levels were mostly not aligned with the targets, and there was a lack of funding and forceful action to prevent the rapid decline of global biodiversity.[305] In 2020, with the outbreak of the COVID-19 pandemic, countries placed greater emphasis on biodiversity conservation, particularly the illegal trade of wildlife. Subsequently, in 2022, the UN Biodiversity Conference COP15 adopted the Kunming-Montreal Global Biodiversity Framework,[306] which called for the ambitious goal of protecting 30% of the Earth's land and ocean area by 2030 (30x30 goal). The 30x30 goal is an ambitious one, but it currently only commits to an area, without fully considering protection efficiency, priority areas, and cost effectiveness.[307] At the national level, different countries significantly differ in their focus, means, and funding for biodiversity conservation policies. For example, China has incorporated "ecological civilization" into its constitution,[308,309] established a protection system centered around national parks,[310] and promulgated and revised multiple laws and regulations related to biodiversity, including the Wildlife Protection Law, the Forest Law, and the Marine Environmental Protection Law. Moreover, various forms of trade, both domestic and international, can contribute to ecosystem disruption and exacerbate biodiversity loss. For example, the global demand for palm oil has led to widespread deforestation in areas like Indonesia and Malaysia, resulting in a significant biodiversity decline.[311,312]

Combating land degradation and desertification requires a comprehensive policy approach that addresses the root causes and promotes sustainable land management practices. The United Nations Convention to Combat Desertification (UNCCD) is an international treaty aimed at addressing desertification and land degradation in arid, semi-arid, and dry sub-humid areas.[313] The UNCCD is the only legally binding international agreement that specifically targets desertification and land degradation and is one of the three "Rio Conventions," along with the CBD and the United Nations Framework Convention on Climate Change. The root causes of land degradation are complex and require cooperation between countries. For example, the unprecedented deforestation in the Brazilian Amazon was caused by soybean and grazing land expansion due to increasing overseas demands for food.[294,314] Land degradation and desertification can also result from overexploitation of land for export-oriented production or servicing markets in different cities or regions within a country.[315] For instance, overgrazing by livestock reared for meat exports or for servicing distant domestic markets has induced desertification in regions of Africa and Central Asia.

A shortcoming of many current environmental policies is the lack of consideration given to the transboundary impacts of environmental pollutants.[316,317] This is especially critical in public areas without proprietary rights, such as air and ocean spaces. These pollutants, whether they be airborne or waterborne, can travel far beyond their point of origin due to natural flows like wind, river currents, and ocean currents.[296,318] This transboundary pollution is a significant concern because it can have far-reaching adverse effects on ecosystems and human health.[319] A case in point is the issue of the planned release of treated nuclear wastewater by Japan into the ocean.[320] Despite assurances that the water will be treated to remove most radioactive material, the plan has raised concerns about marine pollution and the health of shared ocean areas. This incident underscores the interconnected nature of our water systems and the need for international cooperation in managing and protecting these shared resources.[321] Some international conventions have recognized the transboundary impacts of environmental pollutants and strive to foster international collaboration to address these cross-border issues, such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal and the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP).[322,323] The Basel Convention, established in 1989 and effective in 1992, is a globally recognized treaty focused on managing hazardous wastes.[322] The 1979 LRTAP Convention, the earliest international treaty targeting cross-border air pollution, established a regional framework for countries in Europe, North America, Russia, and former Eastern Bloc nations.[323]

iSTEP AND SUSTAINABLE DEVELOPMENT SYNERGIES

The synergy between innovations in science, technology, engineering, and policy (iSTEP) is interdependent.[7] Scientific research and innovation are vital in understanding and addressing the complexities of environmental issues. Science can help answer questions such as why climate changes occur, where the hotspots of land degradation are, what the reasons for biodiversity loss are, and how they can be effectively protected. Additionally, it can help determine the status of environmental pollution and identify its drivers. Knowledge from scientific research contributes to the assessment and monitoring of environmental trends, the identification of potential risks, and the development of technologies to solve environmental issues, as well as the evaluation of the effectiveness of policies and interventions.

Technological advancement plays a pivotal role in promoting the development of science and ensuring the success of engineering projects. As technology advances, new tools, instruments, and methods are developed, enabling scientists to conduct more accurate and efficient research related to sustainable development. For example, advanced imaging technologies, such as electron microscopes and telescopes, allow researchers to explore previously unobservable phenomena. Satellite technology and sensors can help collect space-time large-scale environmental data for environmental scientists.[324,325] High-performance computing, big data analytics, and AI also contribute to the processing and analysis of vast amounts of data, leading to discoveries and insights within various environmental issues.[326] Engineering projects often use cutting-edge technology to design, build, and maintain complex systems and infrastructure. Technology's continuous improvement allows engineers to develop innovative solutions, improve efficiency, and reduce costs.

Formulating innovative policies can drive technological innovation and initiate large-scale environmental remediation projects. Innovative policies can encourage research and development in emerging technologies by providing financial incentives, such as grants, tax breaks, or subsidies. These incentives can attract investments, stimulate private sector involvement, and promote collaboration between academia, industry, and government agencies, ultimately leading to new technological breakthroughs. Innovative policies can facilitate the initiation and implementation of large-scale environmental remediation projects by allocating resources, setting targets, and coordinating efforts across different sectors and stakeholders. Environmental challenges often transcend national boundaries, and global collaboration is essential to effectively address these issues.[295,327-328] Policymakers can promote technological innovation and environmental projects by engaging in international agreements, sharing best practices, and providing technical assistance to other countries.

Synergies in iSTEP could help promote progress towards achieving SDGs. For example, it can lead to significant benefits in achieving SDG 7 (Affordable and Clean Energy), which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Scientific research can unleash the potential of various renewable energy sources, such as solar, wind, hydro, and geothermal power. It also works to improve energy efficiency and storage capabilities, enabling the implementation and optimization of clean energy systems and infrastructure. Technological advancements in renewable energy contribute to the development and deployment of more efficient and cost-effective solutions and strategies. Innovations in solar panels, wind turbines, and energy storage systems have made clean energy more accessible and viable for widespread adoption.[329] Engineers design, construct, and maintain the infrastructure for clean energy production and distribution. This includes renewable energy power plants, smart grids, and energy-efficient buildings. Engineers also develop solutions to integrate renewable energy sources into existing infrastructure, ensuring a smooth transition to cleaner energy systems.[330,331] Policymakers create and implement policies, regulations, and incentives to promote the development of scientific projects in clean energy research and the adoption of renewable energy and energy-efficient technologies. Examples include feed-in tariffs, renewable portfolio standards, and tax credits for clean energy investments. International agreements, such as the Paris Agreement, also play a key role in setting ambitious targets and fostering global cooperation on clean energy to implement important engineering projects.

RECOMMENDATIONS AND FUTURE PERSPECTIVES

First, it is essential to ensure that scientists, engineers, technologists, and policymakers have a common understanding and shared vision of sustainable development. This lays a foundation for strong collaboration and alignment of efforts among diverse stakeholders and fields. Presently, many consensus-driven environmental goals have been set forth, such as SDGs 13 (Climate action), 14 (Life below water), and 15 (Life on land). These goals encompass specific targets, including preventing and significantly reducing marine pollution of all kinds by 2025 and combatting desertification and restoring degraded land and soil by 2030. They also include the long-term temperature goal of the Paris Agreement is to keep the rise in mean global temperature well below 2°C above the pre-industrial levels and preferably limit the increase to 1.5°C, and goal of the Global 30 by 30 initiative is to designate 30% of land and ocean areas as protected areas by 2030. These worldwide accepted sustainability goals have garnered extensive agreement and act as a shared vision for professionals in science, technology, engineering, and policy, thereby directing efforts in diverse sectors. Looking towards the post-2030 Sustainable Development Agenda, we must enhance dialogue and cooperation, clarify the distribution of responsibilities and collaborative pathways across various sectors, and foster synergy among science, technology, engineering, and policy. In this regard, the post-2030 Sustainable Development Agenda should build on the lessons learned from the previous goals while addressing emerging challenges.[332] It should consider factors like technological advancements, socio-economic changes, and evolving environmental conditions.[333]

Second, promoting cross-disciplinary research, innovation, and school-enterprise collaboration, and public perceptions is vital for addressing environmental sustainability. Collaborations between educational institutions and enterprises play a pivotal role in driving environmental sustainability. These partnerships not only facilitate interdisciplinary research but also provide a platform for the exchange of knowledge and technologies, thereby bridging the gap between academia and industry. For local environmental management, it is essential to promote coordination among city governments, academia, the private sector, and civil society. This integrated approach allows us to leverage the strengths and expertise of different stakeholders to create a more holistic strategy for environmental sustainability. Another significant aspect of these collaborations is the encouragement of entrepreneurship. By integrating entrepreneurial principles and mindsets into these partnerships, we stimulate the creation of innovative, sustainable businesses. This entrepreneurial spirit can help translate research outputs into viable, real-world applications, driving cutting-edge solutions to environmental challenges. Furthermore, fostering entrepreneurship within these collaborations can lead to job creation and economic growth, contributing to SDGs beyond the environmental scope. It is a win-win situation that empowers individuals, boosts economies, and protects our environment. To maintain and enhance these collaborations and the entrepreneurial ventures they inspire, comprehensive administrative support is crucial. By providing a conducive environment for these interdisciplinary and school-enterprise partnerships, we not only encourage academic and technological advancement but also further the growth of sustainable businesses. In this way, we can drive continued progress in environmental sustainability.

Third, strengthening transboundary collaboration between different scientific disciplines, sectors (energy, agriculture, economy), and geographical regions (countries, cities), is imperative to effectively address global challenges and promote sustainable development.[334,335] Complex environmental, social, and economic challenges often require a multidisciplinary approach to develop comprehensive solutions. By bringing together experts from fields such as environmental sciences, technology, engineering, and policy, we can foster an environment that encourages interdisciplinary collaboration and partnerships. These connections often lead to innovative solutions to complex environmental challenges. Many environmental issues are closely linked to human activities in sectors such as energy, agriculture, and economy.[336] For example, transitioning to renewable energy sources can significantly impact land use, water resources, and food production, requiring close cooperation between energy, agriculture, and environmental stakeholders. Environmental problems, such as climate change, pollution, and resource depletion, often transcend national borders.[337-339] Concurrently, sophisticated modern engineering can be implemented within local communities.

Another recommendation is to promote sustainable technology and engineering transformation, which is essential for policymakers that work closely with scientists, engineers, and technologists. This collaboration ensures that policy decisions are informed by the latest scientific and technological advancements, enabling effective responses to environmental challenges such as global warming, biodiversity degradation, land desertification, and environmental pollution. Targeted funding and research grants should be provided to encourage the development and dissemination of sustainable technologies and engineering practices. For example, promoting research and local engineering of nature-based solutions can help mitigate global warming by sequestering carbon and preserving ecosystems. Subsidies for research and development of green energy technologies can also accelerate the transition from fossil fuels, reducing greenhouse gas emissions. Support for engineering applications that are beneficial to environmental sustainability is also crucial. This can range from the development of pollution control technologies to combat air, water, and soil pollution, to the design and implementation of sustainable land management practices to prevent desertification and restore degraded lands. In the face of biodiversity degradation, policies should be enacted to support bioengineering and biotechnological solutions that can help restore and preserve biodiversity. This might include gene editing technologies to bolster the resilience of threatened species, and the creation of bio-inspired materials and structures that can replace environmentally damaging substances. Further, by collaborating with other countries and international organizations, we could share best practices, develop joint initiatives, and leverage collective resources for sustainable technology and engineering transformation. Lastly, it's crucial to remember that technological and engineering transformations must accompany by corresponding changes in societal behavior and consumption patterns. While population growth rates around the world are decreasing, the numbers of households still increase substantially due to factors such as divorce.[340,341] Because households are basic units of consumption, household proliferation has significant implications for the environment. Policies should, therefore, also aim to foster sustainable lifestyles and consumption, ensuring the effective utilization of these technological innovations for environmental sustainability.

To summarize, our paper seeks not only to document achievements and challenges but also contribute to designing a roadmap for a more sustainable future by addressing critical questions and uncovering the underlying principles that can guide us toward a harmonious coexistence between humans and the environment. Against the backdrop of escalating environmental challenges, the imperative for sustainable development has propelled an urgent quest for innovation-based solutions at the intersection of science, technology, engineering, and policy. We argue that proposed iSTEP integrated framework can be a key enabler in their respective fields for addressing environmental threats to sustainable development, including global warming and climate change, biodiversity loss, land degradation and desertification, and environmental pollution. However, the true power of iSTEP is seen in their combined efforts; it is the synergy among them that effectively promotes sustainable development, which requires a comprehensive and collaborative approach. The significance of this review lies in its potential to guide future research and policy formulation by providing a nuanced understanding of what has worked, what environmental challenges persist, and how global societies can collaboratively chart a course towards sustainable development.

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AUTHOR CONTRIBUTIONS

L. L., H. G., B. F., J. L., Z. X., Junze Z., Haijun W., W. Y., M. Chen, Q. J., R. B. S., M. E. M., and P. P. conceived, organized, and revised the manuscript, and wrote Abstract, Introduction, and recommendations and future perspectives, and Junze Z., L. L., H. Z., and Y. Z. wrote section about the evolution of sustainability science. Haijun W., W. Y., F. W., Jin Z., W. Z., Y. Z., Z. C., R. V. J., and H. L. wrote section about environmental-related issues and sustainable development. L. L., Junze Z., M. Chen, M. Cao, J. L., F. C., L. H., J. Z., M. J., L. Z., D. Y., and J. S. wrote section about innovations in addressing environmental issues. Z. X., Q. J., H. X., R. L., X. W., E. J., Y. C., D. L., and J. L. wrote sections about iSTEP and sustainable development synergies. All authors reviewed the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data sharing is not applicable, as no new data were created or analyzed in this study.

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