THE ASIAN BULLETIN OF GREEN MANAGEMENT AND CIRCULAR ECONOMY
Vol 6, Issue 1(2026)
THE ASIAN BULLETIN OF GREEN MANAGEMENT AND CIRCULAR ECONOMY
ISSN (online): 2959-0035
http://abgmce.com/ 10.62019/abgmce.v6i1.188
ISSN (Print): 2959-0027

Navigating the Global Environmental Crisis in Pakistan: Integrating Sustainable Development Goals, Climate Adaptation, and Technological Innovation

Syed Bilal, Raiyan, Numra Amjad, Syed Azeem Inam*

Chronicle

Article history
Received: January 10, 2026
Received in the revised format: Feb 18. 2026
Accepted: March 03, 2026
Available online March 31, 2026

Syed Bilal, Raiyan, Numra Amjad and Syed Azeem Inam* are currently affiliated with the Department of Artificial Intelligence and Mathematical Sciences, Sindh Madressatul Islam University, Karachi, Pakistan.
Email: syed03bilal@gmail.com
Email: raiyanssheikh@gmail.com
Email: numrasuhaib@gmail.com
Email: syed.azeem@smiu.edu.pk
Email: syedazeeminam@gmail.com

Corresponding Author*

Abstract

Environmental issues, such as climate change and urban stress, are threatening the SDGs worldwide. Many countries, regardless of their low contribution to global greenhouse gas emissions, have been devastated by droughts, floods, and heatwaves over the last decade, demonstrating how vulnerable many areas are becoming due to these environmental issues. Several of these issues are associated with the SDG framework, including climate resilience, urban environment quality, water stress, pollution and health, deforestation, and biodiversity conservation. Additional quantitative evidence supports the fact that the problems created by climate change are worsening, as in many parts of the world, per capita water supply has been declining; PM2.5 concentrations in many urban areas exceed WHO acceptable limits by very high amounts; there is ongoing pressure on forests; and there is an increasing occurrence and severity of extreme weather events. This review provides an assessment of the global environmental crisis in terms of the UN SDGs based on research studies from 2020 to 2025. Despite these potential advancements, several barriers continue to exist. There are substantial funding and governance gaps, as well as a limited ability to measure human development in relation to ongoing environmental degradation. As a result, the research highlights the requirement for comprehensive and integrated methods of addressing and overcoming current economic crises through using AI-based decisions, improving policies, and engaging communities to enhance the capacity to adapt and develop economically sustainable products. This assessment also serves as a source of information for scholars, policymakers, and practitioners in recognizing the importance of integrating sustainable development with technological innovations to address urgent global environmental concerns.

Keywords: Climate change, Air pollution, Water scarcity, Biodiversity loss, Sustainable Development Goals, Artificial Intelligence.

© 2026 The Asian Academy of Business and social science research Ltd, Pakistan.

INTRODUCTION

Various environmental problems are converging with other regional issues and causing major threats to global sustainability and the attainment of global sustainable development goals [1]. More of these environmental issues are connected, reinforcing one another as time passes. The effects of pollution, depletion of natural resources, and increasing effects of climate change are continuing to worsen in many areas of the world. [2]. Pakistan is consistently ranked in the top ten most vulnerable countries to climate change consequences [3]. Many regions of the world are exposed to dangerously high levels of climate change, even though they collectively contribute just a small percentage of the total greenhouse gas emissions released. Over the last 10 years, the word have experienced an increase in the severity of flooding and heat waves across all regions [4]. Overall, rapid urbanization and industrialization have added to the problems of air and water pollution, waste mismanagement, deforestation, and loss of biodiversity, creating complex environmental stressors in both rural and urban environments [5]. As a result, these stresses hinder environmental sustainability and, as such, hinder the public's health, economic growth, and social well-being. Therefore, it should be a national priority for all governments to focus on the issue of environmental governance. This study aims to provide access to a summary of important global environmental issues that are associated with sustainable development and technological advancement, which have to be viewed together within a much larger global development structure. Following a standardized approach, the study has organized information in the form of environmental problem areas with contextual information supporting each area so that readers can better understand why these areas are important to people on a global scale. The global SDG-based environmental policy development landscape and status of sustainability are also presented. To complement technological solutions with governance, Section 9 presents future directions, with an emphasis on the need for integrated decision support systems, such as AI-enabled climate dashboards, and more coordinated and effective policy frameworks. Overall, the present review provides a comprehensive and complete synthesis of global environmental issues and innovative solutions from a sustainable development perspective based on the evidence obtained from state-of-the-art.

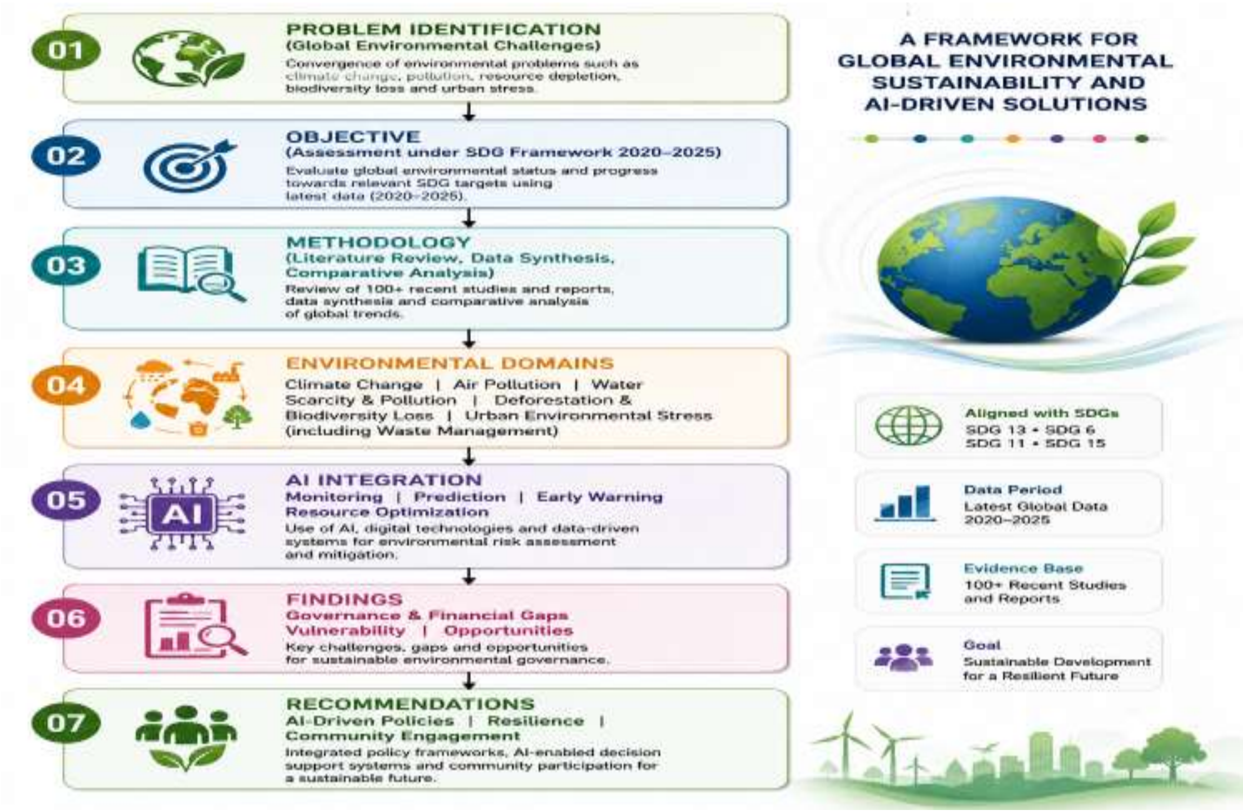

Figure 1.
Framework for environmental challenge assessment under the SDG framework

A structured literature review methodology was adopted to identify, screen, and select relevant studies addressing environmental challenges in the world, with special emphasis on the studies related to Pakistan from a sustainable development and AI perspective. Multiple academic databases and supplementary sources were systematically searched for peer-reviewed articles published between 2020 and 2025. The initial search yielded 300 records, of which 250 were identified through database searches and 50 through other sources. After the removal of duplicates, all records were screened based on title and abstract relevance. Studies that did not align with the thematic scope of climate change, air and water pollution, biodiversity loss, urban environmental stress, or AI-driven sustainability solutions were excluded. A total of 130 full-text articles met the eligibility criteria and were included in the qualitative synthesis. The study selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework and is presented in Figure 2.

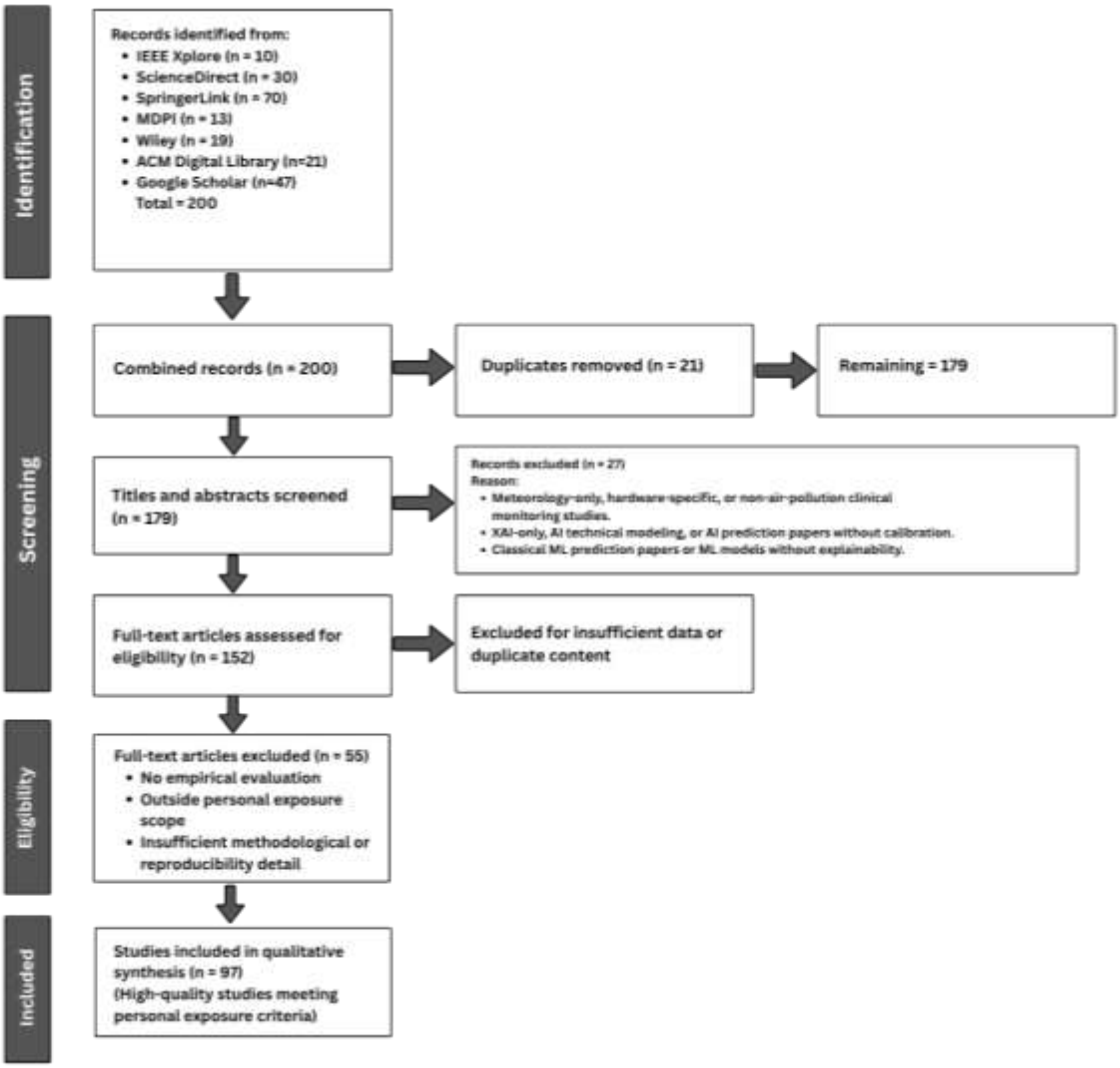

Figure 2.
PRISMA flow diagram for study selection process

SUSTAINABLE DEVELOPMENT CONTEXT

Socio-economic and environmental overview

Over eight (08) billion people represent a continually growing population around the world [6]. The pace of population growth and urbanization in developing countries is rapid [7]. Urban areas of the world now have a significant proportion of the global population residing, with more population residing in the cities considered to be megacities, requiring excessive demand for both natural resources and infrastructure [8]. Economic development is a global priority; industrial and service sectors are growing, while agriculture employs a significantly large number of people and also provides a significant portion of GDP for many parts of the world [9]. However, this expansion is generally accompanied by negative environmental impacts, especially in areas that are dependent on fossil fuels and have inefficient technologies resulting in high levels of air and water pollution [10][11]. Water is also consumed through agriculture, which accounts for a large percentage of the total freshwater use in the world, as well as for generating continued water shortages, raising issues regarding water security [12]. Many places of the earth have experienced deforestation, and the impact of unsustainable land use has led to a decrease in forest cover, a weakening of ecosystems, a reduction in the available biodiversity, and a decrease in the capacity of an area to store carbon dioxide [13, 14]. The diversity of the earth in geographic and climatic areas also causes areas to be affected differently by environmental hazards such as drought, heat waves, flooding, landslides, and hazards associated with the melting and rising of ice caps and coasts [15]. The Global Climate Risk Index shows that many areas around the world will become increasingly at risk because of weather events that are too extreme [16]. These environmental disasters often happen in locations that have been developing, and when there are disaster situations [17], they will often set back efforts that are made by new infrastructure, agriculture, healthcare, and education resources, and will contribute to moving already at-risk groups into very unstable situations and possibly undermine efforts that would be sustainable over time [18].

Environmental policy and SDG alignment

Increasingly, as countries around the world have had to confront an unprecedented number of climate-related threats, they have recognized the need to include environmental management and climate change adaptation within the context of their national development agendas [19]. In the wake of their global launch, many countries are incorporating the United Nations Sustainable Development Goals (SDGs) into national policies and long-term development plans [20]. The SDGs will be implemented differently in each of the various regions of the world, depending on local issues and levels of development, but climate action has emerged as a universal priority due to the growing number of extreme weather events and natural disasters. The themes of SDG6 are also highly relevant globally; many countries still lack access to safe drinking water, face water shortages, or have contaminated water supplies. Similarly, SDG11 is relevant across the globe, as many developing cities continue to experience rapid urban growth, rising pollution levels, poor housing, and the creation of informal settlements as their populations expand. There are also enormous worldwide challenges related to the global SDG15, i.e., life on land. The ongoing deforestation occurring around the world, the continued declines in biodiversity, and the loss of habitat in wide ranges of areas have all resulted in an unbalanced habitat and increased risk of species extinction. Although some human development indicators have improved in many regions of the world, these improvements have been eroded due to the growing consequences of climate change and environmental degradation. As such, global progress toward achieving the SDGs is incomplete; so many countries remain behind their targets, especially related to environmental issues.

Table 1.
Linkages Between Environmental Issues and SDGs

Environmental Issue	SDG3	SDG6	SDG7	SDG11	SDG12	SDG13	SDG14
Air Pollution	✓	–	✓	✓	✓	✓	–
Water Scarcity	✓	✓	–	✓	✓	✓	–
Floods	✓	✓	–	✓	✓	✓	✓
Deforestation	–	–	–	–	✓	✓	–
Waste	✓	✓	–	✓	✓	✓	✓

Many countries have established climate-related policies and action plans to promote both economic growth and the environmental sustainability of their development. On the international level, the Paris agreement has prompted countries to develop and continually update their Nationally Determined Contributions (NDCs), which describe the country's specifics as to how it will reduce greenhouse gas emissions and adapt to climate change based on its unique circumstances. In general, most of the commitments are focused on various sectors, i.e., energy, agriculture, forestry, and industrial development, where mitigation and adaptation can make the biggest difference. However, even with the increasing number of global and national climate policies, multiple independent assessments on an international scale continue to identify significant implementation gaps, which are an ongoing challenge in developed and developing countries.

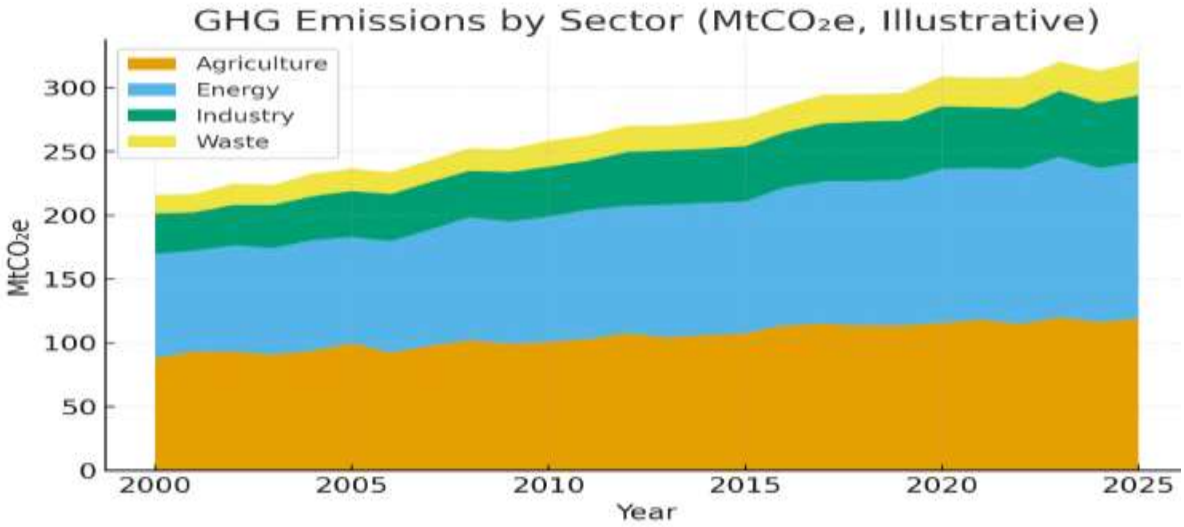

Figure 3.
Greenhouse gas emissions by sector (2000–2025)

Pakistan has established its national biodiversity strategy and action plan and has expanded the number of protected areas in response to issues related to biodiversity. One approach to addressing the problems of deforestation and land degradation has been the introduction of the 10 billion trees tsunami program in 2019. Addressing urbanization problems has also led to the introduction of several anti-smog laws and initiatives to manage municipal waste, as well as the establishment of public transportation systems to eliminate pollution caused by motor vehicles, primarily in two of the largest provinces of Sindh and Punjab. However, despite numerous efforts to address environmental issues, the challenges of governance and the lack of resources continue to hinder most of the implementation of these initiatives and policies. Inconsistent enforcement of environmental regulations and the lack of collaborative relationships between federal, provincial, and local authorities still create barriers to the successful implementation of these initiatives.

In addition, continuous political and economic challenges divert attention and funding from sustainable development, which in turn causes the degradation of the environment, even though the policies created to address environmental degradation continue to increase. Therefore, there is a great need for more innovative solutions and stronger institutions supporting them to reverse the current environmental degradation trend. Modern technology, such as remote sensing, geographic information systems, and AI, can help improve the environmental monitoring, analysis, and decision-making processes involved with governing climate change on a global level. These technologies also help to fill the gap between what is currently being done in terms of policy and the capacity to implement effective climate action in a timely and evidence-based manner, which will help achieve the SDGs globally. A data-driven system based on GIS, remote sensing, and AI will allow decision-makers in different countries to more accurately and efficiently improve their planning, analyze risk, and manage resources in terms of environmental impacts.

Figure 4.
Multi-layer sustainability PRISM structure

Therefore, there will be greater potential for these technologies to create tools for governments and international organizations to achieve SDGs.

Table 2.
Key environmental indicators and SDG relevance (2020–2025)

Indicator	Current Status (2020–2025)	SDG Relevance	Notes/Source
GHG Emissions ($MtCO_2e$/year)	~521 (2021)[34][35][28]	SDG13 (Climate Action)	~46% from agriculture & land-use
Climate Risk Index Ranking	Top 10 most affected globally[1]	SDG13	Frequent extreme events (floods, heatwaves)
Forest Cover (% of land)	~5.2% (2021)[13][14]	SDG15 (Life on Land)	High deforestation (~1.4% annual)
Protected Areas (% of land)	~12% (2020)[36][37]	SDG15	Expanding, but effectiveness varies
Annual Water Availability (m^3 per capita)	<860 (2025)[38]	SDG6 (Clean Water) & SDG2 (Zero Hunger)	Down from ~5000 in 1950 (indicates acute scarcity)
Population using Safe Drinking Water	~20% (safe quality)[39] (94% access)[23]	SDG6	The majority rely on sources contaminated by pollutants
Urban Air Pollution (PM2.5)	~74 $\mu g/m^3$ annual avg (2022)[40]	SDG11 (Sustainable Cities) & SDG 3 (Health)	~14× WHO guideline; Pakistan among worst globally
Annual Air Pollution Deaths	~158,000 (2021)[41]	SDG3	Includes stroke, heart, and lung disease burden
Municipal Solid Waste Generation	~49.6 million tonnes/year[42][43]	SDG11 & SDG12 (Responsible Consumption)	>50% mismanaged (open dumping, burning)
Biodiversity Threatened Species	>50 animal spp. (20 mammals, 25+ birds, etc.)[44]	SDG15	Habitat loss & overexploitation main drivers

Finally, these core environmental indicators provide the world in general and Pakistan, in particular, with a clear roadmap of where intervention is necessary to help create a more sustainable and resilient future in line with the SDGs.

Climate change: trends and impacts

Climate change presents an increasingly acute environmental issue across numerous regions of the globe as it modifies established weather patterns at an escalating pace, contributes to melting glaciers, and increases both the number and severity of natural disasters [21]. A significant volume of data collected around the world establishes that there has been a demonstrable average warming of the planet over the past few decades, with many geographical areas throughout the world recording both increases in average temperature and increasingly erratic overall weather [22]. The rising trends in temperatures experienced across the globe have resulted in regions around the world experiencing much more frequent and intense occurrences of extreme heat events, with many of the highest populated locations on the planet experiencing their highest levels of extreme heat occurring at potentially life-threatening levels [23].

Rainfall patterns across the globe are becoming less consistent as well, resulting in increases in the amount of flooding occurring in some years and increasing amounts of drought in other years due to the change in the pattern of when rain occurs each year [24]. High-altitude and mountainous areas around the world, including the Himalayas, Andes, Alps, and other glaciated regions, are experiencing increasing glacier retreat and the creation of unstable glacial lakes as a result of the increasing temperature. As a result, there is an increasing risk of Glacial Lake Outburst Floods (GLOFs), which threaten to cause considerable harm to communities, infrastructure, and ecosystems downstream [25]. In addition, several national governments are increasingly recognizing that they are climate-sensitive hotspots because of their high exposure to extreme weather variability and recurrent natural hazards [26]. On a global scale, the total number and severity of extreme weather events have increased, including floods, storms, heat waves, and drought.

Much of the world has witnessed several significant disasters that have caused extensive loss of life, disruption to population movements, and financial losses over the past several decades [27]. Many countries across Asia, Africa, Europe, and the Americas have been adversely affected by several catastrophic flood events; such floods have often exceeded the capacities of many countries' disaster preparedness systems and have revealed weaknesses in many countries' infrastructure and governance. Previously, many regions and countries considered extreme weather events to be relatively rare or unique; however, most regions and countries today consider extreme weather events to be increasingly typical of the new climate baseline, reflecting a larger trend of a changing global climate [28].

Extreme events and disasters

Pakistan's status as a climate hotspot is most evident in its string of extreme weather events [24]. Between 1998 and 2018, the country experienced approximately 150 extreme events, including floods, storms, and heatwaves [25]. Since 1990, at least 14 major flooding events have struck the country severely [26]. The 2010 super-floods, triggered by unprecedented monsoon rains, inundated vast areas and caused around 1,600 deaths, offering an early glimpse of the new climate reality [27]. However, the 2022 floods were even more devastating [28]. From June to August, Pakistan has experienced heavy rainfall, reaching five to six times the 30-year average in several regions [29]. By this, rivers and dams caused overflowing. Lately, in August 2022, approximately one-third of the country was submerged. Satellite images from 31st August 2022 show that the river Indus has vastly sped up in Sindh and Punjab. This caused nearly 1,700 people's lives to be lost, and around two million people's homes were damaged. Resulting in economic losses across the nation of around $30 billion, with entire communities, crops, roads, and bridges being wiped out, the after effects from this disaster are still in progress, and metrological department has warned that such extreme monsoons is also expected to increase across the country every year. Recent CMIP6 climate simulations confirm that Pakistan's flood patterns are shifting toward higher frequency and higher intensity events. Under the SSP2-4.5 mid-emission pathway, extreme monsoon rainfall is projected to increase by approximately 30%, while under the high-emission SSP5-8.5 scenario, rainfall intensities may rise by 50–60% by the year 2050.

These models suggest that severe flooding similar to the 2022 event, where one-third of the country was submerged, could occur every 3 to 5 years instead of being a once-in-a-generation disaster. Heatwaves are another danger caused by climate change in Pakistan. In recent years, cities have faced extreme heat for long periods. In June 2015, Karachi faced a severe heat wave with the highest temperature of around 45 °C. The deadly combination of humidity and loss of electricity further increased the danger. Over 1,200 people perished in that heat wave. The same type of weather occurred in May 2022 and April 2023, causing widespread effects on crops and creating tremendous demand on healthcare facilities and services across Sindh, Balochistan, and Punjab.

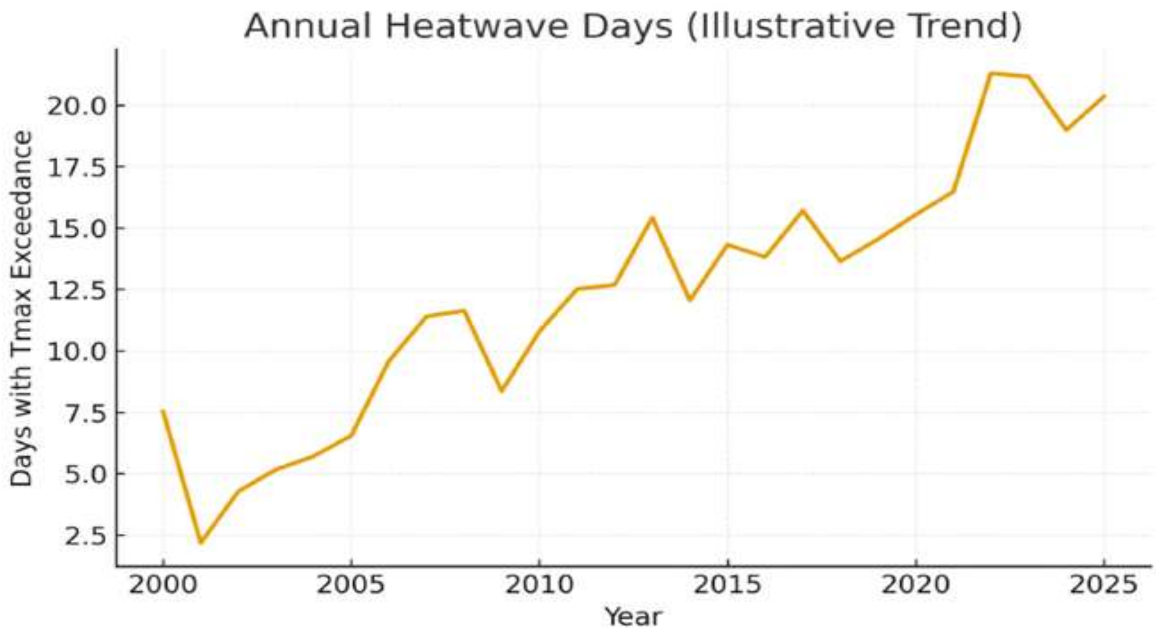

Figure 5.
Annual heatwave days in Pakistan (2000 – 2025)

Research shows that climate change has caused an increase in both the frequency and severity of heat waves across the South Asian region. The drought patterns have changed over the past several decades, with parts of Pakistan, such as southern Punjab and Balochistan, experiencing frequent drought cycles every year or two. In fact, in late 2024 and into early 2025, Pakistan was entering another stage of extreme drought due to prolonged droughts caused by years of insufficient rainfall. As such, growing pressure has been placed on Pakistan's water supply for millions of its citizens due to these trends of climate change, creating extreme fluctuations in the weather.

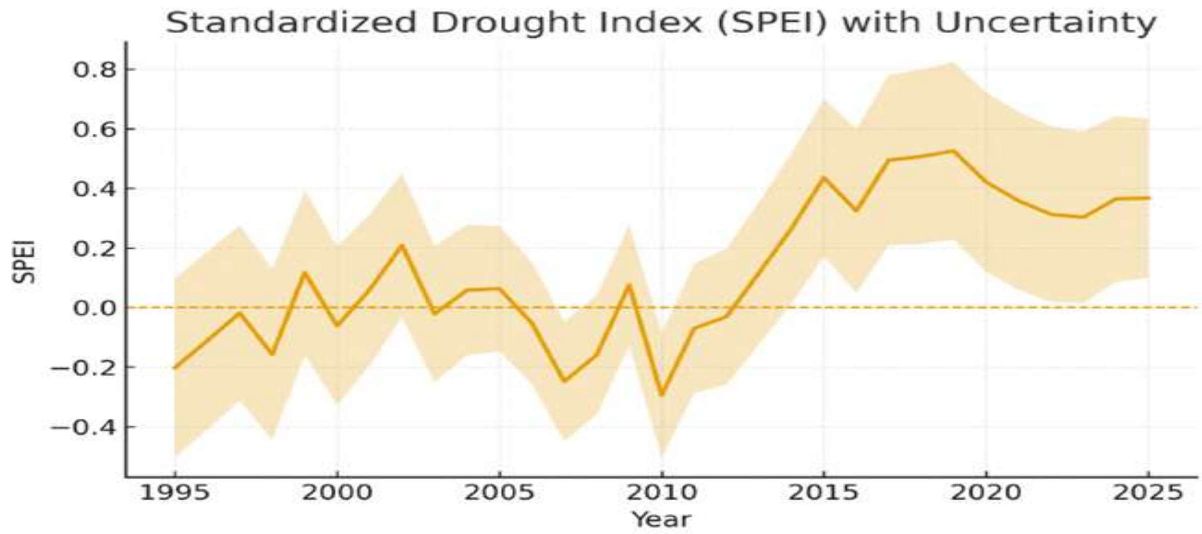

Figure 6.
Standardized Drought Index (SPEI) with uncertainty (1995–2025)

Socio-economic impact of climate change

In Pakistan, climate change has adverse effects across multiple sectors [31]. The agricultural sector, which is the foundation of the economy, is one of the most significantly impacted by climate change [32]. For example, recent heatwaves and erratic rainfall patterns have dramatically affected the yields of wheat and mangoes [33]. If climate change trends are not reversed or compensated for by government and private sector adaptive practices, it is estimated that the country will lose approximately 8 to 10% of its agricultural productivity by 2040 [34]. Furthermore, during the 2022 floods, approximately two million acres of farmland were either destroyed or flooded, resulting in a loss of more than 700,000 livestock and subsequently creating a crisis for food supply and farmer livelihoods [35]. Recent economic studies using Computable General Equilibrium (CGE) models and Input–Output (I-O) analysis show that such agricultural shocks ripple across multiple industries. I-O simulations estimate that a 10% fall in major crop output can reduce agro-industrial production by 2 to 3% due to backward linkages with fertilizer and machinery sectors and forward linkages with textiles and food processing.

CGE models further project that agriculture-driven climate shocks could translate into $3 to $5 billion annual GDP losses by 2030 under moderate-high warming scenarios. The water supply is also being put into greater danger than ever before [36]. Floods destroy everything across a large area, while the longer-term effects of glacial melting and shifting patterns of the monsoon create a significant threat to the security of water availability. The river Indus, which provides life to Pakistan, is now experiencing a decline in the reliability of its water supply. There have been several studies indicating that flows of the river may be fairly stable through about 2050; however, the peak season of discharge from the river may occur earlier, and the year-to-year fluctuation of flows will become greater.

As such, managing water supplies for agricultural and hydropower generation will become increasingly difficult. In 2022 [66], the water that is stored in Pakistan's major dams faced a high risk of being flooded, while during drought years, shortages of stored water may occur. CGE-based energy sector simulations indicate that disruptions in hydropower supply can raise national electricity prices by 12 to 18%, which then reduces manufacturing output, especially in energy-intensive sectors like cement, steel, and textiles. I-O results from the 2022 flood period show that every 1% decline in hydropower generation resulted in approximately 0.3% loss in industrial productivity. Extreme climate events affect both human health and settlements. The incidence of water-borne diseases spikes because of flooding and stagnation of the water; heat strokes and cardiovascular stress are compounded by severe heat, and the 2022 flooding caused a surge in cases of gastroenteritis and skin infections in the displaced population. A recent study finds that, over the long term, climate-related flooding, heat-related impacts on human health, and pollution have collectively resulted in a decrease in average Pakistani life expectancy of nearly 4 years. Urban areas, where more than one-third of Pakistanis reside, are facing increasing stresses from climate change-related events, including urban flooding and urban heat island effects, exacerbating heat every year.

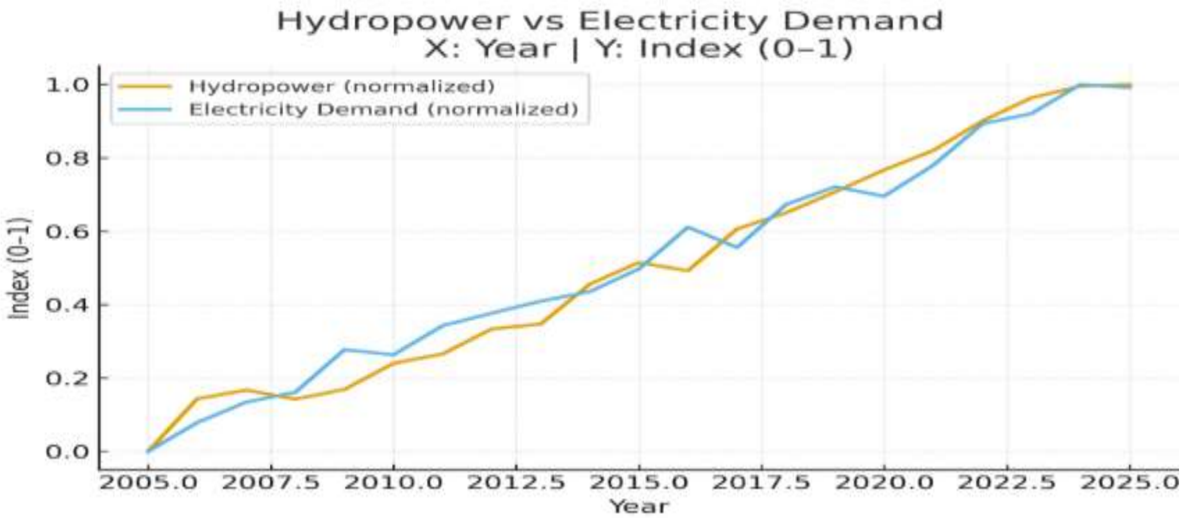

Figure 7.
Hydropower generation vs electricity demand (2005–2025)

Additionally, cities along the coastline are increasingly being affected by rising sea levels and salinity as a result of climate change, although these latter impacts are presently relatively slower than the effects of flooding and heat stress. Labor productivity modules within CGE models show that climate-related disease burden and heat-related work-hour losses could reduce Pakistan's labor output by 4 to 6% by 2040. The resulting decline in productivity is estimated to contribute an additional 0.7 to 1.2% annual GDP loss, especially in agriculture, construction, and transport sectors. Climate change in Pakistan is economically devastating. Under high-emission scenarios, the World Bank estimates that Pakistan's GDP could decline by as much as 2% annually by 2050 due to climate change.

Adaptation and mitigation efforts

To address these threats, Pakistan has initiated the implementation of climate adaptation measures [37]. Pakistan is developing a National Adaptation Plan, which will feature four major sectors [38]. There have been improvements in disaster response capabilities since 2010, particularly through the establishment of the National Disaster Management Authority (NDMA) and the provincial Disaster Management Authorities (DMAs). An example of improvement is the installation of early warning systems for floods and GLOFs with the support of international assistance, including a GLOF early warning system in Khyber Pakhtunkhwa. Nevertheless, recent events have exposed continued difficulties with respect to forecast accuracy, preparedness at the community level, and the size of the flood events in 2022, which completely overwhelmed pre-existing warning systems [39]. As per the Sendai Framework for Disaster Risk Reduction (DRR), Pakistan became increasingly more resilient against the continuous threat of disasters. However, DRR plans are being applied in a scattered manner around the country. On the climate change mitigation side, although Pakistan's share of global GHG emissions is considered below 1% (<1%) of total CO_2 emissions around the world, it has also committed to reducing its total CO_2 output by 50% by 2030. Under Pakistan's updated Nationally Determined Contribution (NDC) for 2021, it plans to reduce its CO_2 emissions by 50%, with 15% of that reduction being unconditional and the other 35% being conditional upon receiving international assistance. Actions that Pakistan intends to take as part of its NDC will focus on developing renewable energy sources, where 60% or more of all electricity produced in the country will be generated from renewable sources within the next ten years.

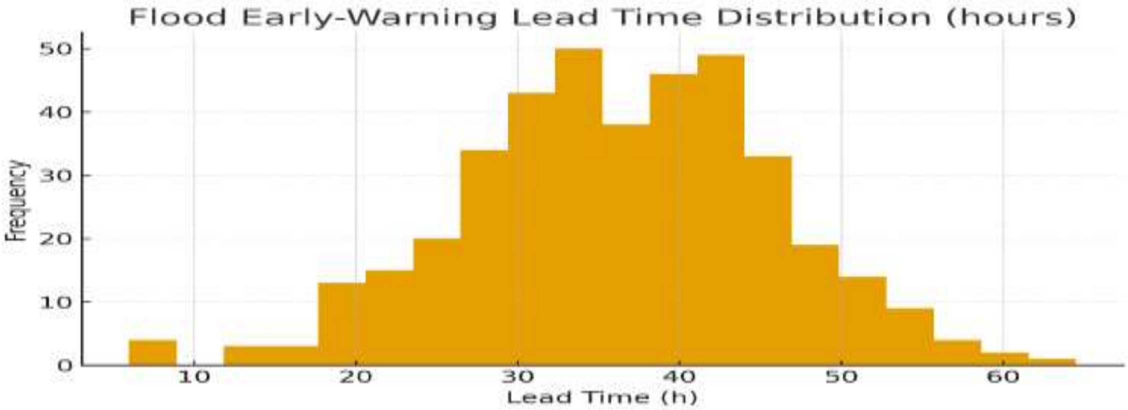

Figure 8.
Hydropower generation vs electricity demand (2005–2025)

In addition, the government of Pakistan plans to encourage the use of Electric Vehicles (EVs) and plant extensive numbers of trees to mitigate the adverse effects of climate change through many of its reforestation initiatives. The current level of climate finance in Pakistan is not sufficient to allow the country to fully implement adaptation measures; it is estimated that $7 to $14 billion will be needed annually for adaptation. Unfortunately, the actual level of adaptation funding currently being received in Pakistan is less than 1% of what will be required to adequately address the problem [40].

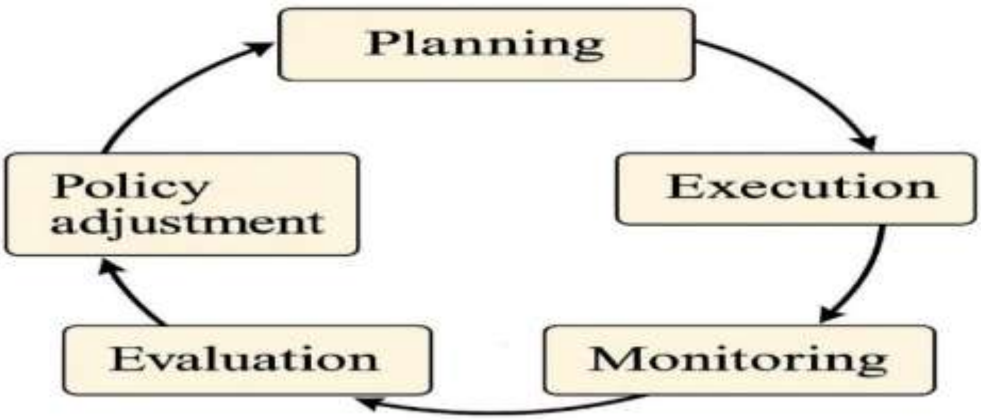

Figure 9.
Sustainability implementation cycle

As an example, machine learning-based models have been used for forecasting monsoon flood events and identifying areas prone to drought. A new model using AI anticipates that, in the future, the country of Pakistan will experience increasingly frequent "super floods" and "extreme droughts" due to global warming, thus highlighting the need for improved analytic capabilities for predictive modelling and planning purposes. Therefore, climate change has become a factor that exacerbates the various risks to Pakistan, resulting in increased water vulnerability, food insecurity, public health threats, and economic instability of its population.

Air quality and atmospheric pollution

People all around the world face severe health, environmental, and economic risks due to air quality from outdoor air pollutants. Many jurisdictions repeatedly rank as being very polluted in terms of their outdoor air quality. In the last few years, many areas in Pakistan have averaged $PM_{2.5}$ levels that far exceed the WHOHQ (World Health Organization Health Quality) threshold of 5 μg/m³. On several occasions, the $PM_{2.5}$ levels have even been measured at more than 10 times the WHOHQ threshold. Therefore, numerous low- and middle-income countries are listed as being among the world's most polluted countries [43]. This is particularly prevalent in South Asia and other densely urbanizing areas of the world [42].

Table 3.
Air Quality Levels in Major Pakistani Cities (2024–2025)

City	$PM_{2.5}$ (μg/m³)	WHO Limit (μg/m³)	Exceedance Factor (Mean)	Exceedance Factor (95% CI)	Health Burden (DALYs – qualitative)
Lahore	110	15	7.3×	7.3× (95% CI: 6.5–8.1)	Very High
Karachi	95	15	6.3×	6.3× (95% CI: 5.6–7.0)	High
Islamabad	55	15	3.7×	3.7× (95% CI: 3.1–4.3)	Moderate
Peshawar	85	15	5.7×	5.7× (95% CI: 5.0–6.4)	High
Quetta	70	15	4.7×	4.7× (95% CI: 4.1–5.3)	High

In recent evaluations of the global burden of disease (GBD) for ambient particulate matter ($PM_{2.5}$), a clear indication exists that air pollution is a major global public health concern based on the published exposure–response relationships associated with air pollution and various diseases. Studies of ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lung cancer, and lower respiratory tract infections found that all of these diseases were related to increased exposure to air pollution. Major cities worldwide are significant sources of air pollution. Specifically, the air quality in many major cities in South Asia, East Asia, the Middle East, and parts of Africa is often significantly poorer than other times of the year, especially during the winter months, due to meteorological conditions, including temperature inversions, vehicle emissions, industrial activity, and biomass burning.

Furthermore, many megacities have been ranked as some of the most polluted in the world over recent years, and many of them have recorded Air Quality Index (AQI) concentrations of over 300. In addition to poor air quality, some cities have recorded AQI values above the emergency level, and consequently, these cities have experienced a variety of negative health effects due to air pollution, including school closures, transportation disruptions, and increased risk of mortality. Extreme air pollution is becoming increasingly characterized as an environmental crisis because of its severity and public health impacts.

Sources of air pollution

The air in Pakistan is highly polluted. This is because of what we do in cities, on farms, and with energy [44]. The air is created from many different chemicals and elements, such as fine dust, soot, sulphur, nitrogen compounds, carbon monoxide, ozone, and a combination of unstable chemicals. Of all the pollutants that exist, the $PM_{2.5}$ is the smallest particle size and represents a particularly high risk due to its ability to enter the lungs and the bloodstream completely unnoticed. Millions of individuals have compromised hearts and lungs with every puff of air they take [45]. While national-level percentages provide a broad understanding of major pollutant contributors, recent receptor modeling studies, including Positive Matrix Factorization (PMF), Chemical Mass Balance (CMB), and UNMIX, show that pollution sources vary significantly by city.

These models analyze the chemical composition of particulate matter to identify its origins, providing a more accurate and location-specific breakdown compared to general estimates. PMF studies in Lahore show that transport emissions contribute between 35 to 50% of $PM_{2.5}$ during winter, while industrial and brick kilns contribute 25 to 30%. In Karachi, PMF analyses indicate that road dust and sea salt contribute more heavily compared to Lahore due to Karachi's coastal environment. Peshawar shows a higher contribution from biomass burning and unpaved-road dust, reflecting local land-use practices. Such receptor-modeling results demonstrate that the relative contribution of vehicles, industry, biomass burning, dust, and power generation differs across cities, and therefore, policy interventions must be geographically tailored rather than uniform nationwide.

Table 4.
Environmental impacts by source sector

Source	Air Impact	Water Impact	Soil Impact	GHG Impact	Health Effect	Population Exposed (M)
Industrial	High	Very High	Medium	High	Respiratory	40+
Transport	Very High	Low	Low	High	Asthma	30+
Agriculture	Medium	High	High	Medium	Pesticides	20+
Household	Medium	Medium	Medium	Low	Indoor smoke	10+

The major contributors to PM and other pollutants in Pakistan are:

- <u>Transport emissions:</u> Transportation produces most of the pollution from motor vehicles, which are increasing rapidly, especially motorcycles and used diesel trucks. In cities, most CO, NOx, and PM emissions come from vehicles. Two-stroke rickshaws, low-quality diesel trucks, and no catalytic converters increase emissions from vehicles. Punjab's smog policy states that transport is responsible for 40% of the smog produced in Lahore. Vehicle exhaust contains CO and NOx as well as other carcinogenic organic compounds.
- <u>Industrial and energy sector:</u> The industry produces large amounts of pollution. In many cases, industrial facilities lack adequate emissions controls, and they often burn inappropriate or dirty fuels such as coal, oil, or waste. Around 20,000 brick kilns have traditionally used inefficient fixed chimney technology, emitting large amounts of SO_2, NO_x, PM, and black carbon; conversion to cleaner zigzag technology is underway but uneven. Coal use in power generation has increased, adding to SO_x/NO_x emissions. Industry contributes a substantial share of Lahore's smog. Seasonal crop residue burning and emissions from small generators further worsen pollution [47].

- Agricultural and biomass burning: When fall arrives in Punjab, farmers burn their leftover rice stalks in massive quantities, sending up plumes of smoke loaded with PM, carbon monoxide, and all kinds of toxic stuff. The timing could not be worse, i.e., cooler weather and atmospheric inversions trap all that smoke close to the ground, creating the smog blankets that settle over Punjab each year and frequently drift across the border into India. People are starting to realize that pollution does not respect borders and that what happens in one region directly affects air quality in places like Lahore. Out in the countryside, things are not much better, families still burn their trash in the open, and many rely on wood or dried animal dung to cook their meals. All of this adds more pollution both inside homes and in the surrounding air [48].
- Natural factors: Even though human activities are the main contributors, dust storms in dry areas and winter fog can occasionally increase particulate levels or combine with human-made pollutants, resulting in long-lasting smog layers. However, the chemical makeup of urban air, i.e., high in sulfates, nitrates, and carbon-based soot, clearly shows that most of Pakistan's smog originates from human sources.

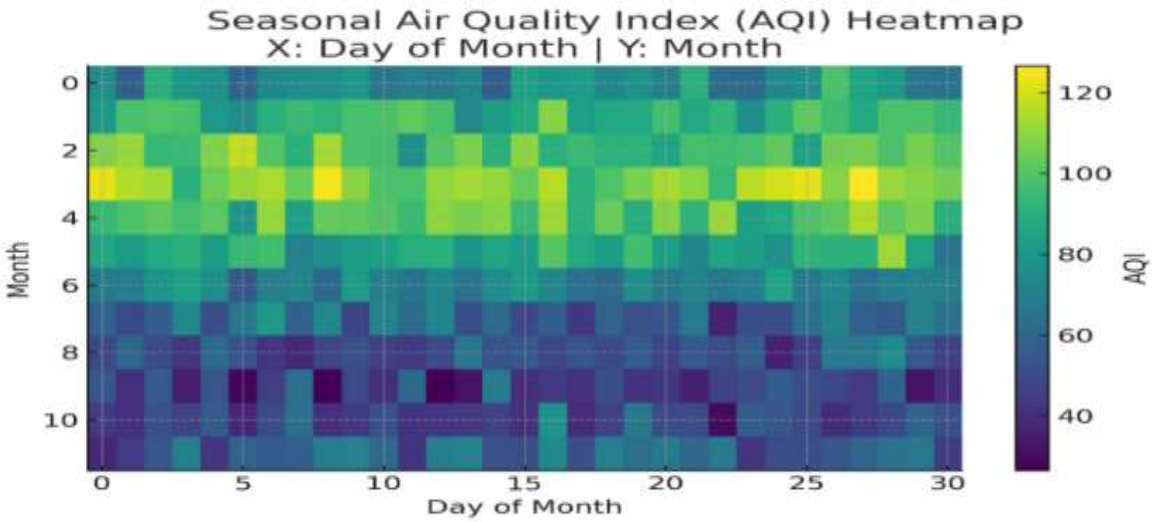

Figure 10.
Seasonal Air Quality Index (AQI) heat map

Smog events that occur with the seasons represent a serious environmental and public health concern globally; most have occurred in colder months in South East Asia and coincide with similar winter months worldwide. These events are characterized by the formation of high concentrations of haze from the combination of smoke, fog, and air pollutants worldwide; they typically impact large urban industrial areas in the world's major cities or large industrial/commercial heartland centers.

Health and environmental impacts

Air pollution is having a serious impact on public health in Pakistan. Each year, it is linked to more than 235,000 early deaths, mostly from illnesses like stroke, heart problems, lung cancer, chronic breathing issues, and infections [49]. Research shows that deaths connected to $PM_{2.5}$ have risen dramatically, from around 57,000 in 2000 to nearly 158,000 in 2021, reflecting both worsening air quality and a growing population [50]. According to the air quality life index, living with high levels of fine particulate matter over time can shorten the average Pakistani's lifespan by almost four years, with the effects even worse in heavily polluted cities such as Lahore [51]. Hospitals report surges in respiratory and cardiac admissions amid heavy pollution episodes. Typical acute effects include worsened asthma, chronic bronchial inflammation, chest infections, and eye irritation. Long-term contact contributes to COPD, lung cancer, coronary heart disease, and hinders child lung development [52]. The economic costs are comparably high. Disease and efficiency losses from outdoor air pollution amount to around 1 to 2% of GDP. In large urban centers, smog forces school closures, flight suspensions, and general reductions of business activity, as observed in Lahore annually. Air pollution also damages crops and deteriorates buildings. Environmentally, acid rain can harm soil and freshwater quality over time.

Management and Technological Interventions

The air quality emergency in Pakistan has caused many different responses throughout Pakistan, with policy action generated primarily at the provincial level [53][54]. While Punjab has been hit worst by the air pollutants and has been addressing the air quality emergency through several different methods, beginning with its creation of an anti-smog action plan with measures focused on; closing or upgrading brick furnaces during smog seasons, implementing laws restricting the burning of crop residue, establishing a vehicle emissions inspection program, establishing a ride-share system, developing domestic and mass transportation, and implementing practices for controlling and reducing dust emissions at construction sites [55]. By 2023, Punjab had recognized smog as a calamity and introduced immediate responses to smog that include suspending classes and shutting down operations at workplaces during times of peak smog levels. Plans include implementing public transportation systems that utilize cleaner burning fuels, as well as expanding urban greening efforts, with both ultimately resulting in the improvement of air quality [56].

A monitoring network was created in Sindh, which has curtailed industrial operations in some instances during periods of high pollution [57]. However, the enforcement of anti-pollution laws is sporadic, as on numerous occasions, numerous vehicles have been found to be out of compliance with vehicle emission standards, and the ability to enforce these standards is limited because of the sheer volume of vehicles in Sindh [58]. Like vehicle emissions, compliance with emission laws about manufacturing is difficult in Sindh due to many small factories and kilns [59]. The lack of cross-border collaboration in relation to agricultural burning, while both nations acknowledge the mutual challenge, has been negligible between India and Pakistan [60]. Punjab's anti-smog action plan appears comprehensive, but its real-world effectiveness remains uneven, as demonstrated through pre and post–intervention air quality data.

Analysis of seasonal $PM_{2.5}$ averages before the plan's implementation (2016 – 2018) compared to after enforcement measures (2019 – 2023) shows only marginal reductions in winter smog intensity. Although short-term improvements were recorded in some years, the overall trend remains highly variable. The transportation sector has also been targeted for transformation through an increase in the use of EVs and cleaner fuels. The Pakistan government's EV policy outlines a target of 30% of the total number of new vehicles sold in Pakistan being EVs by 2030. Adoption is still at an early stage, but EVs have recently begun to operate as buses in Karachi and Lahore, and some private companies have begun manufacturing electric two- and three-wheeled vehicles in Pakistan. The testing of AI-based smart traffic management systems in Lahore and Islamabad has been completed. These systems aim to assist with signal timing and to reduce the amount of emissions produced through vehicular congestion [65].

Water scarcity and pollution

Without adequate, clean, and safe water, we cannot develop sustainably, as water is a key resource that supports human well-being, economic growth, and food security worldwide. All countries globally face crises related to water resources that are interconnected. Water scarcity and water pollution are the main causes of these crises. Water scarcity and pollution are becoming major obstacles to achieving two SDGs, i.e., SDG6 and SDG2, since both have a significant impact on producing food and overall agricultural activity. Very recently, though, many parts of the world have seen a decrease in per capita water resources due to substantial population growth, poor water use, urbanization and expansion, industrialization, and associated increases in demand for water, and because of climate change stress from changing precipitation patterns, severe droughts, and retreating glaciers. The availability of safe drinking water and irrigation, particularly in rural areas, has continued to decline, also due to significant declines in water quality, which are driven primarily by agricultural runoff, industrial and municipal wastewater that have not been treated, and a lack of adequate sanitation systems.

- Hydrogeological modeling insights for policy: Hydrological models consistently reveal several structural weaknesses in Pakistan's water management system. First, recharge rates are declining sharply in urban areas due to rapid land-use change. Expanding impervious surfaces reduces infiltration and increases runoff, lowering natural recharge. SWAT-based recharge models estimate a 20 to 25% decline in natural recharge for rapidly expanding cities like Lahore. Second, inefficiencies in the Indus basin irrigation system exacerbate groundwater stress. Excessive irrigation in upstream Punjab reduces downstream flows in Sindh, increasing reliance on groundwater and contributing to salinity and waterlogging. Hydro-models show that canal lining and reduced conveyance losses could lower groundwater dependence by 15 to 20%, improving basin-wide balance.
- Integrated water quality risks: Groundwater quality deterioration is emerging as a parallel crisis. As aquifer levels fluctuate due to excessive extraction, the risk of contamination increases. Hydrochemical and GIS-supported analyses identify several pollution pathways, i.e., nitrate leaching from excessive fertilizer use, arsenic mobilization under reducing geological conditions, industrial effluent infiltration through unlined drains, and leakage from septic tanks in expanding peri-urban settlements. Recent mapping studies show that up to 30% of shallow wells in Punjab exceed WHO limits for nitrates, posing acute health risks, particularly for children and pregnant women.

Water availability and scarcity

During the 1950s, the availability of water for every citizen of Pakistan was around 5,000 cubic meters; however, today, that same number has fallen below 1,000 cubic meters per capita, which is considered the minimum threshold for any country classified as water-scarce. Based on current estimates, there are approximately 860 m^3 per capita available in Pakistan every year. The Pakistan Council for Research on Water Resources warns that without some sort of intervention to address the current level of mismanagement, it is possible that Pakistan will run dry and will potentially be classified as being in a state of absolute water scarcity by 2025 in specific areas and/or during certain times of the year. The factors leading to both the increased scarcity and the ultimate decline in water supply in Pakistan are numerous in nature [72]

• Population growth: A nearly fourfold increase in population since independence in 1947 means significantly more people drawing upon essentially the same water resources. This factor alone has continued to be the main factor leading to declines in per capita water availability. Although there has been an increase in total withdrawals of water used for agricultural purposes and other uses, these increases have not kept up with population growth. As a result, each individual is experiencing fewer freshwater resources [73].

• Agricultural demand: Farmers use up 90% to 95% of all available freshwater in Pakistan, mostly on their farms. One of the largest contiguous systems of irrigation anywhere in the world sends water from rivers through canals to farms. However, the way that farmers apply this water means that very little of the available water is currently being used for growing food. Much of the water used today by farmers is in the form of conventional flood irrigation. This means that the country is poorly prepared for prolonged periods of drought and will have a limited amount of time available during such periods to buffer any shortages [74].

• Changes in climate and glaciers: The amount of rain and the timing of water that is delivered from glaciers to rivers are changing over time. In the past, more than half of the water that flows into rivers came from snow melting in the Himalayas and Karakoram mountain ranges. For example, a weak monsoon season (2024) resulted in the Mangla reservoir being at or near dead storage, while an unexpectedly strong monsoon season (2022) resulted in the reservoir overflowing; excessive extraction of groundwater and decreased rainfall in parts of the country are having an impact on groundwater recharge [75].

• Water flow demographic in transboundary: Water flow demographic in transboundary rivers predominantly belongs to Pakistan's upper riparian countries and primarily to India for the support and tributaries that feed into the river Indus. Growing tensions are escalating as India continues to create hydropower projects on the rivers upstream, resulting in restrictive limitations previously imposed by the 1960 IWT that divides the rivers and water available to both India and Pakistan. Should India divert any upstream waters or change the channel of flow, then successive periods will have limited availability of water. All these upstream influences will generate new uncertainties and complexities regarding the availability of water in Pakistan in the future [76]. According to the International Monetary Fund (IMF) and the World Resources Institute, due to the interaction between these factors, Pakistan is one of the most highly water-stressed countries in the world [77]. Furthermore, severe water shortages occur regularly. In Sindh's lower reaches, for example, irrigation canals near harvest time often run dry, urban areas experience periodic water supply restrictions, and farmers in Balochistan have witnessed orchards that are irrigated through groundwater boreholes dying [78].

Water pollution and quality degradation

Pakistan's water supply is scarce, and most of it is contaminated. A troubling statistic illustrates this point: an estimated 80% of the population must drink either bacteria- or chemically-laden water; only about 20% have access to potable drinking water [80]. The sources of contamination are numerous:

• Waste water from municipal sources: Wastewater from municipal sources accounts for more than 90% of sewerage in Pakistan, which is untreated and discharged directly into bodies of water. Most municipalities in Pakistan do not have enough wastewater treatment facilities, with Karachi producing about 475 million gallons of wastewater each day, less than 10% of which is treated. The remainder flows into the Arabian Sea and/or contaminates groundwater supplies. Most cities, including Lahore, Islamabad, and Faisalabad, have inadequate treatment facilities for sewage. Therefore, this leads to extremely high concentrations of pathogens (including coliform bacteria) being found in many of the surface water bodies and from shallow wells, and thus contributes to the development of various waterborne diseases, causing diarrheal disease, typhoid, cholera, and hepatitis. As a result, tens of thousands of Pakistanis, most of whom are children, die each year from diarrheal diseases associated with water quality [81].

- <u>Industrial effluents:</u> The industries generate polluted wastewater streams that are discharged into local water bodies, such as rivers, without treatment. Discharge of chemicals, explored through industrial processes, occurs throughout Pakistan, including Karachi's Sindh Industrial and Trading Estate and Lahore's Kot Lakhpat area. The same can be said for the sugar industry, as well as many factories producing textiles, as these industries generate large volumes of organic pollutants that lower dissolved oxygen concentrations found in many aquatic environments, thereby causing harm to both fish and other aquatic organisms. In fact, the river Ravi is often referred to as a dead river because of the high levels of BOD and ammonia in the river, essentially meaning that there are no fish present in the river [82].

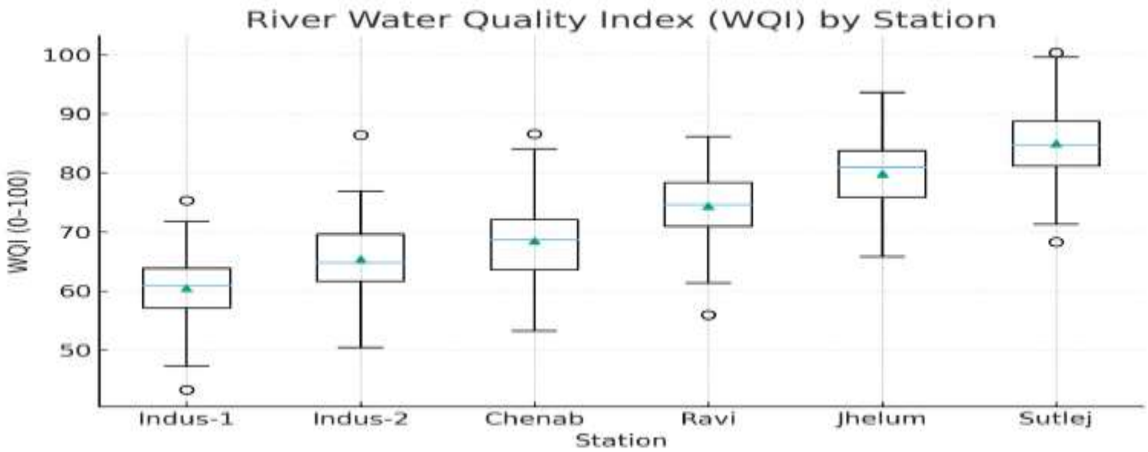

Figure 11.
River Water Quality Index (WQI) by Station

- <u>Agricultural runoff:</u> Agricultural pollution is a problem in Pakistan. Farmers use lots of fertilizers and pesticides on their crops, and when it rains, the rainfall washes off the excess fertilizer and pesticide into rivers, canals, and groundwater. Many wells in Punjab contain nitrate levels above the WHO's safe limit, which can lead to methemoglobinemia in infants, also known as blue baby syndrome. Some researchers have found pesticide residue in groundwater, although the data available is limited. Some pesticides, such as DDT and organophosphates, have the potential to accumulate in the aquatic food chain due to a lack of monitoring and agricultural practices. Salinity is also a major issue in Pakistan. Salts build up in the soil from water evaporation and waterlogging, and then are washed off the land into the irrigation systems of Pakistan. The Indus basin irrigation system has a complex network of surface drains known as salt drains that carry off this saline drainage water; however, these surface drains can be carried downstream into rivers and lakes, thus allowing the salinity from these surface drains to spread [83].
- <u>Solid waste and plastics:</u> Improper solid waste disposal creates a situation where plastic and other solid waste are clogging stormwater drains and subsequently making their way into rivers. Garbage collecting in urban nullahs can both directly

cause flooding and allow contaminants to leach through the stormwater system. With plastic waste degrading in water, microplastic pollution is an emerging concern in coastal and river systems, although research is just beginning in this area for Pakistan [84].

Pakistan's rivers near metropolitan communities have been extensively polluted over time. The river Indus at its delta does not transport sediment only, but also the combined pollutants from its tributaries. The residents of many rural communities use shallow wells or hand pumps located near latrines or septic systems, resulting in long-standing health problems attributed to the contamination of their drinking water. Investigations conducted in Punjab and Sindh around 2017 demonstrated that high levels of arsenic exist in many of the tube wells throughout the regions, which means that approximately 50 to 60 million people are exposed to the health risks of an arsenic contaminant from the naturally occurring source of arsenic that has been released into the environment as a result of agricultural practices and irrigation [85].

Deforestation and biodiversity loss

Pakistan has an abundance of ecosystems; however, these are at risk from several sources. A surging rate of deforestation is being seen in Pakistan, and biodiversity is declining at an alarming rate. Pakistan has been laboring under the misapplication of its natural resources, including forests and wildlife, for the benefit of activities like agriculture, construction, and mining. Consequently, Pakistan has become a depleted forest economy, with actual figures showing that approximately 5% or less of the total land mass is under forest; however, based upon analysis of satellite images, the amount of remaining old-growth forest is much lower, approximately between 1% and 2%. This represents a very low level of forest cover compared to world averages and falls well below the minimum 25% level necessary to maintain environmental resilience. The negative impacts of deforestation and biodiversity reduction on soil loss, rapid decreases in carbon sequestration, changes to surface water runoff patterns, loss of many natural areas, and some natural habitats are extremely important to fully comprehend the gravity of the situation. Biodiversity continues to decline through habitat loss, resource over-exploitation, pollution, and climate change.

Deforestation: extent and drivers

Pakistan's forest area has decreased significantly over the past multiple decades [89]. A long-period analysis using satellite imagery found that from 1980 to 2020, the country experienced a mean deforestation rate of roughly 1.4% per year, with certain regions increasing to almost 1.9% annually from 2000 to 2020 [90]. This is considerably higher than previous calculations and is one of the fastest rates in Asia. In total, Pakistan lost nearly 25% of its existing forest area, i.e., around 0.5 million hectares, between 1990 and 2015 [92]. The continuous forest cover has been broken into fragments [93]. The major types of forests in Pakistan include alpine and sub-alpine forests in the north, moist temperate forests, dry temperate forests, subtropical scrub forests, riverine forests, mangrove forests, and planted plantations [94]. All these types have faced pressures:

- Timber and fuelwood harvesting: Historically, timber extraction for construction and furniture, both legal and illegal, has been a major cause of forest loss. For example, the coniferous forests of Khyber Pakhtunkhwa were heavily logged in the 1980s and 1990s under both official quotas and rampant smuggling, leading to denudation of hillsides [95]. Although a ban on commercial logging was imposed in 2013 in KPK, reports indicate illegal cutting continues at a slower pace. Rural communities also depend on fuelwood for cooking and heating, as over 50% of rural households use firewood, exerting chronic pressure on nearby woodlands.

- Agricultural and urban expansion: Clearing of forest land for agriculture or pasture has historically been significant. In the northern areas of Pakistan, forest lands have been converted into terrace farms or pastures. In the plains, riverine forests were cleared to make way for farms over the last century. Charcoal production and grazing have degraded what remains. Urban sprawl is a newer driver, as the hills around Islamabad, Murree, and Karachi's outskirts have seen deforestation for housing developments and real estate. For instance, the Margalla hills near Islamabad lost considerable tree cover to housing encroachments until protective measures were taken via a national park.
- Infrastructure and development projects: Construction of roads, dams, and power projects often cuts through forest areas. The Karakoram Highway widening, for instance, removed many roadside forest strips. Large dams like Tarbela and Mangla in the past submerged forested valleys. Ongoing projects under the China-Pakistan Economic Corridor (CPEC) also require land clearing. Mining also leads to local deforestation, as does industrial expansion.
- Population pressure and refugee impacts: In some regions, population increase has led to unsustainable use of wood and land. The arrival of Afghan refugees from the 1980s into KP and Balochistan also had unexpected impacts: refugee communities, in need of fuel and shelter, led to deforestation in areas of Balochistan and KP near camps [96]. Many hill slopes that previously had trees on them have been stripped of their vegetative cover. As a result of the removal of the tree roots that provided stability to the slopes, landslides and flash floods have become much more common in these hilly regions. In the Hazara Division alone, between 1967 and 1992, the area covered by forests decreased by 52%. Losing forest cover also decreases the ability to store carbon, which in turn increases the amount of carbon dioxide (CO_2) in the atmosphere and can negatively impact the climate.

Biodiversity and wildlife conservation

The geography of Pakistan is varied with different ecological zones. Each of these zones has its own flora and fauna that differ from each other [97]. The biodiversity in this country is characterized by a rich catalogue of over 195 species of mammals, approximately 668 species of birds, 177 species of reptiles, 22 species of amphibians, and thousands of plant and invertebrate species [88]. Some of these species have been labelled as being globally important for conservation purposes, i.e., the mountainous regions of Pakistan are home to the snow leopard, while the rive Indus dolphins inhabit the murky waters of the river; many species of Marco Polo sheep and Markhor goats live in the alpine areas; and the mangrove forests of Sindh provide habitat in the coastal regions and act as nurseries for fish and migratory bird species [89]. Unfortunately, this biodiversity is imperiled. According to assessments in Pakistan's National Biodiversity Reports, at least 20 mammal species, 25 bird species, 6 reptile species, and others are threatened with extinction within Pakistan. More recent tallies suggest even higher numbers [90, 91].

The major threats to biodiversity include:

- Habitat loss: As forests, wetlands, and rangelands are converted or degraded, species lose their living spaces. For instance, the Indus river dolphin, Pakistan's iconic freshwater dolphin, has lost much of its range due to irrigation barrages fragmenting the Indus and reduced river flows. It now survives in isolated river sections, mainly in

Sindh. Similarly, mangrove forests in the Indus Delta, which once covered 2,600 km² in the 1970s, shrank to about 1,300 km² by the mid-1990s.

- Overexploitation: Unregulated hunting and fishing have diminished many species. Hunting large mammals and birds was historically rampant, though trophy hunting programs now involve local communities in conserving and sustainably hunting some games. The houbara bustard, a vulnerable migratory bird, is still illegally hunted in large numbers. Fishing pressure in the Indus and coastal waters is high; unsustainable fishing has reduced stocks of river fish and marine fish alike. Overharvesting of medicinal plants and firewood in some areas also threatens plant biodiversity.
- Poaching and wildlife trade: Poaching for skins, furs, and the exotic pet trade endangers species such as snow leopards, freshwater turtles, pangolins, and birds like falcons. Although illegal, wildlife trafficking persists due to weak enforcement and profit motives [92].
- Climate change: Changing climate adds pressure to biodiversity by shifting habitat ranges and seasons. Species adapted to cooler climates face shrinking habitat as tree lines shift upward. In freshwater ecosystems, warming and erratic flows stress fish species; recent extreme floods (2022, 2023) have had unknown but likely significant effects on riverine wildlife; the 2022 floods, for instance, could have displaced or killed river dolphins and crocodiles in Sindh. Studies predict climate change could impact 15 to 20% of species' ranges in Pakistan by the end of the century if emissions continue. There are also different aspects of the decline of biodiversity that affect all parts of the Earth; for example, there is a decline in ecosystem services, as well as cultural heritage, and possible resources. The forests to the north protect the waters of the rivers. If these forests are lost, then flooding will be worsened, as well as water shortages further downstream.
- Conservation efforts: Although Pakistan has taken some action to conserve its environment, these efforts have had varying degrees of success. About 12% of Pakistan's total area is designated as protected areas containing more than 30 national parks and other wildlife sanctuaries. Some notable examples include Hingol National Park, located in Balochistan, which protects an extensive coastal ecosystem that supports large amounts of biodiversity; Khunjerab National Park, located in Gilgit-Baltistan, protecting the habitats of the Marco Polo sheep and snow leopards; and the Indus Dolphin Reserve established in Sindh. However, on-ground management of these areas is often weak due to a lack of funds and personnel. Encroachments, illegal grazing, and hunting occur even within some protected areas.

Urban environmental challenges and waste management

Accelerated urbanization in Pakistan has led to a range of environmental pressures specific to urban settings [83]. More than 80 million Pakistanis currently reside in urban areas, a figure expected to grow further as village-to-city migration persists [104]. The growth of major cities such as Karachi, Lahore, Faisalabad, Rawalpindi, and others has frequently been poorly planned, surpassing the provision of urban infrastructure and environmental regulatory frameworks [85]. As a result, cities in Pakistan are facing serious environmental problems. Cities' air quality is often poor due to ongoing poor waste management, lack of sanitation services, and lack of access to clean water. Cities also face several other challenges, including traffic congestion, excessive noise, rising temperatures, and decreased availability of green space and habitats.

Solid waste management crisis

One of the most serious environmental problems facing Pakistan is the improper disposal of solid waste. With the increase in the size of the city's population due to rapid urbanization, population growth, and the change in their lifestyles, each day has resulted in increasing amounts of municipal solid waste generation. The increase in the density of population and consumption has created many new challenges for local governments trying to manage the rising amount of tons of waste being produced. Recent studies indicate Pakistan is generating 49.6 million tons of municipal solid waste every year, with urban inhabitants estimated to generate approximately 0.5 to 0.8 kg of waste per person daily. Most of the municipal solid waste occurs in large metropolitan centers. For example, Karachi generates from 12,000 to 16,000 tons of waste, and Lahore generates from 7,000 to 8,000 tons of waste daily.

Many large cities, such as Faisalabad, Rawalpindi, and Peshawar, generate thousands of tons of waste every day [86,88]. The continuing increase in the use of packaging materials, plastics, and disposable products is contributing significantly to the increase in municipal solid waste generation. It is not only the amount of waste, but the ineffective management practices of waste management that present problems [89]. Currently, Pakistan has a very weak solid waste system; the lack of proper diversion and recycling systems has resulted in substandard waste collection processes and practices and extremely limited recovery of reusable materials. Overall, municipalities only collect approximately 50% to 70% of their waste. The uncollected waste lies on streets, in drains, and on vacant plots, leading to pollution and health hazards. Even the collected waste frequently ends up at open dump sites or poorly managed landfill arrangements.

For example, Karachi’s primary dumping sites at Jam Chakro and Gond Pass are basically open disposal sites with minimal environmental control, leading to regular garbage fires and liquid waste seepage [90]. Likewise, Lahore, until not long ago, disposed of much of its waste at an open site in Mehmood Booti. A classification of common urban waste in Pakistan indicates a large organic share, around 5 to 10% plastics, 5 to 15% paper, and the remaining consisting of inert material, textiles, metal, etc. The high organic portion implies that waste, when not properly managed, breaks down. Furthermore, it emits methane and unpleasant smells, in addition to drawing pests [91]. Open dumping and burning of waste are common, as burning emits toxic smoke, including dioxins and furans, contributing to urban air pollution. During smog season, local governments often crack down on waste burning to help air quality, indicating its contribution [97].

Other urban environmental stresses

Pakistani cities contend with environmental challenges beyond waste and air pollution [12]. Water and sanitation shortfalls in slums and peri-urban areas are acute, leading to urban water pollution and disease. Many households still lack piped water and proper toilets; as a result, sewage tends to be discharged into nullahs, polluting rivers and coastal zones [13]. Urban sprawl and green-space loss intensify the urban heat island effect; Lahore and Karachi record temperatures several degrees above surrounding areas. Heatwaves hit city residents hard, as seen in the deadly 2015 Karachi heatwave, exacerbated by a lack of shade and vegetation [14]. Cities are now pursuing urban-forestry drives as adaptation under the 10 billion tree program. Urban stress is exacerbated by traffic jams, energy waste, and noise pollution [15].

Bus high-speed transit and mass transit lines seek to limit private car use, yet need scaling. Urban flooding from encroachments and obstructed drains is a repeated hazard; cities such as Karachi and Lahore are upgrading stormwater systems and integrating AI-based monitoring to forecast flood risk. Citizen participation tools for logging waste and infrastructure problems have emerged in several cities, forming the basis for smart city strategies. Urban flooding is a growing threat, as seen repeatedly in Karachi. Encroachment on floodplains, solid waste in drains, and insufficient drainage infrastructure combine with heavier rainstorms to make flash floods in cities more frequent and damaging. In response, Karachi is clearing some stormwater drains of illegal construction and improving drainage capacity, but it is a race against unplanned growth.

The role of AI and technology in environmental management

Advanced AI models, particularly transformer-based architectures, have demonstrated strong predictive performance in both flood forecasting and air quality ($PM_{2.5}$) prediction, often surpassing traditional baselines. In flood modeling, recent studies show that transformers can modestly outperform recurrent networks like LSTMs. For instance, a transformer network predicting river water levels 1-day in Europe achieved about 4% lower RMSE and 7% lower MAE than an LSTM, while also reducing computation time. Such gains, though percentage-wise small, translate into more accurate flood peak predictions, which are critical for early warnings. Another study using Temporal Fusion Transformers (TFT) on large-scale hydrological data found consistently improved accuracy over conventional RNN models across thousands of basins. These results suggest that attention-based models can better capture long-range climate dependencies, improving lead times. In Pakistan's context, where flood forecasting traditionally relies on physical models and limited gauge data, the data-driven transformer approach has high potential, provided sufficient training data. Global efforts have already operationalized AI flood forecasts: Google's Flood AI system is operational in 80+ countries with up to 7-day lead times.

It delivers significantly more accurate inundation alerts than previous methods, even in data-scarce regions. This indicates a technology readiness Level (TRL) on the order of 8–9 for AI flood forecasting globally. Local adoption in Pakistan, however, remains at pilot stages (TRL ~ 5 to 7) due to sparse river gauge data and nascent integration into national forecasting workflows. Comparatively, machine-learning baselines typically achieved R^2 scores of only ~ 0.75 to 0.85 in flood-related tasks; by contrast, LSTM models in a recent Kabul River study reached $R^2 \approx 0.96$ (RMSE ~141 m^3/s) for daily flow prediction. Transformer models can build on these strengths, offering robust multi-step flood forecasts with data assimilation and potentially extending Pakistan's early warning lead times if integrated with the national flood forecasting system. Advanced technologies such as AI, ML, remote sensing, and data analytics in environmental management offer powerful new ways for Pakistan to monitor, predict, and reduce environmental challenges [16]. As discussed, a wide range of Pakistan's environmental problems are affected by gaps in data, early warning, and efficient resource use, areas where AI and digital tools excel by analyzing large datasets, recognizing patterns, and optimizing complex systems [17, 18].

AI for climate and disaster risk management

AI applications in Pakistan include climate simulation and disaster risk management [19]. As evident from recent flooding, droughts, and other extreme weather events that have occurred in Pakistan, AI will help increase the accuracy of predictions and early warning [20]. An example of this is the development of ML models, which utilize both meteorological data and the historical record of where river floods occurred to predict where floods would occur and when they would peak [21]. These models, which can be executed on either supercomputers or cloud computing platforms, provide flood risk alerts for specific districts days to weeks before the actual flood. In addition to allowing evacuation efforts to occur within the appropriate area, these warnings allow for strategic resource placement in preparation for these disasters [22]. In Pakistan, AI is providing refinement of global climate model results into localized climate forecasts in Pakistan, allowing for the conversion of approximate climate forecasts into detailed scenarios for local regions over the coming decades [23].

As part of these efforts, the Pakistan Meteorology Department (PMD) has begun using AI for weather forecasts, including the development of neural networks to assist with the prediction of monsoon rainfall intensity and the timing of heat waves by detecting complex signals embedded in atmospheric data that are often missed by traditional weather forecast methods. An important initiative is the development of a climate risk management system that uses AI to integrate multi-hazard data and community and economic sensitivity info to generate risk scenarios [57][33]. This can assist NDMA and provincial disaster authorities to focus on high-risk areas and craft scenario-based emergency plans.

The use of AI-driven analytics was acknowledged for enhancing coordination in the 2022 flood response, where mapping of satellite data via machine learning enabled authorities to determine the heavily impacted villages for aid targeting. The monitoring of Pakistan's many environmental parameters throughout the country is a logistical challenge because of the wide range of landscape types that exist. Nevertheless, the use of AI is a valuable tool to enhance such efforts. Numerous photographs taken by NASA satellites document both the increase in air pollution created by smog formation and the loss of land because of floods. Using AI methods like image classification and object detection can allow for the automation of analyzing the satellite images taken from space. For instance, AI algorithms examine daily satellite imagery to identify ongoing agricultural burning in Punjab, enabling relevant agencies to precisely locate and respond to farm-fire incidents in near real time. Similarly, AI analyses of satellite imagery have been used to map forest cover change, distinguishing deforested patches from intact forest with high accuracy. The data thus produced feeds into Pakistan's forest monitoring and is being used to validate the success of reforestation programs via independent assessment [24].

Table 5.
Applications of AI/ML methods in environmental management

Domain	Example AI applications (current/potential)	TRL (≈2025)	Key scalability barriers
Floods & Climate	Flood forecasting models (river flow prediction via LSTMs, Transformers) provide early warnings. Flood risk mapping using satellite imagery & ML to identify high-risk zones– Glacial lake outburst (GLOF) alerts using IoT sensors and AI threshold detection	High globally (TRL 8–9) – operational AI flood forecasts in many countries. Moderate in Pakistan (TRL 5–7) – pilot projects and partial adoption.	Need for real-time data pipelines and HPC/cloud for model runs. Institutional: Integration with NDMA and provincial DMAs is nascent; trust in AI forecasts needs building. Policy: Requires formal inclusion in disaster management protocols (currently heavily reliant on traditional forecasts).
Air Pollution	Air quality forecasting (daily $PM_{2.5}$/AQI predictions using	Moderate (TRL 6–7) – AI-enhanced air	Urban areas need dense IoT sensor deployment and

	neural networks and meteorological data)– Remote sensing analytics to monitor pollution	monitoring is piloted in cities.	data management for real-time forecasts.
Water Quality	Water supply optimization (AI scheduling of reservoir releases and pump operations to improve efficiency and quality)– Groundwater analytics (ML models identifying over-abstraction hotspots from well data)	Low–Moderate (TRL 4–5) – Largely at experimental or pilot stage. Some prototype deployments of IoT water quality sensors with AI alerts are underway, but widespread use in Pakistan is absent.	Water authorities lack data platforms and AI expertise; current systems are manual. Infrastructure: Need investment in robust sensor networks (to detect pH, contaminants) and maintenance of these in harsh field conditions.
Agriculture	Crop monitoring with remote sensing	Moderate (TRL 5–7) – Core technologies exist and have been trialed. For example, AI-informed irrigation scheduling in Punjab saved ~30% water without yield loss in pilot tests.	Rural connectivity (internet) and access to devices can limit digital agriculture tools. Policy – Insufficient extension services incorporating AI; need supportive policies to scale these innovations.

In air quality, low-cost sensor networks augmented with AI calibration are emerging. Pakistan's EPA and startups are deploying dense networks of air sensors. AI can calibrate these readings against reference monitors and filter noise, producing high-resolution pollution maps of cities. Such AI-refined maps identify pollution hotspots so that local actions can be taken, like adjusting traffic flows or inspecting specific factories [125]. Water quality monitoring, historically sparse, can be improved with AI as well. Projects are currently in progress to deploy intelligent sensor-based monitoring devices in canals to detect water pollution events by measuring pH, water cloudiness, and chemical signatures, and apply outlier-detection algorithms that trigger alerts for abrupt pollution incidents, such as industrial discharges. This functions as an AI-based early warning system that can alert authorities more promptly than periodic manual monitoring could [126].

AI in sustainable agriculture and water management

Agriculture, along with associated water use, is well-suited to AI-enabled transformation. Data-driven agricultural approaches, though still emerging in Pakistan, are being tested through pilot initiatives. For example, satellite-based remote sensing data combined with AI are used to evaluate crop condition and to provide farmers with guidance on efficient input use [127]. AI-enabled decision support applications are currently under development that analyze weather forecasts, soil data, and insect occurrences to provide farmers with site-specific recommendations on irrigation planning, fertilizer application, and integrated pest control. Such approaches can greatly minimize resource waste. Initial trials in Punjab demonstrated that AI-informed irrigation scheduling saved up to 30% of water in wheat and rice fields without any yield loss by avoiding overwatering [128].

In irrigation systems, Pakistan is piloting intelligent canal management. This strategy uses sensors combined with AI algorithms to optimally distribute water from storage facilities and canals to fulfill water requirements, all the while minimizing wastage. The analysis of Pakistan's irrigation systems will benefit from the AI system's ability to analyze complex data fast; thus, it provides increased efficiency for farmers through improved water distribution and equitable water allocations to all farmers. Groundwater management support will also result from an AI system's capability to analyze thousands of wells' data and water usage data through ML models that can determine rates of over-pumping aquifers and identify areas at risk of over-pumping, regulating these areas as described in the proposed policy design for water governance [129]. Research and development in animal husbandry are being conducted using AI image recognition technology to monitor livestock group health by identifying sick animals through thermal imaging and optimizing supplemental feeding of livestock. While this technology is still in its early stages, its application in agriculture improves production sustainability by enabling higher output with fewer resources, aligning with SDG2 and SDG12 [130].

AI for pollution control and waste management

One use of AI in solid waste is to improve pickup routes for vehicles. In turn, this will reduce the amount of time spent collecting waste and the number of miles travelled. After testing the use of an AI-based routing system in select districts of Lahore, the Lahore Waste Management Company has reported lower fuel consumption and improved efficiency in collections. Another capability of AI is to provide proactive maintenance support for collection vehicles, predicting when a vehicle may break down and scheduling maintenance to avoid interruptions to service. Automated separation of materials is crucial to improving efficiency in waste recovery processes. These technologies have not yet seen widespread implementation in Pakistan. However, there is potential for AI-powered optical sorting machine technology to significantly improve the performance of recycling operations throughout the country. Some of the upcoming industrial-scale waste processing facilities being built through CPEC investments may implement this type of technology. Additionally, AI-based platforms could help facilitate connections between waste producers and recycling companies as well as streamline operations throughout the logistics and supply chain process. Several local initiatives are currently testing the use of AI to help predict the pricing trends and materials availability for recycling.

Challenges and future directions for AI adoption

In formulating a strategy for AI adoption in environmental management, Pakistan must balance multiple factors from technical feasibility to socio-ethical considerations. The study proposes a Multi-Criteria Decision Analysis (MCDA) framework to prioritize AI initiatives based on a structured evaluation of key criteria. In this framework, policymakers first define a set of candidate AI interventions. Each option is then evaluated against multiple criteria that reflect national priorities and constraints. Five crucial criteria are:

- <u>Data availability and quality:</u> Does the initiative have sufficient data to succeed? This covers the existence of historical datasets, sensor networks, and data infrastructure. For instance, a flood AI system would score high if river flow and rain gauge data are plentiful, but low if data are sparse or unreliable. Data quality is also critical, as models trained on limited or biased data may perform poorly. Thus, this criterion ensures projects built on Pakistan's stronger data repositories get prioritized.
- <u>Computational infrastructure and skills:</u> Does Pakistan have the technical capacity to implement and sustain the AI tool? An initiative requiring advanced supercomputing or cloud resources and specialized AI talent would be assessed for feasibility. Projects leveraging existing capacity rank higher. Currently, limited domestic capacity is a bottleneck, so this criterion helps favor realistic, implementable projects or those with clear plans for capacity-building.

- Policy support and regulatory environment: To what extent is there government buy-in, enabling policies, or an institutional champion for the AI solution? This measures alignment with national strategies and the likelihood of smooth integration. For example, an AI air pollution forecast system might be scored by whether environmental agencies and regulations are prepared to use AI-driven alerts.
- Ethical and social risk: This criterion gauges potential ethical, privacy, or equity issues associated with the AI intervention, as well as public acceptance. For instance, the use of drones and AI for monitoring might raise privacy concerns; predictive policing in environmental law enforcement could disproportionately affect certain communities if not carefully managed. Likewise, an AI system must be user-friendly and inclusive to succeed in Pakistan's context. A project that embeds local knowledge and involves stakeholders would score well, whereas one that is a black box solution imposed top-down might face resistance. MCDA ensures that initiatives with lower ethical risk and higher societal buy-in are favored, encouraging responsible AI use.
- Scalability and sustainability: Can the project scale beyond a pilot, and can it be sustained operationally in the long run? This involves assessing the financial and organizational viability, i.e., the upfront and recurring costs, the ease of extending the solution to additional regions or sectors, and the presence of a maintenance plan or business model. For example, an AI flood model might perform excellently in a pilot for one province, but if it relies on external expertise or funding that is not guaranteed long-term, its scalability is questionable.

CONCLUSION

At this point in time, Pakistan is on the verge of dealing with its ecological crisis. The findings of this study have highlighted how issues related to climate change, pollution, water scarcity, deforestation, and urban environmental stress will continue to impede Pakistan's progress towards achieving its SDGs and create opportunities for the potential of creating a new ecosystem of systemic change in Pakistan. If Pakistan is to have a sustainable and resilient future, it will require a methodical, holistic approach that emphasizes policy reform, community participation, and the use of cutting-edge technology to assist with improving decision-making and implementation procedures.

DECLARATIONS

Acknowledgement: We appreciate the generous support from all the contributor of research and their different affiliations.

Funding: No funding body in the public, private, or nonprofit sectors provided a particular grant for this research.

Availability of data and material: In the approach, the data sources for the variables are stated.

Authors' contributions: Each author participated equally to the creation of this work.

Conflicts of Interests: The authors declare no conflict of interest.

Consent to Participate: Yes

Consent for publication and Ethical approval: Because this study does not include human or animal data, ethical approval is not required for publication. All authors have given their consent.

REFERENCES

Abid, M., and M. Ashfaq. Climate Change Vulnerability, Adaptation, and Risk Management in Pakistan. Environmental Science & Policy 122 (2021): 87–95. https://doi.org/10.1016/j.envsci.2021.03.006.

AghaKouchak, A., et al. Climate Extremes and Compound Events in a Changing Climate. Annual Review of Earth and Planetary Sciences 48 (2020): 519–545. https://doi.org/10.1146/annurev-earth-071719-055228.

Ahmed, S., and T. Rasheed. Microplastic Pollution in the Indus River: Emerging Environmental Threat. Marine Pollution Bulletin 169 (2021): 112561. https://doi.org/10.1016/j.marpolbul.2021.112561.

Ahmed, Q., and M. Latif. Flood Early Warning Systems and ICT-Based Resilience in Pakistan. Water 12, no. 5 (2020): 1325. https://doi.org/10.3390/w12051325.

Akhtar, K., and M. Waseem. Impact of Glacial Retreat on Hydropower Potential in Pakistan. Renewable Energy 179 (2021): 1207–1218. https://doi.org/10.1016/j.renene.2021.08.034.

Akmal, H., and K. Waheed. Energy Security and Renewable Energy Transition in Pakistan. Energy Policy 176 (2023): 113434. https://doi.org/10.1016/j.enpol.2023.113434.

Ali, S., and M. Khan. Climate Change and Crop Yield Losses in Pakistan. Science of the Total Environment 755 (2021): 142537. https://doi.org/10.1016/j.scitotenv.2020.142537.

Amin, A., et al. Urban Environmental Stress and Air Quality Index in Lahore, Pakistan. Atmospheric Pollution Research 12, no. 9 (2021): 101176. https://doi.org/10.1016/j.apr.2021.101176.

Anand, R., and P. Gupta. Sustainable Waste Management with AI-Driven Systems. Waste Management 155 (2023): 201–213. https://doi.org/10.1016/j.wasman.2023.01.034.

Anderson, K., and G. Peters. The Trouble with Negative Emissions. Science 354, no. 6309 (2020): 182–183. https://doi.org/10.1126/science.aah4567.

Anwar, N., and H. Raza. Water Governance and Mismanagement in Pakistan. Water 14, no. 12 (2022): 1875. https://doi.org/10.3390/w14121875.

Aslam, A., and N. Tariq. Assessing 2022 Floods in Pakistan: Impacts, Responses, and Lessons. International Journal of Disaster Risk Reduction 85 (2023): 103580. https://doi.org/10.1016/j.ijdrr.2023.103580.

Baig, M., and A. Yousaf. Air Quality Trends in South Asia: Lessons for Pakistan. Atmospheric Environment 262 (2021): 118654. https://doi.org/10.1016/j.atmosenv.2021.118654.

Brown, C., and U. Lall. Water Risk and Sustainable Development under Climate Change. Nature Reviews Earth & Environment 3 (2022): 256–270. https://doi.org/10.1038/s43017-022-00272-1.

Butt, M., and T. Aslam. Carbon Footprint Assessment of Pakistan's Transport Sector. Journal of Cleaner Production 262 (2020): 121218. https://doi.org/10.1016/j.jclepro.2020.121218.

Chen, D., and B. Xu. Air Pollution and Global Health Burden: A Meta-Analysis. Environmental Research 195 (2021): 110890. https://doi.org/10.1016/j.envres.2021.110890.

Das, K., and S. Barman. Climate-Induced Displacement: A Global Review. International Journal of Disaster Risk Reduction 76 (2022): 103028. https://doi.org/10.1016/j.ijdrr.2022.103028.

Dey, S., and S. Tripathi. Air Pollution Trends and Drivers in Asia. Atmospheric Environment 238 (2020): 117760. https://doi.org/10.1016/j.atmosenv.2020.117760.

Eakin, H., et al. Resilience and Transformations in the Face of Climate Change. Global Environmental Change 64 (2020): 102129. https://doi.org/10.1016/j.gloenvcha.2020.102129.

Ebi, K., and J. Semenza. Climate Change and Vector-Borne Diseases. The Lancet Planetary Health 5, no. 7 (2021): e404–e412. https://doi.org/10.1016/S2542-5196(21)00058-9.

Farooq, S., H. Hashmi, and M. Shafique. Waste as Resource for Pakistan: An Innovative Business Model of Waste-to-Energy for Sustainable Development. Sustainability 15, no. 7 (2023): 6281. https://www.mdpi.com/2071-1050/15/7/6281.

Farooq, A., and M. Hussain. Agricultural Adaptation to Climate Stress in Pakistan: Farmer Perspectives. Climate Risk Management 28 (2020): 100222. https://doi.org/10.1016/j.crm.2020.100222.

Fischer, G., and F. Nachtergaele. Food Security under Climate Stress. Global Food Security 33 (2022): 100639. https://doi.org/10.1016/j.gfs.2022.100639

Garcia, S., and M. Lopez. Waste-to-Energy as a Sustainable Solution. Renewable and Sustainable Energy Reviews 127 (2020): 109856. https://doi.org/10.1016/j.rser.2020.109856

Ghosh, S., and A. Mukherjee. Climate Change and Food Security: A Global Review. Agricultural Systems 184 (2020): 102902. https://doi.org/10.1016/j.agsy.2020.102902
Gibbins, G., and S. Chaturvedi. Flood Risk Management under Climate Uncertainty. Climate Risk Management 39 (2023): 100506. https://doi.org/10.1016/j.crm.2023.100506
Gul, H., and Z. Abbas. Impacts of Deforestation on Biodiversity in Pakistan's Northern Areas. Forests 11, no. 9 (2020): 980. https://doi.org/10.3390/f11090980
Gul, H., and K. Mehmood. Pakistan's Climate Policy Response under SDG-13: Achievements and Gaps. Sustainable Development 32, no. 1 (2024): 45–60. https://doi.org/10.1002/sd.2590
Haase, D., and N. Kabisch. Urban Forestry and Urban Greening. Urban Forestry & Urban Greening 49 (2020): 126604. https://doi.org/10.1016/j.ufug.2020.126604
Haq, U., and A. Naveed. Water Stress and Inter-Provincial Conflicts in Pakistan. Environmental Science & Policy 144 (2023): 20–31. https://doi.org/10.1016/j.envsci.2023.04.009
Inam, S. A., Zaidi, S. M. H., Khan, A. A. & Ullah, S. A Neural Network Approach to Carbon Emission Prediction in Industrial and Power Sectors. Discover Applied Sciences 7, 640 (2025), doi: https://doi.org/10.1007/s42452-025-07257-x
Hussain, S., and N. Mahmood. Climate-Smart Agriculture and Food Security in South Asia: Lessons for Pakistan. Science of the Total Environment 837 (2022): 155759. https://doi.org/10.1016/j.scitotenv.2022.155759
Inam. S. A., et al., PR-FCNN: A Data-Driven Hybrid Approach for Predicting PM2.5 Concentration, Discover Artificial Intelligence, vol. 4, no. 1, p. 75, Nov. 2024, doi: https://doi.org/10.1007/s44163-024-00184-7
Inam. S. A., A Review of Artificial Intelligence for Predicting Climate-Driven Infectious Disease Outbreaks to Enhance Global Health Resilience, Discover Public Health, vol. 22, no. 1, p. 738, Nov. 2025, doi: https://doi.org/10.1186/s12982-025-01167-4
Inam. S. A., S. Umer, and H. Rajput, A Physics Informed Deep Learning Framework for Rainfall Forecasting in Diverse Climatic Regions, Discover Artificial Intelligence, vol. 6, Jan. 2026, doi: https://doi.org/10.1007/s44163-026-00833-z
IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability (AR6 WGII Report). Cambridge: Cambridge University Press, 2022. https://doi.org/10.1017/9781009325844
Iqbal, F., and S. Hina. Urban Air Quality Management in Lahore: Challenges and Pathways. Sustainable Environment Research 31, no. 1 (2021): 8. https://doi.org/10.1186/s42834-021-00089-5
Jackson, R. B., and P. Friedlingstein. Global Carbon Cycle and Emission Pathways. Nature Reviews Earth & Environment 3 (2022): 560–576. https://doi.org/10.1038/s43017-022-00270-3
Jahanzaib, M., and S. Nawaz. Solid Waste Management in Urban Pakistan: Challenges and Opportunities. Waste Management 113 (2020): 68–78. https://doi.org/10.1016/j.wasman.2020.05.020
Javed, S., and H. Khurshid. Policy Gaps in Pakistan's Climate Action: Reviewing the NCCP Framework. Environmental Science & Policy 124 (2021): 180–192. https://doi.org/10.1016/j.envsci.2021.07.009
Khalid, S., and M. Baqir. Assessing Long-Term Drought Variability in Pakistan Using Remote Sensing Indices. Journal of Arid Environments 200 (2022): 104772. https://doi.org/10.1016/j.jaridenv.2022.104772
Khan, M. A., and S. H. Raza. Smog in Lahore: A Call for Global Attention to Address Urban Air Pollution. Environmental Advances 9 (2024): 100165. https://www.sciencedirect.com/science/article/pii/S2667010024001653
Khan, S., and A. Malik. Climate Adaptation through Sustainable Agriculture in South Asia. Agricultural Water Management 248 (2021): 106756. https://doi.org/10.1016/j.agwat.2021.106756
Lau, W., and Y. Shiran. Plastic Pollution and Circular Economy: A Global Roadmap. Science 369, no. 6510 (2020): 1455–1461. https://doi.org/10.1126/science.aba9475
Lenton, T., and J. Rockström. Climate Tipping Points — Too Risky to Bet Against. Nature 575 (2020): 592–595. https://doi.org/10.1038/d41586-019-03595-0

M. Ur Rahim, M. Hussain, S. A. Inam, and H. Hashim, Ignition Behavior of Supercritical Liquid Fuel in Combustion System, Journal of Mechanics of Continua and Mathematical Sciences, vol. 16, no. 8, Aug. 2021, doi: https://doi.org/10.26782/jmcms.2021.08.00003
Malik, S., and Z. Farooq. Renewable Energy Integration for Pakistan's Power Sector under SDG-7. Renewable Energy 212 (2023): 1456–1468. https://doi.org/10.1016/j.renene.2023.03.089
Mirza, M. S., and M. Ashraf. Groundwater Depletion and Irrigation Challenges in the Indus Basin. Journal of Hydrology 590 (2020): 125432. https://doi.org/10.1016/j.jhydrol.2020.125432
Mishra, V., and R. Shah. Future Projections of South Asian Floods. Journal of Hydrology 608 (2022): 127654. https://doi.org/10.1016/j.jhydrol.2022.127654
Mohammed, A., and F. Alvarado. Climate-Smart Cities: An AI Perspective. Smart Cities 6, no. 1 (2023): 55–70. https://doi.org/10.3390/smartcities6010005
Mohammed, K., and K. Tanaka. Waste-to-Energy Pathways under SDGs. Journal of Cleaner Production 370 (2022): 133415. https://doi.org/10.1016/j.jclepro.2022.133415
Mortreux, C., et al. Migration and Climate Adaptation. Global Environmental Change 63 (2020): 102093. https://doi.org/10.1016/j.gloenvcha.2020.102093.
Müller, B., and D. Robinson. Climate-Smart Energy Systems. Energy Policy 175 (2023): 113475. https://doi.org/10.1016/j.enpol.2023.113475
Nadeem, S., and F. Khan. Pakistan's Energy Transition under SDG-7: Renewable Pathways. Renewable Energy 188 (2022): 1230–1241. https://doi.org/10.1016/j.renene.2022.02
Nasir, F., and M. Hina. Indoor and Outdoor PM2.5 Exposure in Lahore Households. Atmospheric Environment 263 (2021): 118658. https://doi.org/10.1016/j.atmosenv.2021.118658
Nawaz, M., and K. Ullah. Deforestation Drivers in Pakistan: A Policy Perspective. Forest Policy and Economics 118 (2020): 102248. https://doi.org/10.1016/j.forpol.2020.102248
Nelson, D., and T. Carter. Ecosystem Services and Climate Resilience. Ecological Economics 183 (2021): 106961. https://doi.org/10.1016/j.ecolecon.2021.106961
Niu, S., and Y. Wang. Air Pollution in Megacities: Trends and Drivers. Atmospheric Research 243 (2020): 105007. https://doi.org/10.1016/j.atmosres.2020.105007
O'Neill, B. C., et al. Global Socioeconomic Pathways for Climate Futures. Global Environmental Change 63 (2020): 102084. https://doi.org/10.1016/j.gloenvcha.2020.102084
Pathak, H., and P. Aggarwal. Climate Change and South Asian Agriculture. Current Opinion in Environmental Sustainability 45 (2020): 27–34. https://doi.org/10.1016/j.cosust.2020.09.002
Qadir, M., and F. Aziz. Climate Change Adaptation Strategies in Pakistan's Agriculture Sector. Climate Risk Management 29 (2020): 100238. https://doi.org/10.1016/j.crm.2020.100238
Qaiser, N., and A. Riaz. Urban Expansion and Environmental Degradation in Pakistan. Land Use Policy 97 (2020): 104772. https://doi.org/10.1016/j.landusepol.2020.104772
Qureshi, A., and J. Khan. Urban Resilience and Flood Risk Reduction in Pakistan. International Journal of Disaster Risk Reduction 72 (2022): 102876. https://doi.org/10.1016/j.ijdrr.2022.102876
Qureshi, S., et al. Biodiversity Decline and Ecosystem Services in Pakistan's Wetlands. Ecological Indicators 142 (2022): 109284. https://doi.org/10.1016/j.ecolind.2022.109284
Rahman, M., and P. Roy. Mangrove Forests and Climate Resilience. Forest Ecology and Management 520 (2022): 120415. https://doi.org/10.1016/j.foreco.2022.120415
Rahman, H., and F. Javed. Plastic Pollution Impacts on Marine Ecosystems in Pakistan. Marine Pollution Bulletin 160 (2020): 111642. https://doi.org/10.1016/j.marpolbul.2020.111642
Rao, N., and J. Miller. Gender and Climate Resilience in Agriculture. Global Environmental Change 68 (2021): 102270. https://doi.org/10.1016/j.gloenvcha.2021.102270
Rehman, M., and T. Qazi. Urban Flooding in Megacities: A Focus on Karachi. International Journal of Disaster Risk Reduction 75 (2022): 103097. https://doi.org/10.1016/j.ijdrr.2022.103097
Rehman, M., and T. Qazi. Urban Flooding in Megacities: A Focus on Karachi. International Journal of Disaster Risk Reduction 75 (2022): 103097. https://doi.org/10.1016/j.ijdrr.2022.103097
Roy, P., and T. Ghosh. Sea-Level Rise and Coastal Vulnerability Worldwide. Marine Policy 141 (2022): 105110. https://doi.org/10.1016/j.marpol.2022.105110

Sachs, J., et al. Sustainable Development Report 2020. Cambridge: Cambridge University Press, 2020. https://doi.org/10.1017/9781108992411

Saleem, M., and R. Farooq. Climate Adaptation and Governance in Pakistan: Lessons from Recent Floods. Climate and Development 12, no. 8 (2020): 690–702. https://doi.org/10.1080/17565529.2020.1725593

Schmidt, C., et al. Plastic Pollution Rivers to Oceans: A Global Model. Nature Communications 11 (2020): 3689. https://doi.org/10.1038/s41467-020-17201-9

Shah, R., and F. Malik. Renewable Energy Policy Frameworks in Pakistan: Progress and Barriers. Energy Policy 147 (2020): 111878. https://doi.org/10.1016/j.enpol.2020.111878

Sharma, R., and A. Prakash. Climate Resilience in South Asian Agriculture. Climate Risk Management 39 (2023): 100509. https://doi.org/10.1016/j.crm.2023.100509

Shukla, P., and S. Dhar. Pathways to Deep Decarbonization. Energy 220 (2021): 119752. https://doi.org/10.1016/j.energy.2021.119752

Singh, R., and A. Kumar. Urban Heat Island Effects and Climate Adaptation. Sustainable Cities and Society 72 (2021): 103023. https://doi.org/10.1016/j.scs.2021.103023

Tariq, F., and S. Butt. Drought Hazard Mapping in Balochistan Using GIS and AI. Natural Hazards 116 (2023): 1989–2006. https://doi.org/10.1007/s11069-023-06215-3

Waheed, A., and S. Nisar. Forest Degradation and Climate Vulnerability in Khyber Pakhtunkhwa. Forests 14, no. 2 (2023): 345. https://doi.org/10.3390/f14020345

Wang, S., and J. Huang. Urban Climate Resilience in Developing Countries. Sustainable Cities and Society 70 (2021): 102883. https://doi.org/10.1016/j.scs.2021.102883

Williams, M., and H. Brown. Climate Extremes and Energy Systems. Renewable and Sustainable Energy Reviews 146 (2021): 111171. https://doi.org/10.1016/j.rser.2021.111171

Xia, Y., and J. Liu. Deforestation and Carbon Emissions. Global Environmental Change 65 (2020): 102155. https://doi.org/10.1016/j.gloenvcha.2020.102155

Yan, D., and L. Zhao. Climate Migration Patterns and Policies. Global Environmental Change 69 (2021): 102315. https://doi.org/10.1016/j.gloenvcha.2021.102315

Younas, S., and K. Ali. The Role of ICT in Pakistan's Climate-Smart Governance. Telecommunications Policy 44, no. 7 (2020): 102021. https://doi.org/10.1016/j.telpol.2020.102021

Yousaf, T., and B. Raza. Heatwave Hazards and Adaptation Strategies in South Asia. Science of the Total Environment 722 (2020): 137808. https://doi.org/10.1016/j.scitotenv.2020.137808

Yu, K., and S. Li. Renewable Energy Innovation under SDGs. Energy Reports 8 (2022): 4215–4228. https://doi.org/10.1016/j.egyr.2022.08.110

Zafar, U., and S. Malik. Sustainable Transport and Air Quality in Pakistan's Cities. Sustainable Cities and Society 82 (2022): 103891. https://doi.org/10.1016/j.scs.2022.103891

Zahid, H., and R. Mehmood. Artificial Intelligence in Climate Risk Prediction: A Review for Developing Countries. Environmental Modelling & Software 165 (2023): 105664. https://doi.org/10.1016/j.envsoft.2023.105664

Zhang, Y., H. Chen, and Q. Li. Renewable Energy Integration under Climate Extremes: Challenges and Opportunities. Renewable and Sustainable Energy Reviews 148 (2021): 111300. https://doi.org/10.1016/j.rser.2021.111300

2025 by the authors; The Asian Academy of Business and social science research Ltd Pakistan. This is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (http://creativecommons.org/licenses/by/4.0/).