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Pathway, Technology, and Strategy for Synergizing the Reduction of Pollution and Carbon Emissions in China’s Watersheds

Zhang Yajie[1, 2], **Huo Shouliang**[1, 2], **Wu Fengchang**[1, 2]

1. Chinese Research Academy of Environmental Sciences, Beijing 100012, China
2. State Key Laboratory of Environmental Criteria and Risk Assessment, Beijing 100012, China

Abstract: Eco-environmental protection strategies in China have entered a new stage of synergizing reductions in pollution and carbon emissions during the 14th Five-Year Plan period. Watersheds bear heavy loads from economic and social development, and emit large amounts of greenhouse gases and pollutants. Thus, it is important to synergize strategies for reducing pollution and carbon emissions at the watershed scale. This study examined the synergistic mechanisms for reducing greenhouse gases and pollutants, categorized watershed ecosystems into artificial and natural ecosystems, and proposed the main pathways and key technologies for these ecosystems. The specific applications of key technologies were summarized using the Yellow and Yangtze River basins as examples. Negative emissions, agricultural non-point source pollution control, and water eutrophication remediation technologies should be further developed. Additionally, three countermeasures are proposed: (1) refining existing water ecological environment protection standards and establishing a risk prevention and control system, (2) establishing a comprehensive treatment system for pollution and greenhouse gas emission sources to improve watershed management and control mechanisms, and (3) expanding investment in science and technology and participating in international initiatives for addressing climate change.

Keywords: carbon emissions; pollution reduction; synergistic effect; watershed; greenhouse gas; pollutant; negative emissions technology

1 Introduction

To address current global climate change conditions, China is committed to bringing its carbon emissions to a peak by 2030 and achieving carbon neutrality by 2060. During the 14th Five-Year Plan period, energy consumption and carbon dioxide (CO_2) emissions per unit of gross domestic product are proposed to reduce by 13.5% and 18.0%, respectively. Additionally, China plans to achieve a sustained reduction in total emissions of major pollutants, ensure a widespread adoption of green production technologies and lifestyles, a steady decrease in carbon emissions after reaching the 2030 peak, a fundamental improvement in the ecological environment, and the construction of a “Beautiful China” by 2035 [1]. As of 2021, approximately 40% of the cities in China at the prefectural level and above do not meet ambient air quality standards, whereas the development and utilization rate of water resources in the basins of the Yellow, Haihe, and Liaohe rivers exceed the internationally recognized warning threshold. The structural, fundamental, and trend pressures for environmental protection in China have not yet been substantially alleviated. Thus, a long-term conflict remains between protection and development [2].

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Corresponding author: Wu Fengchang, research fellow at the State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, and member of the Chinese Academy of Engineering. Major research field is environmental criteria and pollution prevention. E-mail: wufengchang@vip.skleg.cn

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These combined factors indicate that China must reduce pollution to substantially improve ecological and environmental quality and reduce carbon emissions [3].

Watersheds are complex natural-social-economic systems composed of environmental elements such as water, soil, air, and biota, as well as anthropogenic elements such as population, society, and economy, which are interrelated and interact with each other through the water medium. In this study, watershed ecosystems were divided into two categories: (1) artificial ecosystems, including urban–rural and industrial–agricultural systems, and (2) natural ecosystems, including water, forest, and grassland systems. Studies related to the Global Carbon Project have shown that, over the past decade, the global annual emissions of methane (CH_4) to the atmosphere from the energy and other industrial sectors, agriculture and waste disposal, and natural sources containing inland waters were approximately 111, 217, and 218 Tg, respectively, and the annual emissions of nitrous oxide (N_2O) were approximately 1.6, 6.4, and 15.2 Tg, respectively [4,5]. The Bulletin on the Second National Census of Pollution Sources showed that the emissions of chemical oxygen demand, total nitrogen, and total phosphorus from polluted urban and rural domestic water sources as well as agricultural sources in China in 2017 reached 2.05×10^7, 2.89×10^6, and 3.08×10^5 t, respectively [6]. Different ecosystems in a watershed produce or harbor large amounts of greenhouse gases, which is predominantly CO_2, and other pollutants in the water, air, and soil. This makes watersheds a key area for developing strategies mitigating the effects of climate change, strengthening ecological and environmental controls, and promoting ecological civilization in China [7].

Based on the strategy of watershed zoning management and the goal of carbon peaking and neutrality, this study aimed to clarify the synergistic pathways and key technologies for the reduction of pollution and carbon emissions between artificial and natural ecosystems at the watershed scale. Furthermore, this study aimed to formulate synergistic control measures for emissions of greenhouse gases and pollutants to provide a reference for water ecological environment improvement and greenhouse gas mitigation.

2 Mechanisms underlying a synergistic reduction of pollution and carbon emissions in watersheds in China

According to the data provided by the Emissions Database for Global Atmospheric Research (EDGAR), CO_2 emissions in China since 2000 have been mainly concentrated in the nation's eastern watersheds. Among these, the Yangtze River Basin has the highest total CO_2 emissions, accounting for 29.4% of the national total, followed by the Huaihe River Basin (12.9%) and the Yellow River Basin (12.5%). Owing to a decline in local heavy industries, adjustments in industrial structures, and the promotion of ecological restoration, the Songliao River Basin currently ranks fourth in total CO_2 emissions, accounting for 11.2% [8]. The CO_2 emissions from the western watersheds (southwestern and inland rivers) account for only 3.8% of the total national emissions, but this number is expected to increase in the future owing to western development strategies and construction of the Silk Road Economic Belt [8]. In 2018, the industrial, manufacturing combustion, and transportation sectors were the highest contributors of the CO_2 emissions across all watersheds (Fig. 1).

In the 21st century, the energy structure of China, which is dominated by raw coal and crude oil and continues to rely on crude oil extraction and fossil energy sources such as raw coal for economic development [9]. The high-carbon energy, high-energy consumption industrial, and road freight-based transportation structures determine that a synergistic strategy for reducing pollution and carbon emissions can be effectively deployed in the artificial ecosystem of a watershed. Controlling the emission of greenhouse gases or pollutants from one side of each sector should simultaneously reduce emissions on the other side [10,11]. For natural watershed ecosystems, changes in land use patterns caused by anthropogenic activities can affect carbon sink intensity; for example, the conversion of natural wetlands to other land uses can lead to a reduction in net CO_2 uptake [12]. Furthermore, an increase in the area of construction and agricultural land can affect the nitrogen and phosphorus loads of water bodies, leading to water pollution, especially eutrophication [13]. Eutrophication is the phenomenon of excessive algal growth and increased productivity of water bodies due to high concentrations of nutrients such as nitrogen and phosphorus (mainly total phosphorus) resulting from anthropogenic activities/natural factors [14]. Moreover, higher nutrient levels increase CH_4 and N_2O emissions from water bodies, making them potential sources of greenhouse gas emissions [15]. The emissions of greenhouse gases and environmental pollutants have the same emission processes and characteristics, such as homogeneity and spatiotemporal consistency. Current research shows that the synergistic impact of comprehensive reductions in pollution and carbon emissions in China is increasing annually [16], and that the policies for such reductions have notable synergistic effects [17]. Therefore, an effective promotion strategy for synergistically reducing pollution and carbon emissions can promote changes in

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environmental governance by focusing on end-of-pipe management instead of source prevention and governance [10].

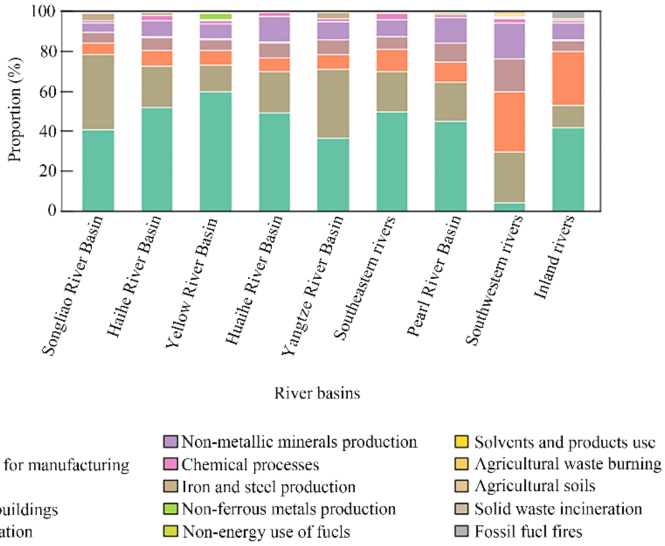

Fig. 1. Share of CO_2 emissions from different sectors in China's watersheds in 2018.

3 Major pathways for synergistically reducing pollution and carbon emissions in watersheds in China

3.1 Major pathways for artificial ecosystems

The first reduction pathway is to adjust the energy structure. Dual controls should be provided for total energy consumption and intensity to improve the efficiency of energy use. Clean and efficient development and use of fossil energy should be promoted; the research, development, and promotion of clean coal technology should be encouraged; and operations of coal–electricity integration or coal–electricity–transportation integration should be implemented. It is necessary to vigorously develop wind and solar power and hydropower sources according to local conditions, effectively use biomass power, develop nuclear power while ensuring safety, and gradually reduce the demand for and consumption of fossil fuel energy [18]. It is also necessary to implement supportive policies for developing the renewable energy industry, create renewable energy markets with continuous and stable growth of demands, improve renewable energy consumption, and promote technological progress in renewable energy [18].

The second pathway is to accelerate the transformation of industrial structures. It is necessary to slow the blind development of high-pollution and -consumption projects, and strictly implement an equal or reduced capacity replacement to expand these projects, while formulating corresponding control policies to continue mitigating excess capacity [18]. The development of service industries should be vigorously promoted as well as strategic emerging and green low-carbon industries such as information technology, biotechnology, new energy, new materials, new energy vehicles, aviation, aerospace, and marine equipment.

The third pathway is to improve green transportation development levels. We should focus on the "highway-to-railway, highway-to-waterway" for bulk cargo and medium- and long-distance cargo transportation and accelerate the construction of a multi-modal transport system integrating railway-waterway, highway-railway/waterway, air-land transportation, among others, to improve the efficiency of combined integrated transport systems [18]. The status of rail transit and other public transportation modes should be improved in the overall transportation system. The usage of new energy vehicles, new energy motor ships, bike-sharing, and electric bike-sharing should be promoted, and the construction of support facilities for charging and refueling should be encouraged.

The fourth pathway is to expand the coverage of clean heating in rural areas. We should adhere to the principles of "localization, multi-energy complementarity, comprehensive utilization, and effectiveness" and create scientific plans for replacing coal with natural gas and electricity and its reasonable redistribution with the continuous implementation of policies. It is necessary to promote the supply and utilization of solar energy, bioenergy, clean energy, and clean coal in rural areas, and deepen the structural reform to rural energy on the supply side [19].

The fifth pathway is to improve the soil carbon sequestration potential of agricultural land. It is necessary to promote and apply conservation tillage measures, such as straw returning, covering crop planting, no-till, less tillage, rotational tillage, and fallow systems. In rice cultivation, we should promote agronomic measures with more carbon sequestration potential, such as dry–wet alternate irrigation and wetting irrigation. It is also suggested to conduct actions to replace chemical fertilizers with organic fertilizers for organic matter sequestration and build a technical support system for carbon sequestration in farmland soils based on the above measures.

3.2 Major pathways for natural ecosystems

The first pathway is to improve the carbon sequestration potential of wetlands. We should increase the extent of water catchment areas and establish hydraulic buffers to maintain stable wetland water levels. It is necessary to introduce and apply straw mulching to restore damaged wetland vegetation layers. Anthropogenic disturbances should be controlled to prevent further wetland fragmentation. The construction of key protected areas for natural enclosures and appropriate return of arable land to lakes should be strengthened [20].

The second pathway is collaborative agricultural non-point pollution control. It is necessary to focus on source management, promote the decrement and synergism of agricultural inputs (chemical fertilizers, pesticides, etc.), and implement formula fertilization by soil testing. A balance between planting and raising should be advocated. It is suggested to establish and improve comprehensive usage of straw, improve the treatment and use of livestock and poultry waste, and enhance the utilization rate of agricultural waste recycling [18]. Biogas engineering should be developed according to local conditions and modern organic agriculture, ecological recycling agriculture, and digestate and biogas slurry recycling should be effectively combined [18]. In addition, we should conduct agricultural non-point pollution management and supervision initiatives, comprehensively analyze the dominant influence factors of non-point pollution, and develop localized assessment models and source apportionment techniques for evaluating agricultural non-point pollution [21,22].

The third pathway is to control the eutrophication of water bodies. A combination of engineering and ecological measures and agricultural reclamation should be applied to increase vegetation cover in the headwater and upstream areas of rivers and control the input load of nutrients (nitrogen and phosphorus) in the middle- and downstream areas of rivers. A comprehensive improvement measures such as dredging sediments to increase the coherence and circulation of water bodies should be adopted to enhance the effective retention capacity of nutrients in watersheds.

4 Key technologies for synergistically reducing pollution and carbon emissions in watersheds in China

4.1 Key technologies for artificial ecosystems

Negative emission technologies (NETs) are key methods for synergistically reducing pollution and carbon emissions in artificial ecosystems, by removing and sequestering CO_2 from the atmosphere to achieve temperature-control goals and reduce carbon emissions. NETs include various options (Fig. 2) [23,24].

Bioenergy and carbon capture, utilization and storage (CCUS) technologies are widely used NETs solutions that allow plants to absorb atmospheric CO_2, produce biomass for conversion into electrical or heat energy, and capture and pump the CO_2 produced during this process into the ground.

Direct air capture can extract atmospheric CO_2 using sorbents, and concentrate and store it in underground oil and gas reservoirs or saline aquifers. Through a series of engineered technologies, direct air capture can regenerate sorbents by transforming the heat, pressure, or temperature to be used continuously for CO_2 capture. Despite its high cost, direct air capture may facilitate CO_2 removal at a large scale and could be applied in different fields in the future [23,24].

Soil carbon sequestration technology is the most effective NETs for increasing the carbon content in soil, largely by adjusting agricultural production methods (e.g., adopting measures such as no-till or crop rotation).

Afforestation and reforestation technology is the most cost-effective solution for NETs and involves fixing atmospheric carbon in biota and soil by planting trees, conserving water and soil, and reducing nutrient loss from soil to water. The cost of this technology is less than a few tens of dollars per 1 t of CO_2 removal [24].

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Overall, applications of different NET solutions must consider cost, effectiveness, availability, safety, and timeliness. Furthermore, competition for land with food production and biodiversity conservation can limit the use of technologies such as afforestation and reforestation [23]. Thus, as the technology continues to mature, NET solutions will be widely used in research on reducing pollution and carbon emissions from watersheds.

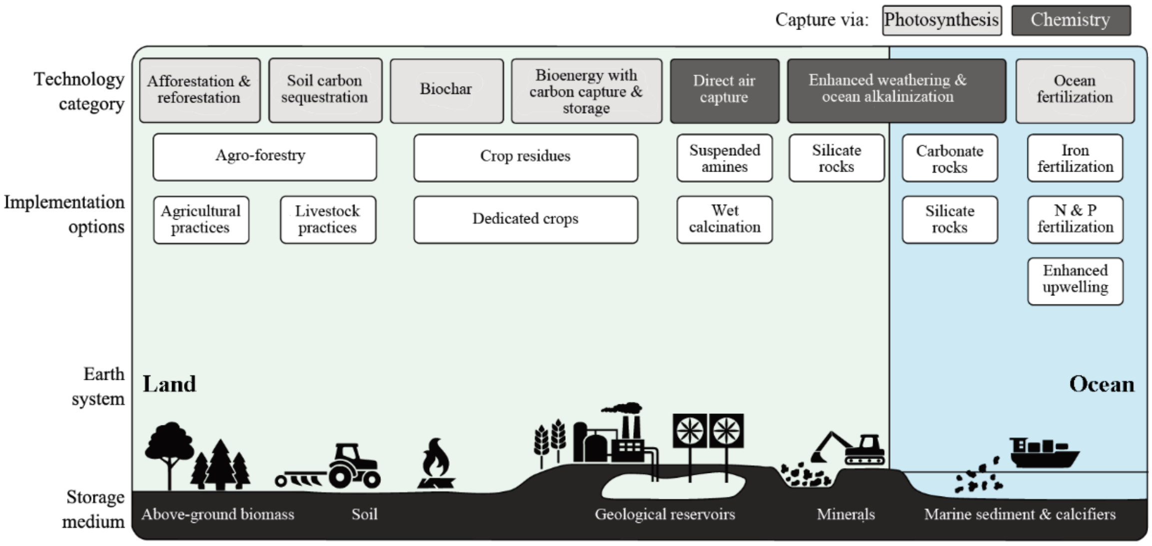

Fig. 2. Key technologies for the synergistic reduction of pollution and carbon emissions in watersheds: A taxonomy of negative emissions technologies (modified from [24])

4.2 Key technologies for natural ecosystems

Agricultural non-point pollution control technology mainly includes head-end control technologies for reducing pollutants such as nitrogen and phosphorus, including the reasonable adjustment of nutrient ratios in fertilizers and livestock feed, and the application of new fertilizers. This also includes middle-end control technologies for pollutant interception, such as the construction of grassed ditches, vegetated buffer strips, and planting hedges, and head-end control technologies for pollutant elimination, such as the construction of artificial wetlands, landscaping green land, grit chambers, and artificial wetland stabilization ponds [25].

Waterbody eutrophication restoration technologies mainly include physical remediation strategies such as substrate dredging, physical algae removal, artificial aeration, and water division. This also includes chemical remediation methods, such as chemical algae removal and chemical fixation, and bioremediation, such as phytoremediation, animal remediation, and microbial remediation [26]. Among these categories, bioremediation technology has become the most popular, cheap, and least harmful to ecological environments in recent years. This technology can reduce the concentrations of pollutants in water bodies by adsorbing, degrading, and transforming concentrations using plants, animals, and microorganisms. Additionally, composite bioremediation technologies are widely used, such as microbial and phytoremediation techniques that combine ecological floating beds and artificial wetlands, which can simultaneously remove multiple toxic pollutants from water bodies and sediments and increase biodiversity [26].

4.3 Case study: application of synergistic technologies for reducing pollution and carbon emissions in watersheds

Several studies on synergistic technologies for reducing pollution and carbon emissions have been conducted in important watersheds, such as the Yellow and Yangtze Rivers. These studies analyzed the effects of adopting NETs, such as CCUS, and afforestation, estimated CO_2 emissions, and identified the main driving factors based on methods such as the environmental Kuznets curve model. Moreover, they provided numerical references and development suggestions for synergistic technologies to reduce pollution and carbon emissions within watersheds in China. The related contents are listed in Table 1.

Table 1. Application of synergistic technologies and suggestions for future development for the reduction of pollution and carbon emissions in China's Yellow River Basin and Yangtze River Basin.

Watershed	Overview	Application of technologies	Suggestions for future development
Yellow River Basin	Total area is approximately 7.95 × 10^5 km^2, spanning nine provinces (autonomous regions). Population and regional GDP account for approximately 30% and 25%, respectively, of China's total figures. In 2021, the primary, secondary, and tertiary industries accounted for 8.8%, 41.4%, and 49.8%, respectively. The industrial structure is mainly based on energy and heavy industries.	Soil organic carbon content increases significantly when cropland or other land use types are converted to forest land and grassland. Increasing soil depth can effectively reduce soil organic carbon loss [27]. The 236 coal-fired power plants in the watershed could capture a maximum of 7.39 × 10^8 t of CO_2 per year and provide approximately 1.31 × 10^{10} t of freshwater before equipment decommissioning if combining technologies of CO_2 capture and storage with enhanced water recovery [28].	Industrial structure, energy intensity, and energy structure are important factors driving the reduction of carbon emissions for the provinces and autonomous regions in this watershed. The green and low-carbon transformation of the industrial sector should be emphasized. For example, the upstream of the watershed has obvious advantages in clean energy development and can drive the optimization of the energy structure of the entire watershed by policy plans such as "west–east gas transmission" and "west–east electricity transportation" [29]. The synergistic benefits of carbon emission reduction and air pollutant control in the watershed are increasing annually. It is worth continuously upgrading the industrial structure, developing modern service industries and high-tech industries, and strictly implementing the industrial environmental access system [30]. Different carbon control pathways should be designed according to the development status of different provinces and regions: Shandong and Henan should increase investment in green technologies, especially oxyfuel technology; Gansu, Qinghai, and Ningxia Hui Autonomous Region can offset some carbon emissions through land use changes and afforestation; Sichuan and Inner Mongolia Autonomous Region should improve energy use efficiency, and Shaanxi and Shanxi can achieve local industrial upgrading by the development of green finance [31]. To achieve efficient management of agricultural non-point pollution in the watershed, there should be emphasis on fertilizer reduction for fruits and vegetables in Shaanxi, Henan, and Shandong provinces, as well as pollution control for cattle and sheep breeding in the western region and pig breeding in the central-eastern region [32].
Yangtze River Basin	Total area is approximately 2.052 × 10^6 km^2, covering 11 provinces and province-level municipalities. Population and regional GDP account for more than 40% of China's totals. In 2021, the primary, secondary, and tertiary industries accounted for 7.6%, 38.3%, and 54.1%, respectively. The industry is mainly labor- and capital-intensive.	The contribution of the Yangtze River Protection Forest Project to the carbon stock and carbon sink of the Yangtze River Economic Zone is higher than other key ecological projects (~81–83%) [33]. During afforestation, more carbon fixation comes from biomass accumulation than soil carbon fixation; optimization of afforestation measures can increase carbon fixation potential [34]. Artificial wetland systems can achieve ecological interception of agricultural drainage with the removal rates of total nitrogen and total phosphorus from water bodies of more than 60% [35].	The secondary industry in the watershed contributes nearly 80% of CO_2 emissions. Among industrial and energy consumption sectors, thermoelectric power production and supply and non-metallic mineral product industry emit the most CO_2. It is necessary to vigorously develop clean energy to form an energy consumption structure by optimizing coal-based energy consumption [36]. To promote industrial upgrading and transfer, eastern provinces should increase independent innovation, improve production capacity, and promote low-carbon industrialization; central provinces should rely on technological innovation to reduce resources dependence during economic development; western provinces and autonomous regions should increase investment in science and technology and conduct industry transfer in developed regions. Meanwhile, inter-regional exchanges and cooperation in science and technology industries should be strengthened, so that regions with strong economic strength and high levels of technology can lead the high-quality development of other regions [37].

Note: Overview data for the Yellow River and Yangtze River basins are from the 2021 Statistical Bulletin of each province, province-level municipality, and autonomous region.

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5 Countermeasures

5.1 Refining the water ecological environment protection standards and establishing a risk prevention and control system

Relevant recommendations are as follows: (1) The key microbial processes and control mechanisms of greenhouse gas production and consumption at different interfaces of water bodies (e.g., water-land, water-gas, and sediment-overlying water interfaces) should be studied to improve the monitoring of greenhouse gas emissions and standardization of data compilation methods [38]. (2) Laws, regulations, and support systems for environmental impact assessments must be improved, and greenhouse gas emissions from water bodies should be gradually incorporated into the environmental impact assessment system and pollution discharge permits in watershed projects. (3) It is necessary to develop standards for water chemistry, eutrophication, and biological monitoring of water bodies in different ecological zones, perform calculations and management of nutrient and pollutant loads, and evaluate watershed ecosystem integrity [39]. (4) We should construct multi-scale and multi-information source systems for watershed monitoring, early warning, and risk control in key tributaries, and even the entire watershed, through watershed environmental risk identification, to prevent pollution occurrences and improve emergency response capabilities to water pollution events.

5.2 Establishing a comprehensive treatment system for pollution and greenhouse gas emission sources to improve watershed management and control mechanisms

Relevant recommendations are as follows: (1) Under the mechanism of “integrated planning, deployment, promotion, and assessment” for reducing pollution and carbon emissions, the synergistic management of greenhouse gas and pollutant emissions in the upper, middle, and lower reaches, rivers, lakes, and reservoirs, left and right banks, and main stream and tributaries in a watershed should be enhanced and promoted through constructing ecological protection compensation mechanisms and industrial layout planning [39–41]. (2) The “Three Lines One Permit” strategy should be applied and promoted, along with the delineation of important water ecological spaces such as ecological functional areas of water, wetlands, and water-containing nature reserves, as well as ecological buffer zones of rivers and lakes in the watershed. Moreover, production and living activities that damage the water ecological environment should also be regulated. (3) Strict controls should be implemented to curb the development of highly water-consuming and highly polluting industries in water-scarce, severely water-polluted, and sensitive areas, along with the encouragement of pilot demonstrations of methods to develop collaborative systems to reduce pollution and carbon emissions in key watersheds [40,41].

5.3 Expanding investment in science and technology and participating in international cooperation on climate change

Relevant recommendations are as follows: (1) Upgrade the recycling capabilities of industrial parks and industrial clusters and promote the co-construction and sharing of public facilities, cascade utilization of energy, resource recycling, and centralized disposal of pollutants [40,42]. (2) Promote advanced technology and equipment for energy conservation, water conservation, and the comprehensive use of resources, and perform comprehensive clean production transformations in key industries [40,42]. (3) Strengthen the innovation, demonstration, and deployment of carbon-neutral technologies, such as CCUS, hydrogen production from renewable energy, and advanced energy storage materials. Increase the achievement transformation of related technologies. (4) Through the Belt and Road Initiative and “South–South Cooperation” platforms, strengthen the exchange, cooperation, and transfer of green low-carbon technologies to promote global climate governance.

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