DOI 10.15302/J-SSCAE-2018.06.008

Development and Prospects of Disruptive Technologies in Environmental Monitoring

Liu Jianguo [1], Meng Deshuo [1], Gui Huaqiao [1], Yin Gaofang [1], Zhang Fu [2], Zhang Shu [2], Zhang Hongzhen [3], Wang Jinnan [3]

1. Key Laboratory of Environment Optics and Technology, Anhui Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Hefei 230031, China
2. Information Center of Hefei Institute of Physical Science, Hefei 230031, China
3. Chinese Academy for Environmental Planning, Ministry of Ecology and Environment of the PRC, Beijing 100012，China

Abstract: Environmental monitoring technology is an important factor in supporting and ensuring environmental management. To help promote China’s ecological civilization and environmental protection, the developmental trends of disruptive technologies for environmental monitoring should be analyzed and predicted. This study combines literature assessment and patent intelligence analysis methods to comprehensively analyze and evaluate the history and determine the present status of disruptive technologies for environmental monitoring in China and abroad. Based on the demands to develop environmental protection in China, this study proposes a multimedia environment and ecosystem sensing technological framework based on big data fusion; environmentally intelligent micro-sensors based on new materials and devices; fast online monitoring of trace pollutants based on mass spectrometry; and high-resolution remote sensing based on satellite imaging of regional/global ecological environmental elements. The results of this work provide a decision-making basis for planning the management and development of China’s environmental protection industry.
Keywords: environmental monitoring; disruptive technology; development status; future expectations

1 Introduction

Environmental monitoring technologies provide a foundation for environmental management. They not only provides a decision-making basis for preventing environmental pollution but also offer advanced technical means to evaluate pollution prevention and treatment. In China, after the *Twelfth Five-Year Plan*, the State Council issued the *13th Five-Year Plan for Ecological Environmental Protection* and the *Eco-Environmental Monitoring Network Construction Plan* to further implement the three main action plans to prevent air, water, and soil pollution. Their aim was to further promote the development of environmental monitoring systems in China. On May 28, 2018, at the Meeting of Academicians from the Chinese Academy of Sciences and the Chinese Academy of Engineering, Xi Jinping emphasized that “the key common technology, cutting-edge technology, modern engineering technology, and disruptive technological innovation should be the breakthrough point” to fundamentally safeguard national economic security and national defense.

Therefore, in the current context, a few items are expected to form the framework for scientific and technological development planning and policies in China: a focus on the major requirements of national ecological and environmental protection, in addition to environmental safety; a thorough analysis of the developmental trends of

Received date: October 30, 2018; **Revised date:** November 15, 2018

Corresponding author: Liu Jianguo, Anhui Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Researcher. Major research field is environment monitoring technology. E-mail: jgliu @aiofm.ac.cn

Funding program: CAE Advisory Project “Strategic Research on Disruptive Technologies for Engineering Science and Technology” (2017-ZD-10); Key project on causes and treatment of heavy air pollution “Result Integration and Application Demonstration of Key Projects” (DQGG0307)

Chinese version: Strategic Study of CAE 2018, 20 (6): 050–056

Cited item: Liu Jianguo et al. Development and Prospects of Disruptive Technologies in Environmental Monitoring. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2018.06.008

disruptive technologies in the field of environmental monitoring measurement; and an evaluation of the future direction of technology development. This study will provide support for decision-making and can be used as an important reference for the future development of China's environmental protection industry.

2 Developmental status of disruptive technology for environmental monitoring

Environmental monitoring was first carried out in the UK and the USA in the early 1800s. Following the rapid industrial development after the Second World War, numerous incidents of severe pollution occurred in the UK and the USA, causing widespread global concern. Monitoring technology rapidly evolved thereafter. The historical development of environmental monitoring technologies can be divided into three stages described below.

2.1 Rapid rise of spectrophotometry and electrochemical technology accompanied by the preliminary establishment of detection standards for environmental pollutants

From the 1950s to the early 1980s, heavy metals, organochlorine compounds, aromatic hydrocarbons, halogenated hydrocarbons, and other pollutants became the focus of environmental monitoring. Spectrophotometric and electrochemical methods rapidly emerged [1], and detection standards for environmental pollutants were gradually established. When monitoring heavy metals in water, the electrochemical method has the advantages of high selectivity, accurate analysis, and online monitoring. These characteristics enabled the shift in environmental monitoring technologies from laboratory testing to on-site, in situ, and online analysis. During this period, the testing standards for various environmental pollutants were initially established.

2.2 Rapid development of technologies such as chemiluminescence and the gradual formation of an environmental automatic monitoring and analysis system

Since the 1980s, the environmental quality of developed countries, such as the UK and the USA, has clearly improved. Research has been focused on $PM_{2.5}$, environmental health, and motor vehicle exhaust emissions. The monitoring components and techniques for water, air, soil, and solid waste analysis have been clearly defined and improved. Concurrent with the rapid development of information, new energy sources, biotechnology, and new materials technologies, optical technologies with faster detection speeds and wider monitoring ranges have been introduced in the field of environmental monitoring [2]. Many cross-domain technologies have begun to be applied to environmental monitoring. For example, the chemiluminescence method, which has high sensitivity, high selectivity, and simple instrumentation, has been rapidly adopted for environmental monitoring. These cross-domain technologies have effectively supported the construction of an automated monitoring network for environmental quality.

2.3 Wide application of optical telemetry and construction of a comprehensive three-dimensional air-monitoring network

During the early 2000s, there were significant advancements in optoelectronic technologies. The rapid development of optical telemetry further promoted the advancement of environmental monitoring technologies, creating a new era of development. Technology based on optical telemetry typically monitors the target environment from a long distance, avoiding the complex steps of sampling, pre-processing, and laboratory testing, and greatly improving the efficiency of environmental monitoring. Since 2005, technologies based on optical telemetry, such as differential optical absorption spectroscopy (DOAS), tunable diode laser absorption spectroscopy (TDLAS), Fourier transform infrared spectroscopy (FTIR), laser radar (LIDAR), and satellite remote sensing, have been widely used.

At present, environmental monitoring technologies have made important advances in China. A technical system was initially created to meet the requirements of routine monitoring. Some high-end scientific research instruments, such as aerosol radar and single-particle aerosol time-of-flight mass spectrometer, were applied to construct China's first comprehensive three-dimensional air monitoring system. Environmental monitoring methods based on biology, mass spectrometry, and chromatography also developed rapidly, providing a foundation for China's modern environmental monitoring systems. In recent years, China has reached an advanced level internationally in the field of satellite remote sensing, laser radar, and other environmental monitoring technologies [3].

To analyze the state of global research on environmental monitoring technology, invention patents from 1930 to 2017 were investigated, and cluster analysis was performed. It is evident that the patents for environmental monitoring mainly focus on chemiluminescence, chromatography, mass spectrometry, FTIR, LIDAR, and laser-

DOI 10.15302/J-SSCAE-2018.06.008

induced breakdown spectroscopy (LIBS). The cluster analysis of patents from 2015 to 2017 shows that there are new technical features in this field, including data processing, intelligent monitoring, biosensors, three-dimensional laser radar, and drones.

From the authorized patents, the core patents in the field of environmental monitoring technology were analyzed by the Innography patent analysis platform [4], shown in Fig. 1. Since 2010, the number of China's core patent grants has grown rapidly, surpassing the USA in 2014, as indicated in Fig. 1. The total number of core patents in the field of environmental monitoring from various countries is shown in Fig. 2. The total number of core patents owned by China is second only to that of the United States. The continuous increase in these core patents in China indicates significant progress in the research and development of environmental monitoring technologies.

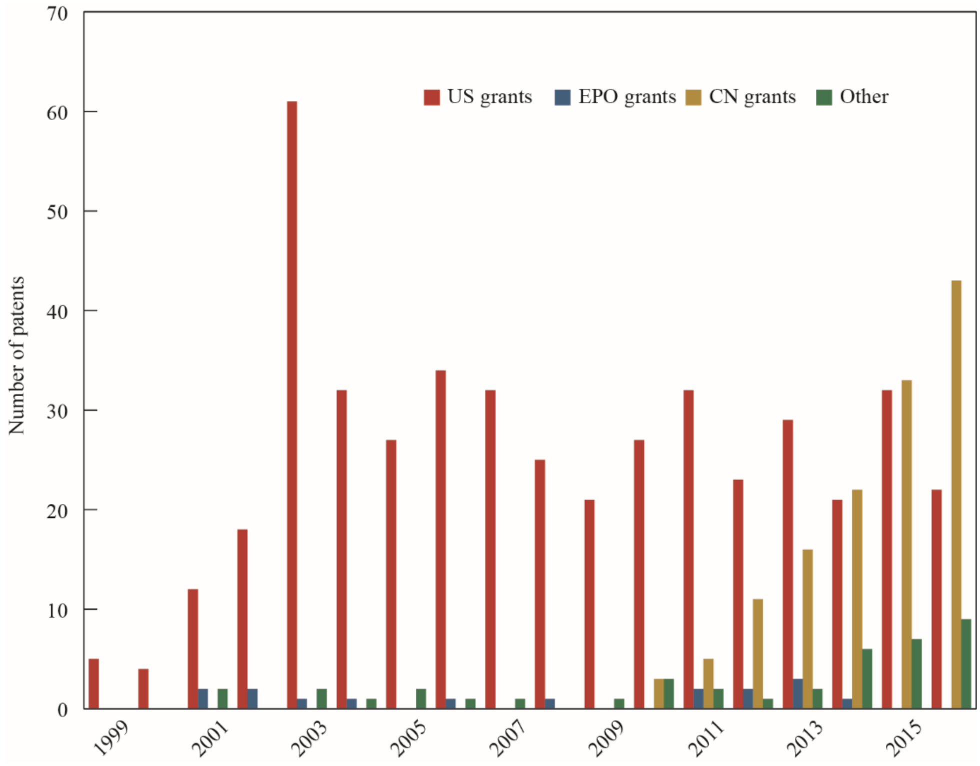

Fig. 1. Number of core patents in the field of environmental monitoring.

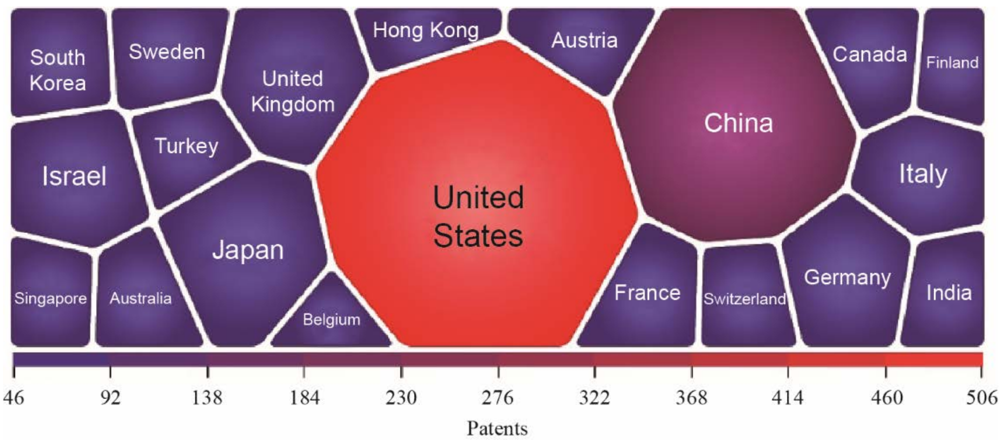

Fig. 2. Distribution of all core patents in the field of environmental monitoring.

3 Development status of disruptive technology in environmental monitoring

Compared with conventional technologies, disruptive technologies in the field of environmental monitoring typically exhibit significant advantages in terms of sample processing methods, monitoring range, and data processing speed and accuracy. Disruptive technologies often evolve into conventional technologies. Disruptive technologies that were developed in the 1950s, such as spectrophotometry and electrochemical technology, have become routine technologies in the field of environmental monitoring. Based on technological advancements in the fields of optics, electronics, information, and biology, disruptive technology for environmental monitoring is developing towards high sensitivity and selective optical/spectral and mass spectrometry/chromatography analysis; multi-parameter, real-time, online, and automated monitoring; regional dynamic telemetry [5]; and multi-element and big data analysis.

3.1 Higher precision

In China and abroad, relatively complete environmental standards, monitoring techniques, and methodologies have been formed. However, some issues still exist, such as low detection limits and low time resolution. These include online measurement of nanoscale particulate matter, monitoring of ultra-low emission pollution sources, online detection of heavy metals in water and soil, and atmospheric oxidative on-site monitoring during the formation of compound pollution. It is necessary to further improve detection accuracy, so that optical monitoring technology could be applied to the research of photochemical reaction mechanisms, industrial process control, and production safety monitoring.

3.2 More components

With rapid industrial development, the types of pollutants to be monitored are rapidly increasing, and the components are becoming increasingly complex. The conventional methods that analyze $PM_{2.5}$, PM_{10}, total suspended particulate matter (TSP), total phosphorus, total nitrogen, chemical oxygen demand (COD), and biochemical oxygen demand (BOD) no longer meet the increasing demand for testing projects. Therefore, there is an urgent need for the development of methods to detect atmospheric free radicals, all components of organic matter, heavy metals, bioaerosols, secondary organic aerosol tracers, water bacteria, phytoplankton, residual pesticides, and other organic pollutants in the soil.

3.3 Larger scope

Regional stereo telemetry and satellite remote sensing can rapidly and accurately determine the pollution status of an area. The development of regional emissions, total transportation, emission source inventory, and pollutant imaging detection technology based on regional stereo telemetry can provide technical support for real-time monitoring and treatment of pollution sources. Pollution source monitoring is an important component of environmental monitoring. Through satellite remote sensing technology, pollution sources can be rapidly located and evaluated; environmental pollution accidents can be tracked and investigated; accident occurrence points, pollution areas, and diffusion speed and direction can be predicted; and trace amounts of pollutants can be detected. The global distribution and changes of study subjects, such as gases and algae, can also be obtained. The impact of pollution on climate can be explored, and data support for pollutant emission control can be provided.

3.4 Higher intelligence

Future efforts to prevent and control ecological environmental pollution will become more scientific and intelligent. Multi-platform, intelligent, networked, and uniquely selective environmental monitoring instruments will be developed to acquire environmental multi-factor monitoring data in real time. Big data will be used to analyze regional and watershed pollution sources through the in-depth mining and model analysis of massive and decentralized data sets. An intelligent management decision-making platform will be constructed, and environmental management will be transformed into a refined and precise process. This process will promote active foresight, big data scientific decision-making, precise supervision and public service, and increased convenience [6].

4 Analysis of China’s strategic needs

With the rapid advancement of industrialization and modernization, China has increasingly focused on environmental quality improvement. Fig. 3 shows the relevant policies in the field of environmental monitoring in China since 2009. The five development concepts of “innovation, coordination, green, openness, and sharing” are indicative of the firm determination to promote an ecologically conscious civilization. The development of environmental monitoring technologies is one of the conditions to ensure the smooth construction of an ecological

DOI 10.15302/J-SSCAE-2018.06.008

civilization.

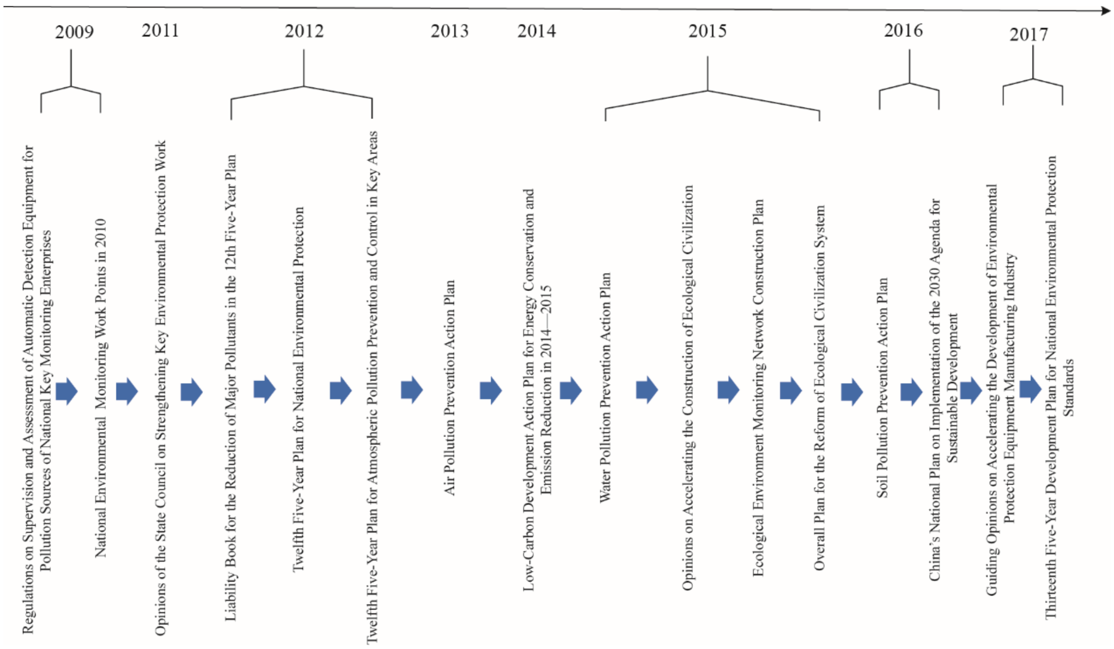

Fig. 3. Environmental monitoring policy of China from 2009 to 2018.

4.1 Promoting the continuous improvement of the ecological environment

Since the "13th Five-Year Plan," China's environmental pollution control has transitioned from total emissions control to environmental quality improvement. In the future, we must actively pursue the "blue sky defense war," focus on ensuring the safety of drinking water, strengthen the control and restoration of soil pollution, and develop rural settlement remediation operations. However, China's ecological environment monitoring network still has problems, including incomplete coverage and influencing factors. The quality of monitoring data needs to be improved. By accelerating the development of environmental monitoring technology and equipment, we can effectively support the construction of China's ecological environment network.

4.2 Preventing environmental risks and ensuring environmental safety

Ecological and environmental security are important components of national security. They guarantee sustained and healthy economic and social development. At present, China's environmental security situation remains poor, and sudden environmental incidents are frequent, which significantly threatens human safety and the ecological environment. China's emergency technology for environmental safety is highly inadequate and lags far behind international emergency monitoring technology. It is difficult to conduct rapid, accurate, and comprehensive monitoring and early warning assessment of pollution accidents. Therefore, rapid remediation of sudden pollution accidents are restricted, which can also compromise accurate decision-making.

4.3 Responding to global environmental change and scientific assessment

With the increasing internationalization of environmental issues, environmental protection work has become increasingly linked to the rights and interests of the state. Mastering environmental monitoring initiatives will allow further control and safeguard of national rights and diplomatic activities. At present, the cross-border transportation of air pollution in China has concerned several countries. The international pressure on China's environmental protection policies is increasing. Therefore, environmental diplomacy faces enormous challenges. Consequently, it is necessary to develop corresponding environmental monitoring technologies and equipment to provide scientific and technical support for environmental diplomacy.

4.4 Promoting the rapid development of China's environmental protection industry

The environmental protection industry is an important element of China's emerging industries. The Ministry of

Industry and Information Technology has formulated the *Guiding Opinions on Accelerating the Development of Environmental Protection Equipment Manufacturing Industry*, noting that by 2020, the output value of China's environmental protection equipment manufacturing industry will reach 1 trillion yuan. However, China's high-end environmental monitoring equipment market is still occupied by foreign companies. Technological development could end the monopoly of European and American enterprises. It could also enhance market competitiveness and promote the rapid development of China's environmental protection industry.

5 Prospects for future development

The construction of an ecological civilization is a fundamental plan for the sustainable development of the Chinese nation. While the international development frontier must be pursued, we must also closely integrate it with China's national conditions, promote industrialization, and develop advanced environmental monitoring technologies and equipment with independent intellectual property rights. The modernization of environmental protection and management systems provides strong scientific and technological support for the construction of an ecological civilization in China. Fig. 4 shows the possible development direction of China's environmental monitoring technology in the next 20 years.

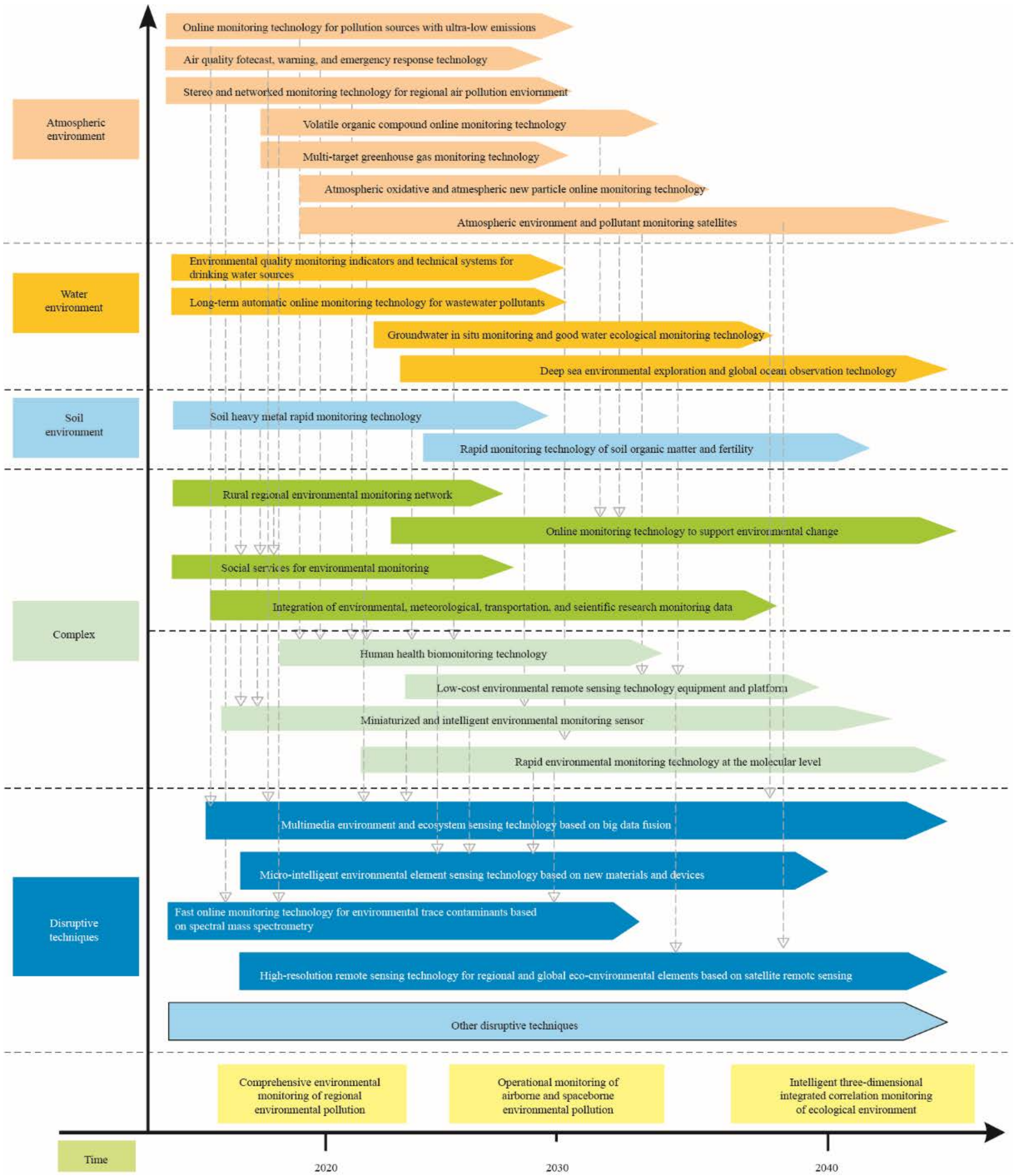

Fig. 4. Future development direction of environmental monitoring technology.

DOI 10.15302/J-SSCAE-2018.06.008

Environmental monitoring technology encompasses many disciplines, including physics, optics, information, electronics, material science, and chemistry. Based on the advances in disruptive technologies, monitoring technologies for single and comprehensive contaminants, such as gas, water, and soil, will be rapidly promoted. As a result, disruptive environmental monitoring technologies with significant impact to environmental science research and operational monitoring will be developed. Below are four possible disruptive technologies.

5.1 Multimedia environment and ecosystem sensing technology based on big data fusion

Next-generation information technologies, such as big data, the Internet of Things, and cloud computing, have promoted the development of environmental protection informationizion. This technology mainly uses innovations to transform environmental management from wide-scale to the refined and precise level, based on large-scale system applications and big data services. Innovations include intelligent and diversified environmental sensors, intelligent management decision-making, information technology, and deep mining and model analysis. Passive response becomes active foresight, and experienced judgement transforms into decision-making based on big data science. A closed loop including source prevention and control, process supervision, comprehensive management, and national governance is developed for environmental management. As a result, “digital environmental protection” transitions to “smart environmental protection.”

5.2 Micro-intelligent sensing technology based on new materials and devices

Technological breakthroughs in new materials, devices, and other fields are expected to result in revolutionary breakthroughs in environmental monitoring or great improvement in the performance of existing instruments. Miniaturized and intelligent elements for environmental sensing monitoring should also be developed. For example, based on colloidal quantum dot nanomaterials, miniature spectrometers could be fabricated [7], reducing costs from tens of thousands of dollars to several dollars. This would be the example of a major breakthrough in environmental monitoring technology based on spectral analysis. Moreover, with the use of microelectromechanical systems (MEMS), high-sensitivity measurements of aerosol mass concentration and particle size distribution are expected.

5.3 Rapid online monitoring technology for trace pollutants based on mass spectrometry

High-end environmental monitoring instruments based on mass spectrometry can provide effective technical support for environmental departments in solving complex pollution problems. Consequently, they can effectively control pollution sources, save energy, and reduce emissions, while coping with environmental changes. For example, based on breakthroughs in high-resolution UV-visible imaging spectroscopy and mass spectrometry modules, it is expected that high-sensitivity and high-temporal-resolution detection of trace environmental pollutants would be achieved. For example, total volatile organic compounds, heavy metals, and ultrafine particulates could be detected. These breakthroughs would also enable further research on environmental sciences and operational monitoring. An industry of high-end instruments for large-scale environmental monitoring could also be developed.

5.4 High-resolution remote sensing technology for regional/global eco-environmental elements based on satellite remote sensing

Technological breakthroughs in the launching of small satellites and rockets are expected to bring major advances in remote sensing monitoring. The development of technology will facilitate the analysis of environmental pollutants based on airborne and spaceborne platforms. In addition, it could improve crop yield estimation, agricultural disaster monitoring, and dynamic monitoring of the atmospheric environment, improving the ecological status of the environment. The comprehensive application efficiency of remote sensing resources is of great significance. For example, breakthroughs in key technologies, such as detectors with a large area array and high quantum efficiency, and the optical design and processing of freeform surfaces will significantly improve the spatial resolution of the load and accuracy of data inversion, thereby realizing spatial resolution at the kilometer scale.

6 Conclusion

In terms of environmental monitoring, domestic technological innovation capabilities are gradually being developed, demonstrating technical reserves and potential, whereas domestic high-end equipment is significantly less advanced. Therefore, improving independent innovation ability and strengthening the advanced layout of disruptive technology has become a highly urgent strategic task. Considering the need to promote China’s economic and social development, a new generation of disruptive technologies in the field of environmental monitoring would effectively enhance China's capability to comprehensively monitor the ecological environment and promote the rapid development of the environmental protection industry.

Reference

[1] Baker A. Fluorescence excitation-emission matrix characterization of some sewage-impacted rivers [J]. Environment Science & Technology, 2001, 35(5): 948–953.

[2] Burrows J P, Weber M, Buchwitz M, et al. The global ozone monitoring experiment (GOME): Mission concept and first scientific results [J]. Journal of the Atmospheric Sciences, 1999, 56(2): 151–175.

[3] Liu W Q, Chen Z Y, Liu J G, et al. Stereoscopic monitoring technology and applications for the atmospheric environment in China [J]. Chinese Science Bulletin, 2016, 61(30): 3196–3207. Chinese.

[4] Allison J, Lemley M, Moore K, et al. Valuable patents [J]. Berkeley Olin Program in Law & Economics Working Paper, 2003, 92(3): 435–479.

[5] Xie H. Status and trends for development of environmental monitoring technology in China [J]. Environment and Development, 2018, 30(2): 161–162. Chinese.

[6] Liu W Q, Yang J W, Gui H Q, et al. Study on the development of multi perception system for "Internet Plus" smart environmental protection [J]. Strategic Study of CAE, 2018, 20(2): 111–119. Chinese.

[7] Bao J, Bawendi M G. A colloidal quantum dot spectrometer [J]. Nature, 2015, 523(7558): 67–70.