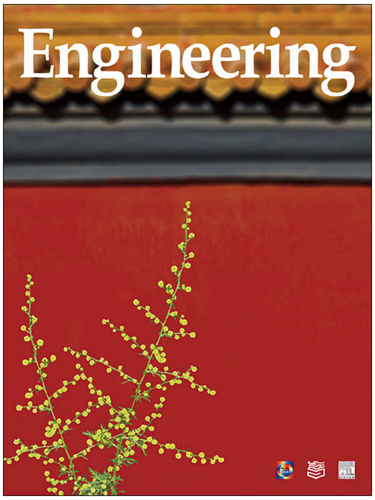

Review

Coordinated Control of Emerging Contaminants and Conventional Pollutants in China: Emission Sources, Technological Pathways, and Multi-Stakeholder Governance

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Coordinated Control of Emerging Contaminants and Conventional Pollutants in China: Emission Sources, Technological Pathways, and Multi-Stakeholder Governance

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ABSTRACT Emerging contaminants (ECs) and conventional pollutants (CPs) coexist and interact with each other in the environment. Their control requires a systematic approach, necessitating the prompt initiation of research on a coordinated control strategy. This study demonstrates that ECs and CPs exhibit differences in their pollution profiles and treatability and present a higher potential for combined environmental risks. These findings indicate mutual influences that may affect their respective removal efficiencies. Key emission sources requiring coordinated control are identified, including chemical manufacturing, pharmaceutical manufacturing, the textile industry, centralized pollution treatment facilities, and electronic equipment manufacturing. To steadily advance coordinated control efforts, this study proposes milestones for the coordinated control of ECs and CPs, with the goal of making the combined risk of ECs and CPs to human health and ecological systems negligible by 2050. It also analyzes the feasibility of coordinated control technologies, specifically noting that many of these technologies can remove more than one category of EC while treating CPs. The study further proposes technological innovation pathways encompassing risk screening and assessment, life-cycle-based risk control, demonstration and promotion, and regional coordination, along with corresponding analyses of challenges and assessment methodologies. Finally, by analyzing the current situation and challenges to the support system, this study suggests establishing a multi-stakeholder governance strategy centered on legal frameworks, institutional mechanisms, and standards, supported by government leadership, technological support, corporate responsibility, and public participation to build a supportive and **sustainability-**enabling system.

KEYWORDS Emerging contaminants; Conventional pollutants; Coordinated control; Whole life-cycle control; Multi-stakeholder governance

1. Introduction

The four modern industrial revolutions have driven a heavy reliance on chemicals, leading to dramatic growth in both the variety and quantity of chemicals globally. This has given rise to the issue of emerging contaminants (ECs) [1], which has attracted worldwide attention. ECs primarily include persistent organic pollutants (POPs), environmental endocrine disruptors (EDCs), pharmaceuticals and personal care products (PPCPs), and microplastics (MPs) [2]. Notably, these contaminants pose significant threats to the health of animals, plants, and humans [3–5]. Global efforts to manage ECs are currently ongoing through international conventions, environmental quality standards, emission standards, and priority pollutant control lists [6]; nevertheless, continuous efforts are required to address the constant emergence of new types of ECs. In contrast to ECs, conventional pollutants (CPs) have long been recognized globally and are subject to routine regulatory management. Representative chemicals categorized as CPs in China include chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), ammonia nitrogen (NH_3-N), total phosphorus (TP), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter.

China has consistently prioritized EC control, achieving steady progress amid ongoing challenges. The nation's *Action Plan for the Control of Emerging Contaminants* was issued in May of 2022 [7], as the first landmark top-tier policy framework specifically targeting ECs in China. This plan outlines comprehensive, systematic action measures across six key dimensions, including regulatory frameworks and pollution investigation/monitoring systems. Furthermore, in January 2024, *The Opinions of the Communist Party of China (CPC) Central Committee and the State Council on Comprehensively Promoting the Beautiful China Initiative* (hereinafter referred to as *Opinions on the Beautiful China Initiative*) established the objective of "effectively controlling the environmental risks by ECs by 2035." It also outlined actionable tasks such as strengthening technological support for EC control and expediting the rollout of major EC control projects.

Compared with China's nascent efforts to address ECs, CP control has long been integrated into all facets of social deve face water sections attaining Class I–III water quality standards stood at 90.4%, and the safe utilization rate of contaminated farmland reached 92% [8]. Despite the positive outcomes achieved in CP control, these gains remain fragile, with management challenges continuing to escalate. Issues such as prolonged and widespread severe pollution episodes, severe rural non-point source pollution, and a sharp increase in the accumulated stock of industrial hazardous waste [9] persist as prominent concerns. A gap remains between the current situation and the goals of building a "Beautiful China."

ECs and CPs coexist in the environment and are simultaneously emitted from multiple sources [10–12]. Given that the pollution issues associated with both categories are intertwined and complex [6], a coordinated control system should be established. However, the specific characteristics of the combined pollution and hazards from ECs and CPs in the environment remain unclear, technology analyses for coordinated control are inadequate, and the pathways and measures for coordinated control require further investigation. Thus, there is an urgent need for strategic and systematic research on the coordinated control of ECs and CPs. This study employs a theoretical framework structured as *objectives–technology–management* to propose a strategic framework for the coordinated control of ECs and CPs. It aims to provide a scientific basis and bridge the gap between scientific foundations and technological applications for the development of a coordinated control system.

2. Feature comparison of ECs and CPs

2.1. Differences in pollution characteristics

CPs have high emission loads and generally elevated environmental concentrations, rendering them relatively amenable to monitoring. In contrast, ECs are characterized by low emission concentrations (typically at the ppb, ppt, or lower level [13]), high ecological toxicity [1], high bioaccumulation potential [14], and complex migration and transformation mechanisms [15]. The lack of standardized monitoring protocols [16] and rapid screening methodologies for ECs poses challenges for the accurate monitoring and quantification of their pollution extent.

In terms of emission sources, ECs are more ubiquitous and less well-defined than CPs. CPs typically have well-characterized emission sources, such as coal-fired power plants, the chemical industry, motor vehicle exhaust, and domestic sewage. In contrast, ECs exhibit high species diversity and have widespread emission sources [17] spanning complex industrial chains. Their emission sources are in multiple sectors, including the pharmaceutical, pesticide, and cosmetics industries; electronic waste recycling; and plastic products manufacturing—with emission inventories remaining poorly characterized [1]. ECs may also originate from unintentionally produced pollutants and environmental degradation products.

In terms of the distribution characteristics of emission sources, CPs exhibit relatively distinct regional distribution patterns, primarily concentrated in industrial clusters and core urban areas. Point-source emissions dominate their discharge mode, showing strong regional agglomeration. In contrast, the spatial distribution of ECs emissions is complex: While correlated with the density of economic activities, ECs exhibit broader diffusivity [17] and cross-medium migration, with both diffuse sources and point sources co-occurring.

2.2. Disparity of treatability

Research on the environmental behavior of CPs is relatively mature, given their well-characterized physicochemical properties (e.g., solubility and volatility) and their relatively straightforward environmental migration pathways and degradation patterns that can be investigated. In contrast, the environmental behavior of ECs is highly complex. ECs are extremely susceptible to cross-medium migration and transformation across water, air, and soil compartments. Their migration and transformation mechanisms are regulated by multiple factors (e.g., photochemical reactions and microbial degradation) [18], while certain EC subgroups, such as MPs and per- and polyfluoroalkyl substances (PFAS), may undergo bioaccumulation through food chains [19,20]. At present, extensive fundamental research and targeted investigations on the environmental behavior of ECs remain necessary.

In terms of treatment technologies and management systems, CPs are subject to clear and stringent emission standards, with high adoption rates of end-of-pipe treatment technologies and relatively mature management frameworks. These technologies are well-established; for instance, wet flue-gas desulfurization [21], membrane bio-reactors (MBRs) [22], and activated sludge processes have been widely applied in wastewater and exhaust gas treatment. However, these measures are inadequate for effectively controlling the environmental risks posed by ECs [23]. Conventional wastewater treatment technologies exhibit low removal efficiencies for many ECs not covered by emission standards. For example, the removal efficiencies of persistent ECs only reach approximately 20%–30% [10]. Technologies targeting EC reduction—such as advanced oxidation processes (AOPs), adsorption (employing materials such as activated carbon, carbon nanotubes, and metal–organic frameworks (MOFs)), and membrane separation [24]—remain largely confined to laboratory-scale research. Bott atic verification of the scalability of these technologies is still required [10]. Additionally, emission standards for the vast majority of ECs remain unestablished, with a lack of corresponding control measures [25].

2.3. Interaction between ECs and CPs

Previous studies have demonstrated that ECs and CPs exhibit complex interaction behaviors in the environment that can impact and interfere with their coordinated control. For instance, microplastics can adsorb heavy metals and organic pollutants, thereby increasing both the mobility of these adsorbed substances in aquatic environments and their accumulation potential in aquatic organisms, while also potentially elevating toxicity and risks [26]. Additionally, atmospheric particulate matter co-occurs with ECs such as polycyclic aromatic hydrocarbons (PAHs) and organic phosphate esters (OPEs) [27], increasing the complexity of toxicity analysis and coordinated removal. In aquatic environments, internal competition between other organic substances and antibiotics could directly reduce the efficiency of antibiotic degradation [28]. In ultraviolet (UV) oxidation processes in wastewater treatment facilities, some CPs may compete with ECs for photon absorption, decreasing the removal efficiency of ECs [29]. In microalgae-based wastewater bioremediation technology, the notable toxicity of OPEs can induce oxidative stress in *Chlorella*, causing DNA damage and consequently inhibiting the alga's efficiency in removing ammonia nitrogen and phosphate [30].

3. Key emission sources and strategic objectives

3.1. Key sources of coordinated treatment

ECs and CPs are embedded in complex industrial chains and span diverse industrial sectors, making it challenging to fully achieve comprehensive coordinated treatment. Identifying and analyzing key emission sources with substantial potential for coordinated treatment will facilitate the targeting of coordinated control efforts and the advancement of practical implementation. According to the *2023 Environmental Statistics Yearbook* [31], the top five industries contributing to emissions of conventional wastewater pollutants (COD, NH_3-N, TN, and TP), conventional exhaust gas pollutants (SO_2, NO_x, particulate matter, and volatile organic compounds (VOCs)), general industrial solid waste, and industrial hazardous waste are overlapped in the following sectors: chemical raw materials and chemical products manufacturing; petroleum, coal, and other fuel processing industries; pharmaceutical manufacturing; textile manufacturing; paper and paper products manufacturing; computer, communications, and other electronic equipment manufacturing; and rubber and plastic products manufacturing. As of May 2023, among the key industries prioritized for EC surveys, monitoring, and control across China's provincial-level administrative regions [32], the top five most frequently identified industries were pharmaceutical manufacturing; petroleum, coal, and other fuel processing; chemical raw materials and chemical product manufacturing; textiles; and animal husbandry. In April 2025, the Ministry of Ecology and Environment (MEE) issued the *Opinions on Strengthening Environmental Impact Assessment for Construction Projects Involving Emerging Contaminants in Key Industries*, focusing on six major industries: petrochemicals, coatings, textile dyeing and printing, rubber, pesticides, and pharmaceuticals. The document emphasizes the importance of identifying ECs and implementing corresponding hierarchical control measures in the environmental impact assessment process.

In China's current development landscape, the cultivation and development of new productive forces is accelerating; yet the emerging industries involved are highly reliant on chemicals. In emerging fields such as electronics, new energy vehicles, and photovoltaics, the volume of electronic waste is growing annually, emitting not only CPs (e.g., COD and heavy metals) but also ECs such as PFAS, MPs, and phthalates [33]. Therefore, EC emissions are acknowledged to be as relevant as CP emissions and are attracting similar levels of national attention. Considering the characteristics of the aforementioned industries and centralized pollution-control facilities (including sewage treatment plants, municipal solid waste treatment facilities, and hazardous waste treatment facilities), the key sources for the coordinated treatment of ECs and CPs are identified and analyzed as follows (Table 1 [10,12,33–37]).

Table 1

Key sources for the coordinated treatment of ECs and CPs.

Key emission sources	Coordinated treatment targets	
	Typical conventional pollutants	Typical emerging contaminants
Chemicals and pharmaceutical manufacturing	COD, ammonia nitrogen, sulfides, VOCs	Antibiotics, EDCs, MPs, and POPs [34]
Textile printing and dyeing industry	COD, colority, suspended solids (SS), sulfides (S^{2-})	MPs, PFAS [33]
Agricultural pollution	COD, ammonia nitrogen	Pesticide residues, veterinary drugs and antibiotics [12]
Electronic waste	COD, heavy metals, VOCs	Polybrominated diphenyl ethers (PBDEs) [35], Short-chain chlorinated paraffins (SCCPs) [36], MPs, PFAS, dioxin precursors
Wastewater treatment plants	COD, ammonia nitrogen	PPCPs, EDCs, MPs [10]
Waste incineration plants	Particulate matter, SO_2, NO_x, HCl, heavy metals	MPs [37], dioxins

COD: chemical oxygen demand, EDCs: endocrine disrupting chemicals, MPs: microplastics, PFAS: perfluoroalkyl and polyfluoroalkyl substances, POPs: persistent organic pollut

3.2. Strategic objectives for coordinated control

Opinions on the Beautiful China Initiative outlines phased objectives corresponding to the years 2027, 2035, and the mid-21st century for the development of a “Beautiful China.” Aligning with these national phased objectives and integrating trends in China’s socioeconomic development, this study proposes short-term (2027), medium-term (2030), medium-to-long-term (2035), and long-term (2050) milestones for the coordinated control of ECs and CPs (Fig. 1).

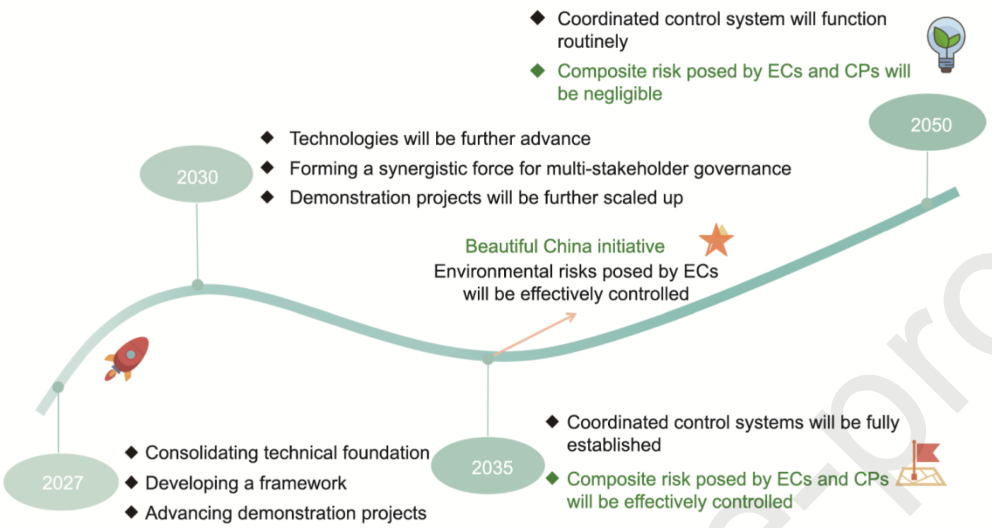

Fig. 1. Milestones for the coordinated control of ECs and CPs.

For the short-term (2027) goal, notable outcomes will be achieved in advancing the Beautiful China Initiative, with China’s total emissions of major pollutants continuing to decline. To underpin this national goal, coordinated control efforts from 2025 to 2027 should focus on consolidating a technical foundation, developing an institutional framework, and advancing a series of demonstration projects. While *Opinions on the Beautiful China Initiative* does not specify interim objectives for the period of 2027–2035, this study proposes establishing an 2030 interim (mid-term) objective to ensure the steady advancement of the coordinated control system. From 2028 to 2030, coordinated control technologies will be further advanced, a synergistic force for multi-stakeholder governance will be formed, and demonstration projects will be scaled up to a greater extent.

In the medium-to-long term (2035), the objectives of the Beautiful China Initiative will be largely realized: The ecological environment will undergo fundamental improvement, and environmental risks posed by ECs will be effectively controlled. To underpin this national goal, coordinated control technologies and integrated management systems for ECs and CPs must be fully established between 2031 and 2035, enabling effective control of the combined environmental risks posed by both types of pollutants. Looking ahead to the mid-21st century, the core objective of the Beautiful China Initiative will be to achieve a comprehensively sound and aesthetically harmonious ecological environment, marking the full maturity of a “Beautiful China” development phase. Accordingly, from 2036 to 2050, the coordinated control system will operate in a standardized and routine manner, and the combined risks of ECs and CPs to human health and natural ecosystems will be reduced to a negligible level.

To guide the government in effectively implementing strategic tasks, corresponding quantitative indicators should be established. For technologies and systems, these indicators should include: er the number of standards, specifications, and guidelines developed; & the number of coordinated treatment technologies; ● the number of coordinated treatment facilities; and ❍ the number of provinces covered. For projects, they should encompass er the number of coordinated treatment demonstration projects and & the number of provinces where such projects are implemented. For multi-stakeholder collaboration, the metrics should include er the competency assessment levels of governmental personnel and & the proportion of enterprises and the public that have received training. For combined ecological risks, the indicators should cover er the reduction rates of concentrations of priority ECs and CPs; and & the decrease in the combined risk index of priority ECs and CPs. Naturally, these quantitative indicators must ensure measurability and account for

4. Technology feasibility and innovation pathways

4.1. Technical feasibility

Among the key sources for coordinated treatment listed in Table 1, significant potential exists for coordinated reduction. For example, activated carbon adsorption enables the synergistic removal of CPs and specific ECs (e.g., antibiotics and MPs) [38,39]. Selective catalytic reduction (SCR) denitrification can remove dioxin precursors (e.g., chlorobenzenes) in coordination with nitrogen oxides (NO_x) removal [40]. Additionally, hazardous waste incineration facilitates the coordinated removal of toxic and hazardous chemicals (e.g., dioxins) while removing VOCs, acidic gases, and particulate matter [41].

However, many control technologies have limitations hindering their direct application in coordinated control. For instance, the thermal decomposition of PFAS typically requires temperatures exceeding 900 °C [42], a process that results in substantial energy consumption. Nevertheless, through targeted process design, optimization, and modification, these technologies can achieve the coordinated treatment of ECs and CPs, thereby improving treatment efficiency (Table 2 [40,43–52]). In the chemical and pharmaceutical industry, the coordinated treatment of COD, TOC, and phthalate esters (PAEs) can be achieved through a combination of AOPs and adsorption technologies, along with modifications to catalytic materials [43]. Enhanced biodegradation techniques enable the simultaneous removal of COD and PAHs [44]. In the textile and dyeing industry, a combination of MBR and ozone oxidation efficiently removes COD and TN [45]; when integrated with reverse osmosis (RO) processes, it can also remove stubborn PFAS [46]. For electronic waste, pyrolysis enables the dehalogenation of brominated flame retardants while permitting metal recovery [47]. For agricultural sources, wastewater treatment plants, and waste incinerators, certain remediation technologies can treat ECs such as pesticides, MPs, PPCPs, and dioxins in coordination with CPs such as TN, TP, NO_x, and colority.

Table 2 Coordinated combinations of treatment technologies targeting key emission sources.

Key emission sources	Coordinated treatment technology	Treatment effect (removal rate)	Ref.
Chemicals and pharmaceutical manufacturing industry	AOPs + adsorption	COD: 72%–79% Total organic carbon (TOC): 64%–74% PAEs: 80%–88%	[43]
	Enhanced biodegradation	COD: over 65% PAHs: 52.52%	[44]
	Catalytic regenerative thermal oxidation (RTO) + dioxin degradation catalyst	Effectively suppress dioxin formation while removing VOCs	[48]
Textile printing and dyeing industry	MBR + ozone oxidation + RO	COD: 99.8% TN: 97.4% Remove 20 kinds of aromatic amines PFAS: reach up to 99%	[45,46]
Agricultural pollution	Ecological ditches (containing zeolite and activated carbon substrates) + Fenton's reagent (Fe^{2+} + H_2O_2)	TN: 48%–64% TP: 41%–70% Pesticides: 99.7%	[49,50]
Electronic waste	Electrochemistry (electro-leaching, electrodeposition, and electrorefining) + thermochemistry (pyrolysis and hydrothermal treatment)	Selective separation and recovery of metals Dehalogenation of brominated flame retardants	[47]
Wastewater treatment plants	Upgrading biological treatment processes (e.g., MBR + ozone oxidation)	Removal of organic matter, TN, and TP while removing 99% of microplastics Reducing colority while achieving over 90% removal efficiency for certain PPCPs, effectively	[51,52]

		lowering estrogenic activity	
Waste incineration plants	Pre-treatment before incineration + process optimization + end-of-pipe flue gas purification system (combination of SCR denitrification, baghouse dust removal, and activated carbon adsorption)	NO_x: approximately 100% Dioxins and their precursors (chlorobenzenes): approximately 90%	[40]

AOPs: advanced oxidation processes, MBR: membrane bio-reactors, PAEs: phthalate esters, PAHs: polycyclic aromatic hydrocarbons, RO: reverse osmosis, SCR: selective cataly

4.2. Technological innovation pathways

The strategy for the coordinated control of ECs and CPs should shift from end-of-pipe treatment to whole-life-cycle risk control, and technical innovation pathways for coordinated control should be established (Fig. 2).

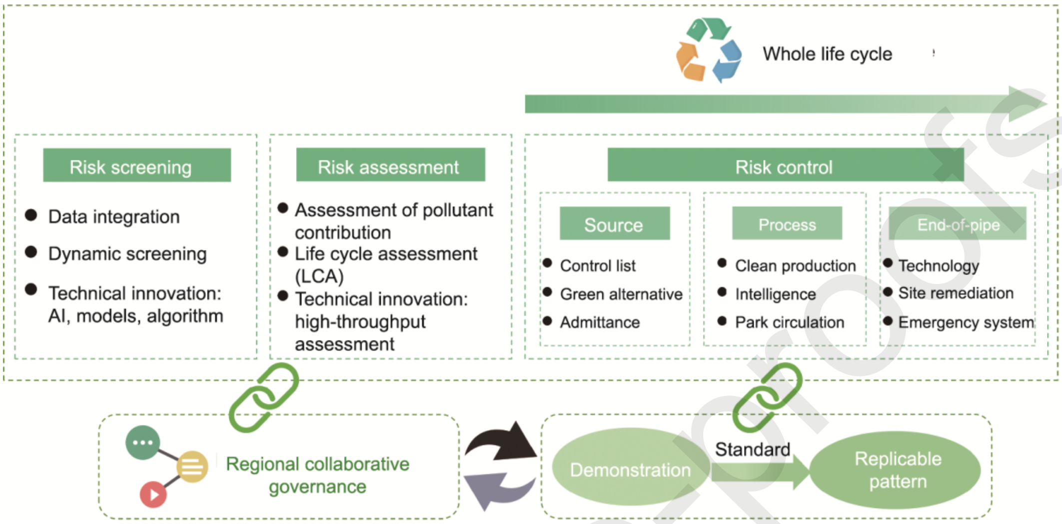

Fig. 2. Pathways to technological innovation for the coordinated control of ECs and CPs.

Risk screening plays both a guiding and a driving role in coordinated control. Based on data-integration methods, EC screening data should be supplemented using existing CP monitoring networks, and a dynamic risk-screening mechanism should be established. The application of artificial intelligence (AI) algorithms is recommended to predict the toxicity of chemical substances and integrate non-targeted screening with computational toxicology innovations [53]. However, current monitoring data for emerging pollutants remain fragmented. In scenarios with poor existing data quality and high complexity, the prediction reliability of AI algorithms is relatively low [54]. Additionally, non-targeted screening presents challenges related to complex procedures and high time consumption [55]. Therefore, efforts should focus on establishing a standardized toxic substance monitoring database, enhancing the generalization capabilities of prediction models, researching high-throughput screening technologies, and developing algorithms that can adapt to dynamic fluctuations in data quality [54]. Furthermore, integrating technologies such as machine learning into non-targeted screening will help improve efficiency.

Risk assessment is a crucial means for identifying coordinated control targets. Assessment technologies and tools rooted in environmental toxicology should be developed to evaluate the combined toxicities and cumulative risks of CPs and ECs [56]. Additionally, life-cycle assessments (LCAs) should be conducted to systematically analyze pollution emissions and associated risks throughout the entire process. However, the mechanisms underlying the combined toxicities of ECs and CPs remain unclear. Furthermore, LCA data are insufficient, particularly for the disposal and degradation phases [57]. To address these challenges, efforts should focus on developing combined toxicity-prediction frameworks based on adverse outcome pathways [58]. Meanwhile, a comprehensive and transparent chemical LCA database should be constructed by integrating machine learning technologies, and large language models should be introduced to mine process-related and textual knowledge [57].

Technological innovations in risk control should be advanced via a system based on the principles of source prohibition, process reduction, and end-of-pipe treatment. Efforts should be directed toward promoting the research of non/low-toxic alternative materials in key industries such as the chemical and electronics sectors. Coordinated clean production standards should be established for ECs and CPs. Moreover, an intelligent monitoring system for materials, energy, and pollutant flows within enterprises should be developed, along with coordinated removal technologies for ECs and CPs. However, the current development of alternative green materials is associated with high costs and lengthy cycles, and the efficiency of most coordinated removal technologies is relatively low [59]. To address these issues, a dedicated research program for alternative materials should be established, integrating computational materials science with green chemistry to design molecules with the desired properties [60]. Furthermore, it is necessary to innovate modular, adaptive, and combinatorial end-

Engineering applications of coordinated control processes should be initiated with demonstration projects. Efforts should focus on key industries, key regions, and river basins, advancing coordinated treatment technologies at the enterprise, park, and region/basin scale. This will include conducting engineering demonstrations, performing effectiveness evaluations, establishing technical standards and specifications, and ultimately developing replicable and scalable patterns.

Addressing the transboundary transport of pollutants necessitates a regional coordinated governance framework. Specifically, typical air pollutants (e.g., particulate matter lower than 2.5 μm ($PM_{2.5}$) and O_3) and water pollutants (e.g., POPs and MPs) are prone to cross-border diffusion [62,63], affecting neighboring regions. Therefore, regional coordinated control plans should be developed, with clear delineations of inter-regional responsibilities and work division. Cross-regional ecological compensation mechanisms should be established by offering appropriate economic incentives to upstream pollution-control regions in order to advance environmental equity and inter-regional control cooperation.

4.3. Technology assessments

Coordinated treatment technologies and pathways demand multidimensional evaluations. A comprehensive evaluation framework should be developed that is grounded in technical feasibility, attainable environmental quality, and a clear understanding of environmental health risks and economic costs to support scientific assessment and decision-making. In the dimension of technical feasibility, priority should be given to assessments of pollutant removal rates, treatment efficiency, material availability, and applicable scale; in the dimension of environmental quality, key indicators should cover the extent of reductions in pollutant concentrations in the environment and cross-medium blocking effects; in the dimension of environmental health risks, emphasis should be placed on evaluating the degree of mitigation of ecological toxicity and the reduction of exposure risks for different populations [64]; and in the dimension of economic cost, it will be necessary to conduct comprehensive cost accounting covering material, equipment, technical, and human resource costs.

5. Support system

5.1. Current situation and challenges

Technology serves as the primary tool for the coordinated control of ECs and CPs, and its sustainable advancement requires the support of legal frameworks, institutional mechanisms, and technical standards. At the legal level, the draft Environmental Protection Code was submitted to the Standing Committee of the National People's Congress for review in April 2025. It incorporates provisions to strengthen the risk control of chemical substance pollution, establish a coordinated control system for ECs such as POPs, and develop an environmental risk control framework. This code elevates the legal and strategic positioning of coordinated control; however, specific legal clauses remain insufficient.

In terms of institutional frameworks, the existing environmental-impact assessment system and pollutant-discharge permit system, which primarily target CPs, have undergone certain developments toward addressing ECs. The MEE has issued guidelines on environmental impact assessments of construction projects involving ECs in key industries. In December 2024, Shanxi province released a list of enterprises associated with key controlled ECs and their corresponding control measures for the 2023 fiscal year. However, the effectiveness of these initiatives still needs improvement, and there is a lack of institutional frameworks for coordinated control.

In terms of standard development, emission standards for CPs and environmental quality standards are relatively well-developed, and some regions have already incorporated certain ECs into these standards. For instance, the 2022 *Sanitary Standards for Drinking Water* (GB 5749-2022) includes four disinfection byproducts, perfluorooctanoic acid (PFOA), and perfluorooctanesulfonic acid (PFOS), along with other ECs as monitoring indicators. In July 2025, Sichuan province established emission limits for PFOA and PFOS within chemical industrial parks. However, these existing standards apply only to specific regions, industries, and pollutant types, and more comprehensive implementation is needed.

5.2. Institutions for support and guarantees

It is imperative to leverage the regulatory and constraining capabilities of the law in order to establish a comprehensive legal framework for the coordinated control of CPs and ECs. The government should revise existing laws to integrate the concept of the coordinated control of ECs and CPs. The law should clarify the framework for coordinated control, highlight the principles involved, and define the responsibilities of all relevant parties.

Government and research institutions should advance the integration and innovation of institutional mechanisms, and consolidate existing cross-media pollution-control systems targeting atmospheric, aquatic, and soil environments. It is necessary to strengthen the identification of ECs, list-based management, the updating of technical standards, and the screening of feasible alternatives in environmental impact assessments. The ECs from key industries should be legally incorporated into the pollutant-discharge permit and registration system, and a dynamic pollutant-discharge registration shou [illegible] tax expansion, green financial incentives, and corporate environmental credit evaluations. It is also crucial to refine the technical standards system for coordinated control, including the establishment of specifications for technical requirements, equipment parameters, and pollutant-reduction efficiency. In addition, emission standards and limits should be formulated for the coordinated control of ECs and CPs.

5.3. Multi-stakeholder governance strategies

The coordinated control system should adopt a multi-stakeholder governance strategy, as outlined in Fig. 3.

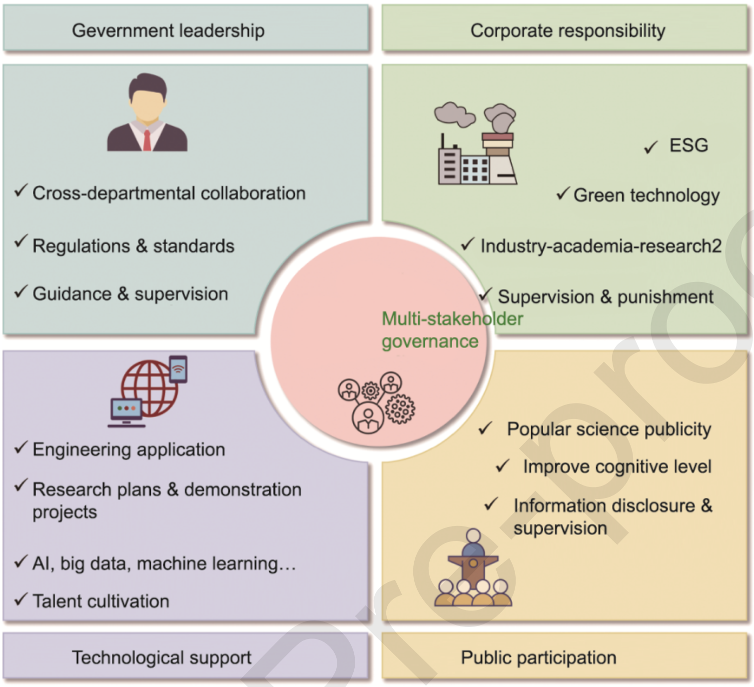

Fig. 3. A multi-stakeholder governance strategy for the coordinated control of ECs and CPs.

The government plays a leading role in control efforts and should take the lead in top-level design. Government-led initiatives should focus on improving regulations and standards, clarifying top-level design, and strengthening supervision and law enforcement related to pollution control. At the national strategic level, it is necessary to clarify the strategic significance and value of the coordinated control of ECs and CPs and to formulate long-term development strategies. More specifically, interdepartmental coordination mechanisms should be strengthened through collaborative efforts, such as establishing a data-sharing and joint regulatory platform that engages departments. It is recommend to establish and consolidate a joint prevention and control mechanism for ECs and CPs in key river basins and to improve national guidance and supervision over local governments.

Enterprises are the primary participants in coordinated control, as they are involved throughout the entire pollutant discharge process and should bear the primary responsibility for pollution control. Corporate environmental responsibility should be enhanced, and polluting enterprises should be mandated to conduct remediation. Relevant regulatory authorities and policymakers should specifically advance the implementation of environmental, social, and governance (ESG) systems, incorporate the pollution costs of ECs and CPs into corporate financial accounting, and incentivize enterprises to pursue green technological innovation. Meanwhile, promoting the in-depth integration of industry, academia, and research institutions in the field of pollution control is recommended. Additionally, the supervision and penalization of enterprises that engage in the illegal discharge of ECs or CPs should be intensified.

Technological support serves as the main tool for coordinated control. Efforts should focus on strengthening research institutions' technological support capabilities and launching special scientific research programs and major demonstration projects. At the same time, research institutes should prioritize tackling key bottlenecks in coordinated treatment technologies, while placing emphasis on bridging the gap between laboratory-scale research and full-scale engineering applications. It is also imperative to develop the integrated innovation of materials and processes and fully leverage emerging technologies such as AI, big data, and the Internet of Things [65].

The public, comprising an enormous number of individuals, can provide oversight throughout the entire process, effe and relevant departments should focus on encouraging public participation and social supervision. More specifically, they should enhance science popularization and publicity through diversified channels and improve the public awareness of ECs by comparing ECs with CPs. They should also develop mechanisms for the disclosure of comprehensive information pertaining to ECs, CPs, and environmental risks in order to facilitate effective social supervision.

6. Conclusions and prospects

The coordinated control of ECs and CPs constitutes a key task in supporting the Beautiful China Initiative. The strategic objectives of this coordinated control can effectively align with and underpin the strategic milestones of the Initiative. ECs and CPs co-occur across diverse environmental media; while they exhibit distinct pollution and emission characteristics, significant potential exists for coordinated treatment at numerous key emission sources, with coordinated treatment technologies demonstrating high feasibility. However, the realization of this potential presents multiple challenges, including gaps in policy and regulatory frameworks, limitations in technological maturity, and constraints related to economic costs. On the technological front, innovation and breakthroughs must be pursued in risk screening and assessment, life-cycle-based risk control, demonstration and promotion, and regional coordination, with timely assessments conducted to guide progress. In terms of management measures, a multi-stakeholder synergistic governance strategy, supported by relevant legal frameworks, standards, and institutional systems, must serve as the foundational pillar. At present, the priority should be to address key technical challenges in order to provide effective tools for the government, businesses, and the public. Looking ahead, the systematic advancement of the coordinated control of ECs and CPs will contribute significantly to the development of a “Beautiful China” and the pursuit of harmony between humanity and nature.

CRediT authorship contribution statement

Xiaogang Wang: Investigation, Writing – original draft, Writing – review & editing, Visualization, Methodology. **Bin Wang:** Conceptualization, Investigation, Writing – review & editing, Funding acquisition, Project administration, Resources, Methodology. **Qianxin Zhang:** Investigation, Writing – original draft, Writing – review & editing. **Gang Yu:** Conceptualization, Writing–review & editing, Funding acquisition, Project administration, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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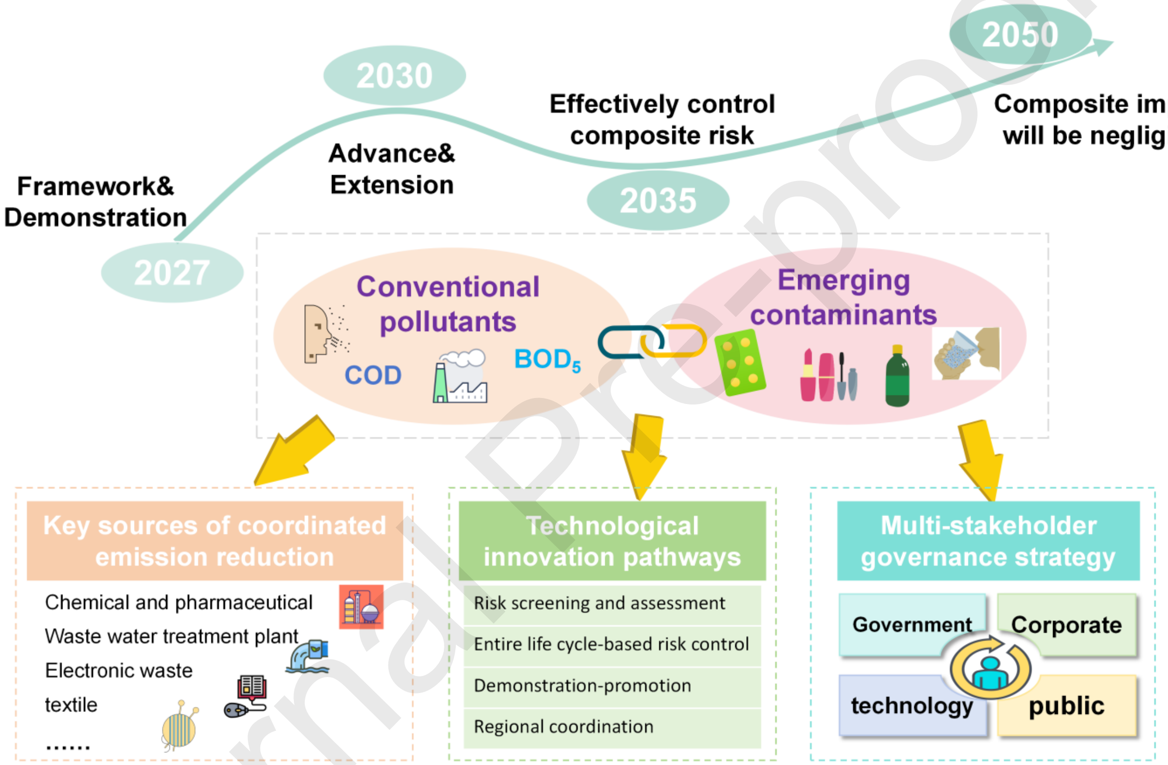

Highlights

- Feature comparison of ECs and CPs and its impact for control are analyzed
- Key sources and feasibility for coordinated control of ECs and CPs are identified
- Milestones of coordinated control of ECs and CPs are proposed
- Multifaceted technological pathways and multi-stakeholder governance are outlined

Declaration of Interest Statement

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for this journal and was not involved in the editorial review or the decision to publish this article.

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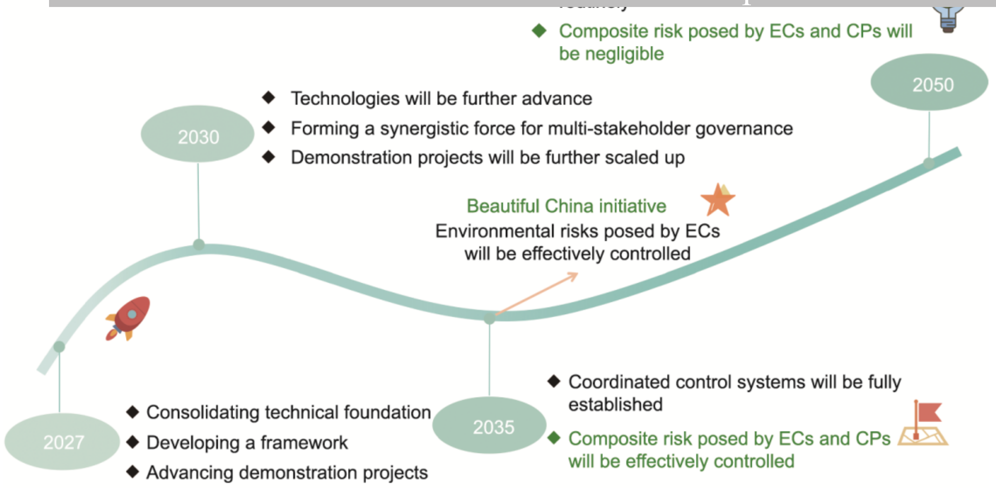
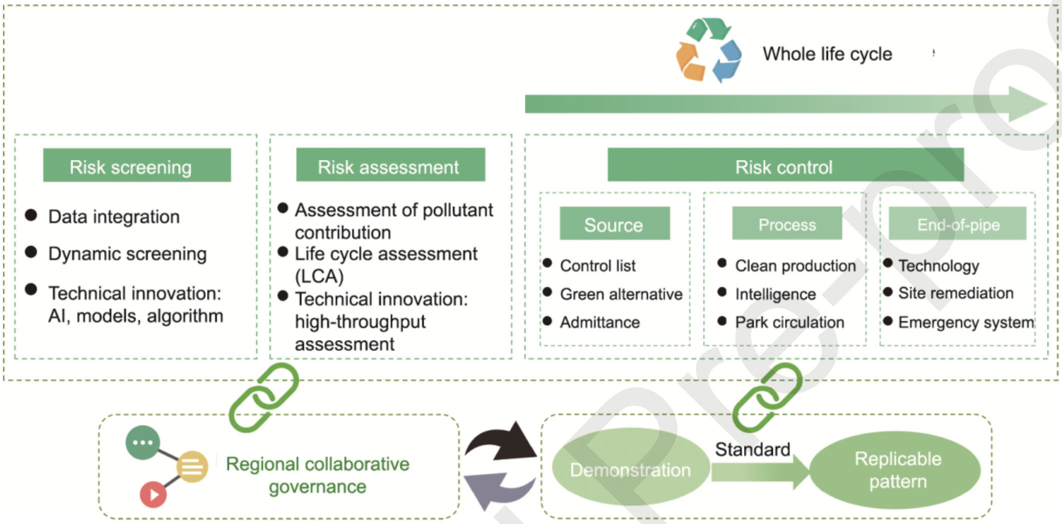
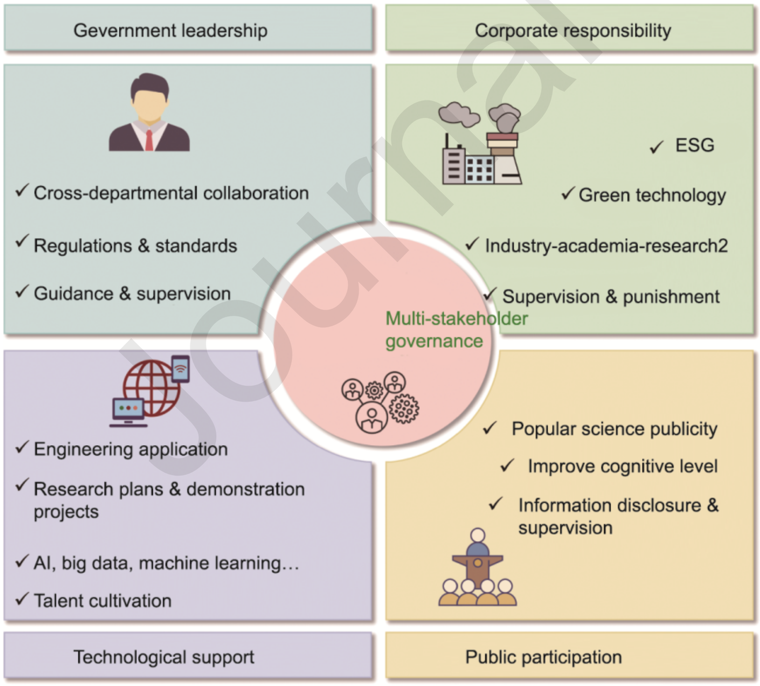

Composite risk posed by ECs and CPs will be negligible
2050
2030
Technologies will be further advance
Forming a synergistic force for multi-stakeholder governance
Demonstration projects will be further scaled up
Beautiful China initiative
Environmental risks posed by ECs will be effectively controlled
Coordinated control systems will be fully established
Composite risk posed by ECs and CPs will be effectively controlled
2035
2027
Consolidating technical foundation
Developing a framework
Advancing demonstration projects


Whole life cycle
Risk screening
Data integration
Dynamic screening
Technical innovation: AI, models, algorithm
Risk assessment
Assessment of pollutant contribution
Life cycle assessment (LCA)
Technical innovation: high-throughput assessment
Risk control
Source
Control list
Green alternative
Admittance
Process
Clean production
Intelligence
Park circulation
End-of-pipe
Technology
Site remediation
Emergency system
Regional collaborative governance
Demonstration
Standard
Replicable pattern


Government leadership
Cross-departmental collaboration
Regulations & standards
Guidance & supervision
Corporate responsibility
ESG
Green technology
Industry-academia-research2
Supervision & punishment
Multi-stakeholder governance
Engineering application
Research plans & demonstration projects
AI, big data, machine learning…
Talent cultivation
Technological support
Popular science publicity
Improve cognitive level
Information disclosure & supervision
Public participation