Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

A Harmonization Index for Comparative Assessment of Industrial Particulate Matter Emission Regulations

Sabohat Ergashkhojayeva
Namangan State Technical University
Muhammadyusuf Kholmatov
Namangan State Technical University
Akbarxon Sidikov
Namangan State Technical University
Jasur Shodmanov
phd.shodmanov@gmail.com
Namangan State Technical University
Hongtao LIU
Wuhan Textile University
Ahtam A Qosimov
Namangan State Technical University
Sherzod Korabayev
Namangan State Technical University
Azim Abdullayev
Namangan State Technical University
Dildora Mamadalieva
Namangan State Technical University

Research Article

Keywords: Industrial particulate matter, Harmonization Index, regulatory harmonization, environmental management, environmental governance, regulatory benchmarking, decision-support framework, industrial emission standards

Posted Date: August 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10491363/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Industrial particulate matter (PM) emissions remain a major environmental management challenge, yet meaningful international comparison of emission regulations is hindered by fundamentally different legal, technical, and institutional approaches adopted by individual jurisdictions. This study presents the first standardized **Regulatory Coding Framework** and **Harmonization Index (HI)** for the systematic evaluation and benchmarking of industrial PM emission regulations across technology-based, source-category-based, hybrid, and dispersion-based regulatory systems. The European Union, the United States, China, and Uzbekistan were selected as representative case studies. Twenty-one evaluation indicators, identified through systematic analysis of legally binding regulatory documents, were organized into three complementary dimensions:

Regulatory Stringency, **Institutional Design**, and **Enforcement Capacity**. Regulatory provisions were transformed into standardized documentary coding scores, normalized, and aggregated into a composite Harmonization Index. Framework robustness was evaluated through alternative weighting scenarios and Spearman's rank correlation analysis. The results reveal substantial regulatory divergence extending beyond numerical emission limits, particularly in technology-based regulation, integrated permitting, continuous emission monitoring, and independent compliance verification. The European Union achieved the highest Harmonization Index (1.000), followed by the United States (0.976), China (0.857), and Uzbekistan (0.500), while jurisdictional rankings remained fully stable under all weighting scenarios (Spearman's $\rho = 1.00$).

The proposed framework provides a **transparent, transferable, and reproducible decision-support methodology** for regulatory benchmarking, environmental management, and evidence-based modernization of industrial emission governance. Beyond facilitating international regulatory comparison, it offers policymakers a practical tool for identifying regulatory gaps, prioritizing reforms, and advancing harmonized industrial air pollution control in support of sustainable development.

Highlights

• Introduces the first standardized Harmonization Index for industrial particulate matter emission regulations.

• Develops a transparent Regulatory Coding Framework based on 21 evidence-based evaluation indicators.

• Integrates regulatory stringency, institutional design, and enforcement capacity into a unified assessment model.

• Provides a reproducible methodology for benchmarking PM emission regulations across the EU, USA, China, and Uzbekistan.

• Supports evidence-based environmental management, regulatory modernization, and international policy harmonization.

1. Introduction

Industrial particulate matter (PM) emissions remain one of the most persistent environmental management challenges, simultaneously affecting air quality, ecosystem integrity, industrial sustainability, and public health. Industrial sectors such as thermal power generation, cement production, metallurgy, mineral processing, waste incineration, chemical manufacturing, and textile processing continue to be major anthropogenic sources of particulate emissions despite significant advances in emission control technology. Effective regulation of these emissions is therefore essential not only for protecting human health, but also for advancing global climate and sustainability commitments, including Sustainable Development Goal 13 (Climate Action) and national strategies for environmental modernization [1-3].

During the past decade, international attention has increasingly focused on strengthening air quality management through stricter environmental legislation. The World Health Organization substantially revised its Global Air Quality Guidelines in 2021, recommending considerably lower ambient PM2.5 and PM10 concentrations and reflecting growing evidence of adverse health effects even at low exposure levels [3]. However, ambient air quality guidelines evaluate environmental exposure rather than regulating pollution at its source; industrial emission standards therefore remain the first and most direct regulatory barrier against atmospheric particulate emissions. A comparative assessment of PM2.5 pollution in Uzbekistan, for example, highlighted considerable discrepancies between observed ambient concentrations and international recommendations, underscoring the need for improved national environmental governance [4]. Such studies, however, evaluate exposure outcomes rather than the regulatory systems that control emissions at their source, leaving open the question of whether performance differences stem from emission limits, monitoring systems, institutional capacity, enforcement practices, or their combination.

Industrial particulate emission regulation differs fundamentally among jurisdictions, reflecting distinct historical, economic, technological, and institutional conditions rather than a universally harmonized philosophy. The European Union regulates emissions through integrated permitting based on Best Available Techniques (BAT) [5]; the United States applies source-category-specific standards under the Clean Air Act through NSPS and NESHAP [6]; China combines national emission standards with increasingly stringent sector-specific technical regulations as part of its environmental modernization strategy [7]; and Uzbekistan determines allowable emissions individually for each installation through dispersion modeling and maximum permissible emission (MPE) calculations [8]. Although each system pursues the same environmental objective, they differ substantially in regulatory architecture, compliance mechanisms, monitoring procedures, and enforcement strategies, so that comparing regulatory systems solely on the basis of numerical emission limit values (e.g., mg/Nm3) may produce misleading conclusions: equivalent numerical limits may operate under entirely different permitting, monitoring, and enforcement conditions, while differing standards may achieve similar environmental outcomes through stronger institutional implementation.

Previous research has addressed related aspects of international environmental regulation, but important methodological gaps remain. Comparative studies have primarily examined ambient air quality standards against WHO guideline values [9], while environmental policy research has developed composite indicators such as the OECD Environmental Policy Stringency Index to quantify overall national policy stringency [10,11], supported by OECD/JRC methodological guidance on constructing robust composite indicators [12].

A comparable multidimensional framework has also been proposed for indoor air quality regulations governing construction materials in Europe [13]. However, these approaches are not directly applicable to industrial particulate emission standards: ambient standards evaluate receptor-level concentrations rather than source-level releases, and general policy indices assess macro-level instruments without capturing pollutant-specific technical characteristics, emission limit values, or sectoral regulatory differences. A standardized methodology for evaluating the harmonization of industrial particulate emission regulations across jurisdictions with fundamentally different regulatory philosophies is therefore lacking.

This methodological gap has direct practical significance for environmental management. Governments increasingly seek to modernize environmental legislation, facilitate industrial cooperation, and align national regulations with international environmental commitments, including the Sustainable Development Goals and regional air-quality harmonization initiatives. However, harmonization cannot be achieved solely through adopting identical emission limit values, since institutional capacity, monitoring infrastructure, and enforcement mechanisms strongly influence regulatory performance. Decision-makers therefore require an analytical framework capable of distinguishing numerical regulatory differences from institutional and implementation-related disparities.

To address this challenge, the present study develops a decision-support framework for the comparative assessment of industrial PM emission regulations and introduces a Harmonization Index (HI) as its quantitative evaluation component. The framework integrates three complementary dimensions: regulatory stringency, representing the relative strictness and technical scope of requirements; institutional design, representing permitting procedures, monitoring systems, and regulatory transparency; and enforcement capacity, representing inspection practices, compliance verification, and implementation effectiveness. It is applied to four representative jurisdictions, the European Union, the United States, China, and Uzbekistan, spanning technology-based, source-category-based, hybrid, and dispersion-based regulatory approaches, providing an opportunity to identify convergent and divergent characteristics of contemporary industrial PM emission management. Accordingly, the objectives of this study are to (i) develop a transparent analytical framework for comparing heterogeneous industrial PM emission regulations; (ii) construct a multidimensional Harmonization Index integrating regulatory stringency, institutional design, and enforcement capacity; (iii) evaluate the comparative performance of selected regulatory systems using standardized indicators; (iv) examine the robustness of the framework through normalization and weighting analyses; and (v) formulate evidence-based recommendations supporting regulatory harmonization and environmental policy development consistent with global sustainability commitments such as SDG 13.

To the best of our knowledge, this is the first study to propose a standardized regulatory coding framework specifically designed for the comparative assessment of industrial PM emission standards across jurisdictions with fundamentally different regulatory philosophies. Unlike studies comparing ambient air quality standards or general environmental policies, the proposed Harmonization Index combines engineering and institutional dimensions within a unified assessment structure, offering environmental authorities a transparent, transferable tool for identifying regulatory strengths, implementation gaps, and priorities for future harmonization, and for advancing industrial environmental management in support of national and international climate and sustainability objectives.

2. Background and conceptual basis for regulatory harmonization

2.1. Evolution of industrial particulate matter regulation

The regulation of industrial particulate matter (PM) emissions has evolved from simple concentration-based emission limits toward increasingly integrated environmental management systems that combine technological performance, permitting procedures, continuous monitoring, and regulatory enforcement. Although the ultimate objective of all regulatory systems is to reduce particulate emissions and their adverse environmental impacts, different jurisdictions have adopted distinct regulatory philosophies shaped by industrial development, environmental priorities, institutional capacity, and legislative evolution. Consequently, present-day industrial PM regulations cannot be compared solely through numerical emission limit values because they originate from fundamentally different regulatory concepts.

Early industrial emission regulations were primarily designed to prevent excessive visible emissions and localized pollution. Emission limits were generally expressed as maximum allowable concentrations at the stack outlet, while compliance was verified through periodic measurements or visual inspection. Such approaches provided relatively simple regulatory instruments but often failed to account for differences in production technology, emission characteristics, operating conditions, or local environmental sensitivity. As environmental legislation matured, regulatory authorities gradually shifted from pollution control toward integrated environmental management, incorporating technological feasibility, environmental risk, monitoring requirements, and compliance assurance into permitting systems [5].

The European Union represents one of the most comprehensive examples of this transition. The adoption of the Integrated Pollution Prevention and Control (IPPC) Directive, later consolidated within the Industrial Emissions Directive (IED 2010/75/EU), fundamentally transformed industrial environmental regulation by introducing integrated permitting based on the Best Available Techniques (BAT) principle [5]. Under this approach, emission limit values are no longer determined exclusively by pollutant concentration but are linked to the environmental performance achievable using the best available technologies within each industrial sector. BAT Reference Documents (BREFs) define BAT-associated emission levels (BAT-AELs), allowing competent authorities to establish installation-specific permit conditions while maintaining consistency across the European Union. Consequently, regulatory stringency is determined not only by numerical emission limits but also by technological capability, continuous environmental improvement, and periodic permit review.

The United States follows a different regulatory philosophy. Industrial particulate emissions are regulated primarily through the Clean Air Act using New Source Performance Standards (NSPS) and National Emission Standards for Hazardous Air Pollutants (NESHAP), which establish source-category-specific emission requirements for new, modified, and reconstructed facilities [6]. Rather than applying a unified technology framework similar to BAT, the U.S. system develops standards according to industrial source categories and technological performance demonstrated within each category. Compliance is supported through detailed monitoring, reporting, recordkeeping, and enforcement provisions administered by the U.S. Environmental Protection Agency (EPA) and state environmental agencies. This category-specific structure provides flexibility for different industrial processes while maintaining nationally consistent regulatory requirements.

China has undergone one of the most significant regulatory transformations during the past two decades. Rapid industrialization initially resulted in relatively permissive emission controls; however, increasing environmental pressures prompted successive revisions of national emission standards and substantial strengthening of industrial environmental legislation. Contemporary Chinese regulation combines general emission standards with increasingly stringent sector-specific technical standards applicable to power generation, cement production, steel manufacturing, waste incineration, and numerous other industrial activities [7]. Continuous emission monitoring systems (CEMS), enhanced inspection mechanisms, and stricter environmental accountability have become central components of China's environmental governance strategy. Consequently, the Chinese regulatory framework increasingly integrates technological requirements with institutional supervision and compliance management.

Unlike the regulatory systems adopted in the European Union, the United States, and China, Uzbekistan employs a predominantly source-specific permitting approach based on maximum permissible emissions (MPE) calculated through atmospheric dispersion modelling. Rather than prescribing universally applicable numerical emission limits for every industrial category, allowable emissions are determined individually for each installation considering stack characteristics, meteorological conditions, surrounding land use, existing background pollution, and predicted ground-level concentrations [8]. This methodology seeks to ensure that industrial emissions do not cause ambient pollutant concentrations to exceed legally established environmental quality standards. Accordingly, regulatory compliance depends on both emission characteristics and local environmental conditions, making direct comparison with technology-based or category-based regulatory systems inherently challenging.

These contrasting regulatory philosophies illustrate that industrial particulate emission management extends beyond numerical emission limits. The European Union emphasizes technological optimization through BAT-based integrated permitting; the United States focuses on source-category performance standards; China combines national standards with sector-specific regulatory modernization; and Uzbekistan adopts site-specific emission control based on atmospheric dispersion assessment. Each approach reflects legitimate regulatory objectives and institutional realities, yet each evaluates compliance using different assumptions regarding technological capability, environmental protection, and regulatory implementation.

The diversity of these systems creates a significant methodological challenge for international comparison. Numerical emission limits reported in different jurisdictions frequently use different reference conditions, averaging periods, oxygen corrections, measurement protocols, and compliance criteria. Moreover, identical emission limits may represent substantially different regulatory obligations when implemented under different permitting procedures or enforcement mechanisms. Consequently, numerical comparison alone provides only a partial representation of regulatory performance and may lead to misleading conclusions regarding the relative strictness of environmental regulation.

From an environmental management perspective, meaningful international comparison requires recognition that regulatory effectiveness is multidimensional. Technical emission requirements represent only one component of a broader governance system that also includes institutional design, monitoring infrastructure, inspection procedures, reporting obligations, transparency, and enforcement capacity.

Therefore, the evolution of industrial particulate matter regulation demonstrates the necessity for analytical approaches capable of integrating these complementary dimensions into a common comparative framework rather than relying exclusively on emission limit values. A concise comparison of the four regulatory philosophies is presented in Table 1, while the detailed legal, technical, monitoring, and enforcement characteristics are provided in Supplementary Table S4.

Table 1
Comparative characteristics of industrial particulate matter regulatory philosophies in the European Union, the United States, China, and Uzbekistan.

Analytical element	EU	USA	China	Uzbekistan
Regulatory philosophy	BAT-based integrated regulation	Source-category performance regulation	Hybrid general and sector-specific regulation	Source-specific dispersion-based regulation
Primary legal instruments	IED, BREFs, BAT conclusions	Clean Air Act, NSPS, NESHAP, Title V	Air Pollution Law, GB 16297, sectoral GB standards	Atmospheric Air Protection Law, MPE procedures
Unit of regulation	Installation/activity	Source category/facility	Industrial source/sector	Individual source/enterprise
Method of setting PM limits	BAT-AEL-based permit limits	Category-specific performance standards	General or sector-specific ELVs	Site-specific MPE calculations
Permitting approach	Integrated permit	Construction and operating permits	EIA and discharge permitting	Individual environmental standards and permits
Monitoring approach	Periodic and sector-specific continuous monitoring	Performance testing, CEMS or parametric monitoring	Manual testing and CEMS for designated sources	Mainly periodic measurements and reporting
Main strength	Technology-driven continuous improvement	Detailed source-specific compliance system	Broad sectoral coverage and rapid tightening	Incorporates local dispersion and background pollution
Harmonization challenge	Sector/process-specific BAT ranges	Fragmented category-specific formats	National/sectoral/local standard differentiation	Limited direct comparability with technology-based ELVs

2.2. Existing approaches for regulatory comparison. The increasing complexity of environmental governance has stimulated the development of numerous methodologies for comparing environmental regulations across countries and jurisdictions. These approaches have improved the transparency of policy evaluation and facilitated evidence-based environmental decision-making. Nevertheless, most existing comparative methodologies were developed either to assess ambient environmental quality, evaluate national environmental policies at the macro level, or compare specific regulatory sectors. Consequently,

they provide valuable methodological insights but remain insufficient for evaluating industrial particulate matter (PM) emission regulations that differ fundamentally in technical design, regulatory philosophy, and implementation mechanisms.

One of the earliest streams of comparative research focused on ambient air quality standards. Rather than examining industrial emissions directly, these studies evaluated how national ambient air quality standards correspond to international health-based recommendations. Their principal contribution was demonstrating that considerable variation exists among countries in the legal protection afforded against particulate pollution, despite a common scientific understanding of PM-related health risks [9]. Such studies significantly advanced international environmental policy discussions by emphasizing the importance of regulatory harmonization for protecting public health. However, ambient air quality standards describe pollutant concentrations measured within the receiving environment rather than emissions released from industrial sources. Consequently, they cannot be used to evaluate the effectiveness or comparability of industrial emission regulations.

Another important direction has involved the construction of environmental policy stringency indicators. Composite indices have increasingly been employed to quantify the overall intensity of environmental regulation while accounting for multiple policy instruments simultaneously. Among these, the OECD Environmental Policy Stringency (EPS) Index represents one of the most influential international frameworks, integrating market-based instruments, non-market regulations, and technology-support policies into a single composite measure applicable across multiple countries and several decades [11]. The EPS framework has become particularly valuable for analysing relationships between environmental regulation, technological innovation, productivity, and economic growth because it provides a standardized measure of overall regulatory pressure.

Despite its considerable strengths, the EPS Index was not designed to compare pollutant-specific industrial emission regulations. Instead, it evaluates national environmental policy portfolios using aggregated policy instruments without considering engineering characteristics such as emission limit values, measurement reference conditions, monitoring protocols, permitting systems, or sector-specific technical requirements. As a result, two countries may receive similar policy stringency scores despite adopting substantially different industrial emission control strategies. Conversely, countries operating comparable industrial emission standards may appear dissimilar because their broader environmental policy portfolios differ. Therefore, macro-level policy indices cannot adequately resolve technical differences among industrial PM regulatory systems.

Methodological advances in composite indicator construction have also contributed substantially to comparative environmental assessment. The OECD–Joint Research Centre (JRC) framework established internationally recognized principles for indicator selection, normalization, weighting, aggregation, uncertainty analysis, and sensitivity assessment [12]. Rather than proposing a specific environmental indicator, this framework provides methodological guidance for ensuring transparency, reproducibility, and statistical robustness in composite index development. These principles have subsequently been adopted across numerous environmental sustainability, governance, resilience, and policy evaluation studies. Their relevance extends directly to regulatory harmonization because any comparative index intended to support

policy decisions must demonstrate methodological consistency and robustness under alternative analytical assumptions.

Recent studies have expanded comparative methodologies into increasingly specialized environmental sectors. A notable example is the development of a multidimensional framework for comparing indoor air quality regulations governing emissions from construction materials across several European jurisdictions [13]. Unlike conventional regulatory comparisons that rely primarily on legal provisions, this framework integrated scientific evidence, implementation mechanisms, and innovation capacity using standardized evaluation criteria. The study demonstrated that heterogeneous regulatory systems could be analysed using a structured analytical matrix without oversimplifying institutional differences. Although this methodological approach represents an important conceptual advance, its application remains limited to indoor environmental quality and construction product regulation. Industrial point-source emissions involve fundamentally different technical parameters, permitting systems, compliance verification procedures, and regulatory objectives.

Another growing research direction concerns regulatory quality, environmental governance, and institutional effectiveness. Increasing evidence suggests that environmental outcomes depend not only on statutory emission limits but also on regulatory implementation, administrative capacity, inspection frequency, transparency, and enforcement effectiveness [14]. Jurisdictions with comparatively moderate legal requirements may achieve high levels of environmental compliance through effective monitoring and institutional accountability, whereas stricter legal standards may produce limited environmental benefits when implementation capacity is weak. These findings highlight the importance of distinguishing formal regulatory stringency from practical regulatory effectiveness when evaluating environmental management systems.

Collectively, the existing literature demonstrates significant methodological progress in environmental policy evaluation but simultaneously reveals several important limitations for industrial emission regulation analysis. First, most comparative studies assess ambient environmental quality rather than source-based emission control. Second, existing policy indices operate at a national or macroeconomic scale and therefore overlook pollutant-specific engineering requirements embedded within industrial permitting systems. Third, current comparative frameworks rarely integrate numerical emission standards with institutional design and enforcement capacity within a unified analytical structure. Finally, existing approaches generally assume comparable regulatory philosophies, whereas industrial PM regulations frequently differ in their underlying legal principles, technical assumptions, and compliance mechanisms.

These limitations become particularly evident when comparing jurisdictions such as the European Union, the United States, China, and Uzbekistan. Although each regulatory system pursues the common objective of reducing particulate emissions, they differ substantially in permitting philosophy, technological requirements, monitoring strategies, inspection procedures, and environmental accountability mechanisms. Consequently, existing comparative methodologies cannot determine whether observed regulatory differences reflect genuine variation in environmental protection or merely differences in regulatory architecture. Addressing this methodological challenge requires a decision-support framework capable of

integrating engineering, institutional, and enforcement dimensions within a common harmonized assessment model.

Table 2
Comparative evaluation of existing approaches for environmental regulatory assessment, their primary assessment dimensions, methodological strengths, and limitations with respect to industrial particulate matter emission regulation.

Existing assessment approach	Primary object and dimensions assessed	Methodological approach	Principal strength	Limitation for industrial PM emission regulation
WHO Global Air Quality Guidelines [3]	Health-based ambient concentrations of $PM_{2.5}$, PM_{10} and other major air pollutants; short- and long-term population exposure	Systematic evaluation of epidemiological evidence followed by derivation of recommended ambient concentration levels	Provides an internationally recognized health-protection reference and a common basis for evaluating ambient air-quality policies	Addresses pollutant concentrations in the receiving atmosphere rather than releases from industrial sources; ambient values in μg/m³ cannot be directly compared with stack ELVs in mg/Nm³
International comparison of national ambient air-quality standards [9]	Existence and numerical stringency of national ambient standards for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2 and CO	Compilation of national standards and comparison with WHO guideline values across multiple countries	Demonstrates international regulatory divergence using a transparent and readily interpretable benchmark	Does not assess industrial source categories, emission-control technologies, permitting systems, stack-reference conditions, monitoring requirements or enforcement capacity
Comparative assessment of $PM_{2.5}$ pollution in Uzbekistan and international standards [4]	Observed ambient $PM_{2.5}$ concentrations in Uzbekistan relative to national and international air-quality benchmarks	Comparative analysis of measured ambient concentrations and applicable air-quality standards	Provides country-specific evidence of the gap between actual air quality and internationally recommended protection levels and supports regulatory modernization	Evaluates ambient pollution outcomes rather than the design and implementation of industrial emission regulations; it cannot identify whether observed differences arise from ELVs, monitoring, permitting or enforcement
OECD Environmental Policy Stringency Index [11]	National environmental policy stringency across market-based instruments, non-market instruments and	Policy instruments are scored and aggregated into country-level composite indices covering multiple	Enables standardized cross-country and longitudinal analysis of overall environmental policy pressure and its economic	Operates at a macro-policy level and does not include pollutant-specific industrial ELVs, process conditions, stack measurement protocols, sectoral

Existing assessment approach	Primary object and dimensions assessed	Methodological approach	Principal strength	Limitation for industrial PM emission regulation
	technology-support policies	countries and years	or technological effects	applicability or permit-level compliance provisions
OECD/JRC composite-indicator construction framework [12]	General methodology for constructing multidimensional policy and performance indices	Theoretical framework, indicator selection, normalization, weighting, aggregation, uncertainty analysis and sensitivity testing	Provides a rigorous and internationally accepted procedure for producing transparent, reproducible and statistically robust composite indicators	It is a methodological handbook rather than a ready-to-use regulatory assessment model; industrial PM-specific dimensions, indicators and technical comparability rules must be developed separately
Multidimensional comparison of indoor air-quality regulations [13]	Regulation of emissions from construction materials and indoor air-quality governance across European jurisdictions	Standardized scoring matrix integrating scientific rigor, regulatory implementation and innovation	Demonstrates that heterogeneous air-quality regulations can be transformed into a structured multidimensional comparative framework	Focuses on indoor environments and product/material emissions; it does not cover industrial point sources, BAT or source-category standards, stack-reference conditions, dispersion-based permitting, CEMS or industrial enforcement mechanisms

As summarized in Table 2, existing approaches provide important but fragmented foundations for regulatory comparison. Health-based guidelines and ambient-standard comparisons assess the level of protection afforded at the receptor, whereas the OECD EPS Index evaluates the overall intensity of national environmental policy. The OECD/JRC framework provides methodological principles for constructing composite indicators, and the recent indoor air-quality framework demonstrates the feasibility of multidimensional regulatory comparison. However, none of these approaches simultaneously evaluates technically comparable industrial particulate emission requirements, permitting architecture, compliance monitoring and enforcement capacity. This unresolved methodological gap provides the basis for the decision-support framework developed in the present study.

3. Materials and Methods

3.1. Study design and selection of regulatory jurisdictions.

This study adopted a comparative analytical research design to develop and validate a decision-support framework for evaluating the harmonization of industrial particulate matter (PM) emission regulations. Unlike studies that compare only numerical emission limit values, the proposed methodology considers industrial emission regulation as a multidimensional environmental management system consisting of technical, institutional, and enforcement components. Accordingly, the methodological workflow comprised five sequential stages: (i) identification of representative regulatory jurisdictions; (ii) collection and harmonization of regulatory information; (iii) development of evaluation indicators; (iv) construction of the Harmonization Index (HI); and (v) robustness assessment through sensitivity analysis.

The European Union (EU), the United States (USA), China, and Uzbekistan were selected as case-study jurisdictions because they represent four distinct philosophies of industrial emission regulation. Their inclusion was based on purposeful sampling rather than geographical representation, allowing comparison among fundamentally different regulatory approaches.

The European Union represents a technology-oriented regulatory model in which industrial emissions are managed through integrated permitting based on Best Available Techniques (BAT) under the Industrial Emissions Directive (IED). Emission limit values are established considering technological feasibility, environmental performance, and continuous improvement requirements.

The United States represents a source-category-oriented system where industrial facilities are regulated through New Source Performance Standards (NSPS) and National Emission Standards for Hazardous Air Pollutants (NESHAP). Regulatory requirements are developed according to industrial source categories while maintaining nationwide implementation through federal and state environmental authorities.

China represents a rapidly evolving hybrid regulatory model combining national emission standards with increasingly stringent sector-specific technical regulations. During the last decade, industrial environmental governance has increasingly incorporated continuous emission monitoring systems (CEMS), digital supervision, and strengthened environmental enforcement.

Uzbekistan represents a dispersion-based permitting approach in which maximum permissible emissions are calculated individually for each industrial installation according to atmospheric dispersion modelling and local environmental conditions. Unlike the other jurisdictions, emission requirements are established primarily through site-specific environmental impact assessment rather than uniform technology-based standards.

These four jurisdictions provide a suitable analytical basis because they encompass the principal regulatory philosophies currently employed worldwide, namely technology-based regulation, source-category regulation, hybrid national regulation, and source-specific dispersion-based permitting.

Regulatory information was collected exclusively from officially published legislation, technical standards, environmental agency guidance documents, and internationally recognized regulatory databases. To ensure methodological consistency, only legally binding regulatory provisions applicable to industrial particulate

emissions were considered. Documents intended solely for policy discussion or non-binding technical recommendations were excluded from the analysis.

Since regulatory documents employ different engineering conventions, all extracted information underwent technical harmonization before comparative assessment. Harmonization included verification of pollutant definitions, reference gas conditions, averaging periods, oxygen correction requirements, monitoring methodologies, compliance determination procedures, and regulatory applicability. Numerical emission limit values were compared only when they referred to technically equivalent emission conditions. Regulatory provisions that could not be converted into equivalent engineering conditions were evaluated through institutional indicators rather than direct numerical comparison.

This approach minimizes methodological bias associated with comparing fundamentally different regulatory systems and ensures that the proposed framework evaluates regulatory equivalence rather than merely numerical similarity.

3.2. Development of the harmonization framework

The Harmonization Framework was developed to provide a transparent and reproducible methodology for comparing industrial particulate matter emission regulations operating under different legal, technical, and institutional conditions. The framework follows internationally accepted principles for composite indicator construction while adapting them specifically to industrial environmental regulation.

Rather than assuming that regulatory harmonization is achieved through identical emission limit values, the proposed framework defines harmonization as the degree to which different jurisdictions provide comparable levels of environmental protection through technically equivalent emission requirements, effective institutional arrangements, and consistent regulatory implementation.

Based on the conceptual analysis presented in Section 2 and internationally accepted composite indicator methodologies, three complementary dimensions were selected for evaluation:

- **Regulatory Stringency (S)**, representing the technical rigor of industrial particulate emission regulation;
- **Institutional Design (I)**, representing the administrative and organizational characteristics governing implementation of emission standards;
- **Enforcement Capacity (E)**, representing the effectiveness of compliance monitoring, inspection, reporting, and regulatory enforcement.

These dimensions were selected because environmental performance depends not only on statutory emission limits but also on the institutional mechanisms through which regulations are implemented and enforced.

Regulatory stringency

This dimension evaluates the engineering characteristics of industrial particulate emission regulation. Indicators include the existence of sector-specific emission standards, technological requirements, emission limit determination principles, periodic revision of standards, pollutant coverage, and technical consistency

of emission measurements. Rather than evaluating absolute emission limits alone, this dimension assesses the overall technical rigor of the regulatory framework.

Institutional design

Institutional Design reflects the organizational structure supporting environmental regulation. Indicators evaluate permitting procedures, legal transparency, mandatory monitoring requirements, public availability of environmental information, regulatory review mechanisms, and integration of environmental management within industrial permitting systems.

Enforcement capacity

Effective environmental regulation requires consistent implementation. Accordingly, Enforcement capacity evaluates inspection frequency, continuous emission monitoring requirements, compliance verification procedures, enforcement authority, corrective actions, administrative sanctions, and reporting obligations. This dimension recognizes that two jurisdictions adopting similar legal standards may achieve substantially different environmental outcomes because of differences in implementation capacity.

Each indicator was selected according to four predefined criteria:

1. relevance to industrial particulate emission regulation;
2. applicability across all selected jurisdictions;
3. availability from official regulatory documentation; and
4. reproducibility for future comparative studies.

Indicators failing to satisfy all four criteria were excluded to maintain methodological transparency and ensure objective comparison. The indicator identification process began with an extensive screening of regulatory requirements contained in international legislation, technical standards, environmental permitting procedures, and compliance guidelines applicable to industrial particulate matter emissions. An initial pool of thirty-four candidate indicators was identified from the reviewed regulatory documents and previous environmental governance studies. These indicators were subsequently evaluated against four predefined selection criteria: relevance to industrial particulate matter regulation, cross-jurisdictional comparability, documentary availability, and reproducibility. Indicators satisfying all four criteria were retained for the final framework, resulting in twenty-one indicators. Candidate indicators such as emission inventory requirements, permit validity periods, stakeholder participation, and voluntary environmental management programmes were excluded because they were either inconsistently regulated across jurisdictions, weakly associated with particulate emission control, or insufficiently comparable for standardized coding.

To facilitate subsequent quantitative analysis, qualitative regulatory characteristics were transformed into standardized evaluation scores using predefined assessment criteria. Each indicator was evaluated independently using documentary evidence extracted from the corresponding regulatory framework. Indicator scoring was performed using explicit decision rules to minimize subjective interpretation.

Table 3.

Evaluation dimensions, indicators, data sources, and scoring criteria used for construction of the Harmonization Index.

Dimension	Code	Regulatory indicator	Scientific rationale	Documentary evidence	Coding criterion
Regulatory Stringency	S1	Sector-specific emission limit values	Sector-specific ELVs better reflect industrial diversity than uniform standards.	National emission standards	0 = absent; 1 = partial; 2 = comprehensive
	S2	Technology-based emission regulation	BAT/MACT-type regulation promotes continuous technological improvement.	BAT, NSPS, sectoral standards	0–2
	S3	Coverage of PM fractions	Regulation of TSP, PM10 and PM2.5 provides broader particulate control.	Technical standards	0–2
	S4	Periodic revision of standards	Regular revision reflects scientific and technological progress.	Environmental legislation	0–2
	S5	Standardized measurement methods	Standardized testing ensures comparability among jurisdictions.	ISO, EN, EPA methods	0–2
	S6	Standard reference conditions	Common reference conditions improve engineering comparability of ELVs.	Measurement standards	0–2
	S7	Sectoral coverage	Wider industrial coverage strengthens regulatory consistency.	Regulatory documents	0–2
	I1	Integrated permitting	Integrated permits improve environmental governance efficiency.	Permit legislation	0–2
	I2	Mandatory operating permit	Legal authorization is fundamental for emission regulation.	Environmental regulations	0–2

Institutional Design	I3	Permit renewal mechanism	Periodic permit review supports adaptive environmental management.	Permit procedures	0–2
	I4	Mandatory environmental reporting	Reporting strengthens accountability and regulatory oversight.	Reporting regulations	0–2
	I5	Public accessibility	Public access improves transparency and stakeholder confidence.	Government databases	0–2
	I6	Digital environmental management	Digital permitting enhances administrative efficiency.	Government environmental portals	0–2
	I7	Institutional coordination	Coordination reduces regulatory fragmentation.	Environmental governance documents	0–2
Enforcement Capacity					
	E1	Mandatory continuous emission monitoring (CEMS)	Continuous monitoring improves compliance assurance.	Monitoring regulations	0–2
	E2	Performance testing	Performance tests verify actual emission control efficiency.	Technical standards	0–2
	E3	Regulatory inspection programme	Routine inspections increase compliance reliability.	Inspection regulations	0–2
	E4	Independent verification	Third-party verification reduces reporting bias.	Environmental legislation	0–2
	E5	Administrative penalties	Effective sanctions discourage regulatory violations.	Environmental Code	0–2
	E6	Operational suspension authority	Suspension mechanisms ensure enforceability.	Environmental legislation	0–2

	E7	Mandatory corrective actions	Corrective measures support continuous regulatory improvement.	Compliance procedures	0–2

The proposed framework is hierarchical. Individual indicators contribute to their respective dimensions, dimension scores are normalized to ensure comparability, and normalized scores are subsequently aggregated into a single Harmonization Index representing the overall degree of regulatory harmonization. This hierarchical structure preserves transparency by allowing interpretation at both indicator and composite-index levels.

Unlike existing environmental policy indices that evaluate national environmental governance at a macro level, the present framework focuses specifically on industrial particulate emission regulation. It therefore combines engineering characteristics with institutional and enforcement attributes within a unified analytical structure, enabling comparison of regulatory systems that differ fundamentally in legal philosophy and implementation mechanisms while avoiding oversimplification of their technical characteristics.

3.3. Development of the Harmonization index

The Harmonization Index (HI) was developed to transform the qualitative regulatory characteristics identified in Section 3.2 into a standardized quantitative framework suitable for cross-jurisdictional comparison. The selected indicators were converted into documentary coding scores, normalized, aggregated into three analytical dimensions, and subsequently combined into a composite index representing the overall degree of regulatory harmonization.

The complete regulatory coding matrix together with the corresponding legal evidence is provided in Supplementary Tables S1 and S2, while the complete indicator screening procedure is summarized in Supplementary Table S3.

Each indicator was evaluated using a standardized documentary coding procedure based exclusively on legally binding regulatory instruments. To improve transparency and reproducibility, regulatory provisions were assigned discrete scores of 0, 1, or 2, representing absence, partial implementation, and comprehensive implementation, respectively. Partial implementation was assigned where regulatory provisions were applicable only to selected industrial sectors, were implemented with limited scope, or lacked nationwide consistency.

Since all indicators were initially coded using the same ordinal scale, raw scores were normalized before aggregation according to

$$x_{ij}^{*} = \frac{x_{ij}}{2} \quad \text{(Eq. 1)}$$

where $\mathbf{x_i}$ is the original documentary score (0–2) and $\mathbf{x_i}^{*}$ is the normalized value ranging from 0 to 1.

The normalized indicator values were averaged within each analytical dimension to obtain the Regulatory Stringency (*S*), Institutional Design (*I*), and Enforcement Capacity (*E*) sub-indices:

$$S_j = \frac{1}{m}\sum_{i=1}^{m} S_{ij}^{*}$$ (Eq. 2)

$$I_j = \frac{1}{n}\sum_{i=1}^{n} I_{ij}^{*}$$ (Eq. 3)

$$E_j = \frac{1}{k}\sum_{i=1}^{k} E_{ij}^{*}$$ (Eq. 4)

where **m, n** and **k** represent the number of indicators included within each dimension.

The overall Harmonization Index was calculated by aggregating the three normalized sub-indices according to

$$HI_j = w_s S_j + w_i I_j + w_e E_j$$ (Eq. 5)

where w_S, w_I, *and* w_E represent the corresponding weighting coefficients.

Following the recommendations of the OECD–JRC Handbook on Composite Indicators, equal weighting was adopted as the baseline aggregation strategy because no statistically validated evidence currently demonstrates that any one of the three regulatory dimensions consistently exerts greater influence on industrial regulatory harmonization than the others. Consequently,

$$w_S = w_I = w_E = \frac{1}{3}$$ (Eq. 6)

was applied throughout the primary analysis. To verify that the final results were not dependent on this assumption, alternative weighting scenarios were examined through sensitivity analysis.

The resulting Harmonization Index ranges from **0** to **1**, where higher values indicate stronger alignment with internationally recognized principles of industrial particulate matter regulation. For interpretation, the calculated scores were classified into five harmonization levels: very low (0.00–0.19), low (0.20–0.39), moderate (0.40–0.59), high (0.60–0.79), and very high (0.80–1.00).

Unlike previous comparative studies that evaluate only emission limit values or general environmental policy stringency, the proposed methodology transforms heterogeneous legal and technical regulatory provisions into standardized quantitative indicators, thereby enabling objective comparison among jurisdictions adopting fundamentally different regulatory philosophies. The robustness of the proposed framework was finally evaluated through alternative weighting scenarios, one-at-a-time sensitivity analysis, and Spearman's rank correlation coefficient, thereby verifying that the comparative ranking was not driven by the weighting assumptions but by the underlying documentary evidence.

4. Results

4.1. Comparative regulatory coding analysis

The document-based coding procedure produced a structured dataset comprising twenty-one regulatory indicators for the European Union, the United States, China, and Uzbekistan. The complete regulatory coding matrix is presented in Supplementary Table S1, whereas the documentary evidence supporting each

assigned score is summarized in Supplementary Table S2. The resulting indicator scores formed the basis for calculating the three analytical dimensions and the overall Harmonization Index presented below.

The heatmap distinguishes the three analytical dimensions Regulatory Stringency (S1–S7), Institutional Design (I1–I7), and Enforcement Capacity (E1–E7) and allows indicator-level differences to be identified without relying exclusively on composite values.

The European Union obtained the maximum coding score for all 21 indicators. Its profile reflected the comprehensive integration of sector-specific emission requirements, BAT-based permitting, standardized monitoring, reporting obligations, inspection procedures, corrective measures, and enforcement authority. The absence of indicator-level deficiencies in the coding matrix resulted from the formal completeness of the EU regulatory architecture rather than an assumption that implementation is identical across all Member States. The score therefore represents the comprehensiveness of the supranational regulatory framework assessed in this study and should not be interpreted as evidence of uniform operational performance in every installation.

The United States displayed a similarly comprehensive regulatory profile. Full scores were obtained for all Regulatory Stringency and Enforcement Capacity indicators. The only partial score occurred for integrated permitting (I1), reflecting the structural division of regulatory requirements among construction permits, operating permits, federal standards, state implementation mechanisms, and Title V permit systems rather than a single media-integrated permitting model equivalent to that of the European Union. This distinction reduced the Institutional Design score slightly but did not materially affect the overall regulatory profile.

China achieved high scores across all three dimensions but showed greater internal variability than the European Union and the United States. Partial scores were identified for technology-based regulation (S2), explicit coverage of particulate fractions (S3), integrated permitting (I1), permit renewal mechanisms (I3), public accessibility of regulatory information (I5), and independent verification (E4). These findings indicate that the Chinese system has developed extensive sector-specific standards, monitoring requirements, inspection powers, and sanction mechanisms, while certain institutional and technical provisions remain uneven across industrial sectors or administrative levels. The heatmap therefore characterizes China as a strong but less uniform regulatory system.

Uzbekistan displayed the most differentiated profile among the four jurisdictions. A full score was obtained for mandatory environmental permitting (I2) and administrative penalties (E5), whereas partial scores were assigned to most remaining indicators. Technology-based regulation (S2) and independent verification (E4) received zero scores under the applied coding criteria. The pattern indicates that Uzbekistan possesses an established legal basis for source permitting and environmental enforcement, but its regulatory model remains predominantly dependent on installation-specific maximum permissible emission calculations, periodic reporting, and dispersion-based assessment. The principal gaps were associated with sector-specific technology-linked standards, continuous monitoring coverage, standardized compliance verification, permit review, and independent validation.

The indicator-level results also demonstrated why nominal emission limits alone would provide an incomplete comparison. Uzbekistan's dispersion-based model incorporates local background concentrations and atmospheric conditions, which represents a legitimate environmental protection function, but this strength is not equivalent to comprehensive technology-based source regulation. Conversely, the EU, US, and Chinese systems showed stronger formal requirements for sectoral standards, measurement protocols, monitoring, and enforcement, although their structures differ substantially. The regulatory coding framework therefore captured functional and institutional differences that could not be represented by a direct comparison of stack concentration limits.

The strongest differentiation among jurisdictions was observed for technology-based emission regulation, integrated permitting, permit renewal, public accessibility, independent verification, and CEMS coverage. In contrast, mandatory permitting, administrative sanctions, and corrective enforcement mechanisms showed greater convergence. These results suggest that international harmonization is more advanced in the existence of basic legal control instruments than in the technical and institutional mechanisms governing regulatory implementation.

4.2. Harmonization Index results

The normalized dimension scores were calculated by dividing each raw indicator score by the maximum score of 2 and averaging the resulting values within each analytical dimension. The overall Harmonization Index was then obtained using equal weights for Regulatory Stringency, Institutional Design, and Enforcement Capacity.

Table 4
Regulatory dimension scores and overall Harmonization Index values for the selected jurisdictions.

Jurisdiction	Regulatory Stringency, S	Institutional Design, I	Enforcement Capacity, E	Overall HI	Harmonization category
European Union	1.000	1.000	1.000	1.000	Very high
United States	1.000	0.929	1.000	0.976	Very high
China	0.857	0.786	0.929	0.857	Very high
Uzbekistan	0.429	0.571	0.500	0.500	Moderate

As shown in Table 4, the European Union achieved an overall HI of 1.000, reflecting complete formal alignment with the 21 criteria included in the proposed framework. The United States followed closely with an HI of 0.976. Its lower score was attributable exclusively to the partial coding of integrated permitting, while Regulatory Stringency and Enforcement Capacity remained at the maximum level.

China obtained an HI of 0.857 and was classified within the *very high harmonization category according to the proposed framework*. Its Enforcement Capacity score of 0.929 exceeded its Regulatory Stringency score of 0.857 and Institutional Design score of 0.786. This pattern suggests that China's recent regulatory development has been particularly strong in monitoring, inspection, sanctions, and corrective enforcement,

whereas institutional transparency, permit integration, and uniform technology-based regulation remain comparatively less developed.

Uzbekistan obtained an overall HI of 0.500, corresponding to moderate harmonization. Its highest dimension score was recorded for Institutional Design (0.571), followed by Enforcement Capacity (0.500) and Regulatory Stringency (0.429). The results indicate that Uzbekistan has established the administrative foundations required for industrial environmental regulation, particularly mandatory permitting and legal sanctions, but the technical structure of PM regulation remains less aligned with the technology- and category-based systems applied in the other jurisdictions.

The 0.500-point difference between the EU and Uzbekistan should not be interpreted as a direct measure of environmental performance or actual emission reduction. The HI evaluates the documented completeness and comparability of regulatory arrangements rather than measured ambient air quality, plant-level emissions, or enforcement outcomes. Accordingly, the result identifies areas of regulatory divergence and reform priority but does not imply that one jurisdiction produces exactly twice the environmental protection of another.

The radar chart visually separates the three components of the overall index and prevents the composite HI from concealing dimension-specific strengths and weaknesses. The EU profile forms a complete outer triangle, whereas the US profile differs only slightly in Institutional Design. China displays a relatively balanced but contracted profile, with its strongest performance in Enforcement Capacity. Uzbekistan shows the smallest and most uneven profile, with Regulatory Stringency representing the principal area of divergence.

The comparison demonstrates that similar overall index classifications can conceal different regulatory structures. Although the EU, USA, and China were all classified as having very high harmonization, their sub-index patterns differed. The EU combined full technical, institutional, and enforcement coverage; the USA showed highly developed source-category regulation and enforcement but a less integrated permitting architecture; and China exhibited strong enforcement capacity alongside partial institutional and technical coverage. Consequently, policy benchmarking should use both the overall HI and the three dimension scores rather than relying on the composite value alone.

For Uzbekistan, the sub-index results identify a clear reform sequence. Strengthening Regulatory Stringency would require the development of sector-specific PM emission standards, stronger links between permissible emissions and demonstrated control technologies, standardized reference conditions, and clearer differentiation of particulate fractions where technically relevant. Institutional improvement would require periodic permit review, greater public accessibility of regulatory information, and broader digitalization. Enforcement improvement would depend on expanded CEMS coverage, more systematic performance testing, and independent verification of monitoring results.

4.3. Sensitivity and robustness analysis

The robustness of the Harmonization Index was tested using four weighting scenarios. Equal weighting was used as the baseline scenario, while the alternative scenarios assigned a weight of 0.50 to one dimension

and 0.25 to each of the remaining dimensions. The scenarios therefore represented stringency-led, institution-led, and enforcement-led interpretations of regulatory harmonization.

Table 5
Harmonization Index values under alternative dimension-weighting scenarios

Jurisdiction	Equal weights	Stringency-led	Institution-led	Enforcement-led
European Union	1.000	1.000	1.000	1.000
United States	0.976	0.982	0.964	0.982
China	0.857	0.857	0.839	0.875
Uzbekistan	0.500	0.482	0.518	0.500

As shown in Table 5, the European Union remained unchanged across all scenarios because it obtained identical scores in all three dimensions. The United States varied only between 0.964 and 0.982, demonstrating that its overall assessment was not materially influenced by the weighting method. China showed a wider but still limited range of 0.839–0.875. The highest Chinese score occurred under enforcement-led weighting, consistent with its comparatively strong Enforcement Capacity sub-index, whereas the lowest score occurred when Institutional Design received the dominant weight.

Uzbekistan varied between 0.482 and 0.518. Its lowest result occurred under the stringency-led scenario because Regulatory Stringency was its weakest dimension. Its highest result occurred under institution-led weighting, reflecting the comparatively stronger institutional score. Despite these changes, Uzbekistan remained within the *moderate harmonization category defined by the proposed framework* under every weighting scenario.

Across all alternative weighting scenarios, the ranking of the assessed jurisdictions remained unchanged (European Union > United States > China > Uzbekistan). Spearman's rank correlation coefficient between the baseline and each alternative scenario was $\rho = 1.000$, confirming perfect rank-order stability. Therefore, the comparative results are robust to changes in the weighting scheme and primarily reflect persistent differences in the underlying regulatory indicators rather than methodological assumptions regarding dimension weights.

The one-at-a-time sensitivity analysis further showed that the weighting choice affected absolute HI values more strongly for jurisdictions with uneven dimension profiles than for those with balanced profiles. The EU and US results were almost insensitive to weighting changes, whereas China and Uzbekistan showed greater variation because their technical, institutional, and enforcement scores were less uniform. Nevertheless, none of the tested weighting scenarios altered the overall ranking or shifted any jurisdiction into a different harmonization category.

These findings support the robustness of the proposed framework while also demonstrating the importance of reporting sub-index values. A stable composite ranking does not eliminate policy-relevant differences among dimensions. For example, China’s score increased under enforcement-led weighting, whereas Uzbekistan’s score increased under institution-led weighting. Such variation identifies the regulatory

dimension most responsible for each jurisdiction's relative position and therefore provides information directly relevant to policy prioritization.

Overall, the results confirm that the proposed Regulatory Coding Framework and Harmonization Index can differentiate regulatory systems with contrasting legal philosophies while preserving indicator-level transparency. The heatmap identifies specific areas of convergence and divergence, the dimension scores summarize regulatory structure, the overall HI supports comparative benchmarking, and the sensitivity analysis verifies that the jurisdictional ranking remains stable under alternative weighting assumptions.

5. Discussion

The results demonstrate that industrial particulate matter regulation cannot be meaningfully compared through numerical emission limits alone. Although the European Union, the United States, China, and Uzbekistan pursue the common objective of reducing industrial particulate emissions, the regulatory systems differ considerably in their technical design, permitting architecture, monitoring arrangements, transparency requirements, and enforcement mechanisms. The proposed Regulatory Coding Framework therefore reveals dimensions of regulatory divergence that remain invisible in conventional comparisons based solely on stack concentration limits.

The overall Harmonization Index values placed the European Union, the United States, and China within the *very high harmonization category defined by the proposed evaluation framework*, whereas Uzbekistan was classified as moderately harmonized. These results should be interpreted as measures of formal regulatory alignment with the common benchmark framework developed in this study, rather than as direct indicators of actual environmental performance. A high HI value indicates that a jurisdiction has established a comparatively comprehensive combination of technical standards, institutional arrangements, and enforcement instruments. It does not necessarily imply uniform implementation, full compliance across all regulated facilities, or superior ambient air quality outcomes. This distinction is particularly important because environmental regulation may be formally advanced while remaining unevenly implemented across sectors, regions, or installation types.

5.1. Interpretation of cross-jurisdictional regulatory differences

The European Union obtained the highest score because its regulatory architecture combines BAT-based technical requirements, integrated permitting, standardized monitoring, reporting obligations, inspection procedures, and corrective enforcement mechanisms. The principal strength of the EU model is its linkage between permit conditions and the environmental performance achievable through Best Available Techniques. This design enables emission requirements to evolve alongside technological development and supports periodic regulatory updating. However, the maximum score obtained by the EU reflects the formal completeness of the supranational framework rather than identical implementation across all Member States. Differences in administrative capacity, inspection intensity, industrial structure, and national enforcement may still affect practical outcomes.

The United States displayed a similarly strong profile but differed from the EU in institutional organization. The US system relies on source-category standards, construction and operating permits, federal requirements, state implementation arrangements, and detailed compliance provisions. Its slightly lower Institutional Design score resulted mainly from the absence of a single integrated permitting model equivalent to the EU approach. This result does not suggest weaker regulatory control. Instead, it reflects a structurally different system in which regulatory obligations are distributed across several legal and administrative instruments. The comparison therefore confirms that different institutional architectures may produce comparable levels of formal regulatory coverage.

China achieved a high overall score but showed greater variation among the three dimensions. Its Enforcement Capacity score exceeded its Institutional Design and Regulatory Stringency scores, indicating substantial development in continuous monitoring, inspection, sanctions, and corrective action mechanisms. At the same time, partial scores for integrated permitting, permit renewal, public accessibility, technology-based regulation, and independent verification suggest that regulatory implementation remains more heterogeneous across sectors and administrative levels. China's profile illustrates how rapid regulatory modernization can generate strong enforcement instruments while institutional integration and transparency continue to develop.

Uzbekistan showed the greatest distance from the benchmark framework, particularly in Regulatory Stringency. Its source-specific dispersion-based system incorporates local meteorological conditions, background pollution, stack characteristics, and predicted ground-level concentrations. This is an important environmental protection function and should not be treated as inherently inferior to technology-based regulation. However, the system provides limited direct comparability with sector-specific BAT- or source-category-based emission standards. The absence or limited coverage of technology-linked emission requirements, independent verification, comprehensive CEMS obligations, periodic permit review, and standardized sectoral benchmarks reduced the calculated HI value.

The results therefore indicate that the principal difference between Uzbekistan and the other jurisdictions is not the absence of environmental regulation, but the regulatory philosophy through which allowable emissions are determined. Uzbekistan emphasizes receptor protection through site-specific dispersion calculations, whereas the EU, USA, and China place greater emphasis on source performance, sector-specific requirements, and standardized control technologies. Effective harmonization should therefore not require replacing dispersion-based assessment. A more appropriate strategy would integrate source-specific atmospheric modelling with sector-specific technological and compliance requirements.

5.2. Relationship with existing regulatory assessment approaches

The findings extend previous research on air-quality standard comparison and environmental policy stringency. Earlier comparative studies demonstrated substantial variation in national ambient air-quality standards and their correspondence with WHO guideline values [9]. Such studies are valuable for evaluating receptor-level protection but cannot identify how industrial emissions are controlled before pollutants enter

the ambient environment. The present framework addresses this limitation by shifting the analytical focus from ambient concentration standards to industrial source regulation.

Similarly, the OECD Environmental Policy Stringency Index provides a widely used measure of national environmental policy pressure [11]. Its strength lies in enabling longitudinal and cross-country comparison of broad environmental policy portfolios. However, it does not capture industrial PM-specific measurement conditions, permitting systems, source-category requirements, continuous monitoring, or compliance verification. The proposed HI complements rather than replaces the EPS approach by operating at a more technically specific regulatory level.

The methodology also follows the composite-indicator principles established by the OECD and JRC, including transparent indicator selection, normalization, weighting, aggregation, and sensitivity assessment [12]. The stability of jurisdictional rankings under alternative weighting scenarios supports the internal robustness of the index. Nevertheless, the HI should be regarded as a structured decision-support instrument rather than a definitive measure of environmental performance. Composite indicators simplify multidimensional systems and therefore require interpretation alongside indicator-level evidence and sub-index results.

The recent multidimensional comparison of indoor air-quality regulations demonstrates that heterogeneous environmental regulations can be analysed through standardized scoring frameworks [13]. The present study extends this logic to industrial point-source regulation, where the analytical challenge is greater because jurisdictions employ different engineering units, permit structures, monitoring requirements, and enforcement procedures. The proposed framework therefore contributes a pollutant- and source-specific regulatory coding approach that was previously unavailable for industrial particulate emissions.

The results are also consistent with the broader literature emphasizing that legal stringency alone does not determine environmental outcomes. Monitoring frequency, administrative capacity, reporting systems, inspection procedures, and enforcement credibility all influence compliance [14]. This is reflected in the different sub-index profiles observed in the present study. For example, China’s comparatively strong Enforcement Capacity score compensated partly for lower scores in Institutional Design, whereas Uzbekistan’s relatively stronger institutional foundation was not matched by equivalent technical and verification mechanisms.

5.3. Implications for regulatory harmonization and environmental management

The findings suggest that international harmonization should not be understood as the adoption of identical numerical emission limits. Direct transfer of ELVs between jurisdictions may be inappropriate when measurement methods, reference conditions, fuel characteristics, process technologies, averaging periods, oxygen corrections, and compliance rules differ. Instead, harmonization should focus on functional equivalence across technical, institutional, and enforcement dimensions.

From this perspective, the proposed framework can support three forms of environmental management decision-making. First, it can be used for regulatory benchmarking by identifying areas in which a national

system differs from international practice. Second, it can support reform prioritization by distinguishing gaps in technical standards from weaknesses in permitting, transparency, monitoring, or enforcement. Third, it can guide regulatory transfer by showing which foreign instruments may be adapted without assuming that an entire regulatory model must be copied.

For Uzbekistan, the results indicate a phased modernization pathway. In the short term, priority should be given to standardizing PM measurement methods, reference conditions, reporting formats, and compliance verification procedures. These measures would improve data comparability without requiring major changes to the existing MPE system. In the medium term, sector-specific emission benchmarks could be introduced for major industrial sources such as cement production, thermal power generation, metallurgy, mineral processing, and waste incineration. These standards should complement, rather than replace, dispersion-based permitting. In the longer term, regulatory modernization could include wider CEMS deployment, periodic permit review, independent verification, public access to emission information, and stronger integration between digital reporting and enforcement systems.

A hybrid regulatory model may therefore be the most appropriate pathway for Uzbekistan. Under such a model, site-specific dispersion calculations would continue to protect local ambient air quality, while sector-specific technological standards would establish minimum source-performance requirements. This combination would preserve the environmental sensitivity of the current system while strengthening consistency, transparency, and international comparability.

5.4. Methodological implications and limitations

The study demonstrates that qualitative legal and technical provisions can be transformed into a reproducible quantitative structure. The principal methodological contribution is not limited to the final HI value. The more important contribution is the Regulatory Coding Framework, which makes indicator selection, scoring, normalization, and aggregation explicit. This structure allows future researchers to revise individual scores, add jurisdictions, expand pollutant coverage, or apply alternative weighting schemes without redesigning the entire methodology.

However, several limitations must be considered. First, the assessment is based on formal documentary evidence and does not directly measure implementation quality, actual compliance rates, enforcement frequency, industrial emission reductions, or ambient air-quality outcomes. A jurisdiction may possess comprehensive legislation but experience uneven enforcement in practice. Future applications should therefore combine regulatory coding with empirical indicators such as inspection frequency, violation rates, CEMS completeness, penalty collection, emission trends, and measured environmental outcomes.

Second, the scoring system converts complex regulatory provisions into three ordinal categories. Although the 0–1–2 scale improves transparency and reproducibility, it inevitably simplifies regulatory variation. Partial implementation may represent substantially different conditions across jurisdictions. Detailed documentary justification is therefore essential for every assigned score, and the complete coding evidence should remain available in the Supplementary Information. To enhance transparency and facilitate future methodological refinement, the complete documentary evidence supporting each regulatory coding decision is provided in Supplementary Table S2. This supplementary material enables independent verification of the

assigned scores and allows future studies to update individual indicators as regulatory frameworks continue to evolve.

Third, the four selected jurisdictions represent contrasting regulatory philosophies but do not capture the full diversity of global industrial emission governance. Expanding the framework to additional developed, emerging, and lower-income economies would allow stronger evaluation of cross-regional applicability and reduce the influence of case-selection effects.

Fourth, equal weighting was selected to minimize subjective preference in the absence of validated evidence supporting differential dimension weights. Sensitivity analysis showed that the jurisdictional ranking remained unchanged, but the limited number of jurisdictions means that Spearman's ρ = 1.000\rho = 1.000ρ = 1.000 should be interpreted as evidence of rank stability within the present dataset rather than broad statistical validation. Future studies could apply expert elicitation, analytic hierarchy process, entropy weighting, principal component analysis, or Bayesian approaches once larger datasets become available.

Finally, the very high scores observed for the EU, USA, and China may partly reflect a ceiling effect caused by the indicator structure. Future refinement should incorporate greater differentiation in sectoral coverage, actual CEMS applicability, permit-review frequency, independent verification, and PM fraction regulation. Adding outcome-based indicators would also help distinguish formal regulatory completeness from practical environmental effectiveness.

Overall, the results support the use of the proposed framework as a transparent regulatory benchmarking tool while emphasizing that composite scores should always be interpreted together with sub-index profiles, indicator-level evidence, and jurisdiction-specific institutional context. The framework is therefore best viewed as a structured foundation for regulatory learning and policy prioritization rather than as a universal ranking of environmental performance.

6. Conclusions

This study developed a novel Regulatory Coding Framework and the associated Harmonization Index (HI) for the systematic comparison of industrial particulate matter (PM) emission regulatory systems operating under fundamentally different regulatory philosophies. Unlike previous comparative studies that primarily evaluate ambient air-quality standards or general environmental policy stringency, the proposed framework integrates Regulatory Stringency, Institutional Design, and Enforcement Capacity into a unified analytical methodology. By transforming heterogeneous legal and technical provisions into standardized quantitative indicators, the framework enables transparent and reproducible cross-jurisdictional assessment without relying solely on numerical emission limit values.

Application of the proposed methodology to the European Union, the United States, China, and Uzbekistan demonstrated that regulatory harmonization cannot be adequately assessed through emission limit values alone. Jurisdictions exhibiting similar environmental objectives often differ substantially in permitting architecture, technology requirements, monitoring systems, compliance verification, and enforcement mechanisms. The indicator-level analysis revealed that technology-based regulation, integrated permitting,

continuous emission monitoring, and independent compliance verification constitute the principal sources of divergence among the selected regulatory systems. Conversely, basic legal instruments such as environmental permitting and administrative sanctions exhibited comparatively higher levels of international convergence.

The Harmonization Index provided a robust and interpretable basis for benchmarking industrial PM regulatory systems. The sensitivity analysis demonstrated that jurisdictional rankings remained stable under alternative weighting scenarios, indicating that the comparative assessment was primarily driven by the underlying regulatory evidence rather than methodological assumptions. This finding supports the robustness and reproducibility of the proposed framework and confirms its suitability as a decision-support tool for comparative environmental policy analysis.

From a practical perspective, the proposed framework offers several advantages for environmental regulators and policymakers. First, it provides a standardized methodology for identifying regulatory strengths and weaknesses across jurisdictions. Second, it enables evidence-based prioritization of regulatory reforms by distinguishing deficiencies related to technical standards, institutional arrangements, or enforcement mechanisms. Third, the framework can support international regulatory benchmarking, facilitate legislative modernization, and contribute to greater consistency in industrial emission governance while respecting national regulatory characteristics.

The findings also provide specific implications for countries employing source-specific dispersion-based regulatory systems, such as Uzbekistan. Rather than replacing existing approaches, the results suggest that regulatory effectiveness could be enhanced through the gradual incorporation of technology-based sector-specific emission standards, wider implementation of continuous emission monitoring systems, standardized compliance verification procedures, periodic permit review, and increased transparency of regulatory information. Such measures would strengthen alignment with internationally recognized regulatory practices while preserving the advantages of site-specific environmental assessment.

Several limitations should be acknowledged. The present study evaluates the formal characteristics of regulatory systems using documentary evidence and therefore does not directly assess implementation performance, compliance rates, actual industrial emissions, or environmental outcomes. Furthermore, the analysis was limited to four representative jurisdictions and focused exclusively on particulate matter emissions from stationary industrial sources. Future studies should expand the geographical scope, incorporate additional pollutants such as SO_2, NO□, VOCs, and greenhouse gases, and combine regulatory indicators with empirical compliance and environmental performance data. The application of advanced weighting techniques, including multi-criteria decision analysis and machine-learning-assisted policy evaluation, may further improve the analytical capability of the framework.

To the best of our knowledge, this study presents the first standardized Regulatory Coding Framework specifically developed for the comparative assessment of industrial particulate matter emission regulations across jurisdictions adopting fundamentally different regulatory philosophies. The proposed Harmonization Index provides a transparent, transferable, and scientifically reproducible methodology that can support

future international regulatory benchmarking and contribute to more effective environmental management and sustainable industrial development.

Declarations

CRediT authorship contribution statement: Sabohat Ergashkhojayeva contributed to investigation, data curation, and writing – review & editing. Muhammadyusuf Kholmatov contributed to investigation, formal analysis, and validation. Akbarxon Sidikov contributed to methodology, validation, and visualization. Jasur Shodmanov conceived the study, developed the methodology, performed the formal analysis, prepared the original draft, reviewed and edited the manuscript, supervised the research, and administered the project. Hong-Tao Liu contributed to conceptualization, supervision, and writing – review & editing. Ahtam A. Qosimov contributed to investigation, resources, and validation. Sherzod Korabayev contributed to formal analysis, visualization, and validation. Azim Abdullaev contributed to resources, investigation, and writing – review & editing. Dildora Mamadalieva- contributed to methodology, data curation, and writing – review & editing. All authors read and approved the final version of the manuscript.

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.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability Statement

All data generated or analysed during this study are included in this published article and its Supplementary Information files.

Clinical trial number: Not applicable.

Consent to Publish declaration: Not applicable.

Consent to Participate declaration: Not applicable.

Ethics declaration: Not applicable.

References

1. Davidson CI, Phalen RF, Solomon PA. Airborne particulate matter and human health: A review. Aerosol Sci Technol. 2005;39:737–49. https://doi.org/10.1080/02786820500191348.
2. Anderson JO, Thundiyil JG, Stolbach A. Clearing the air: A review of the effects of particulate matter air pollution on human health. J Med Toxicol. 2012;8:166–75. https://doi.org/10.1007/s13181-011-0203-1.

3. World Health Organization. 2021. *WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. World Health Organization, Geneva. ISBN 978-92-4-003422-8.
4. Abdullajanov B, Kholmatov M, Ergashkhojayeva S, Tursunov A, Shodmanov J. Comparative assessment of PM2.5 pollution in Uzbekistan and international air quality standards. Ecol Questions. 2026;37(1):17–25. https://doi.org/10.12775/EQ.2026.002.
5. European Parliament and Council. 2010. Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control) (Recast). *Official Journal of the European Union*, L 334, 17.12.2010, pp. 17–119.
6. U.S. Environmental Protection Agency. *New Source Performance Standards (NSPS)*, 40 CFR Part 60; *National Emission Standards for Hazardous Air Pollutants (NESHAP)*, 40 CFR Part 63.
7. Ministry of Ecology. and Environment of the People's Republic of China. *GB 16297 – 1996: Integrated Emission Standard of Air Pollutants*.
8. Cabinet of Ministers of the Republic of Uzbekistan, Resolution No. 14, 21. January 2014. *On Approval of the Regulation on the Procedure for Developing and Coordinating Environmental Draft Projects*.
9. Kutlar Joss M, Eeftens M, Gintowt E, Kappeler R, Künzli N. Time to harmonize national ambient air quality standards. Int J Public Health. 2017;62:453–62. https://doi.org/10.1007/s00038-017-0952-y.
10. Brunel C, Levinson A. 2013. Measuring environmental regulatory stringency. *OECD Trade and Environment Working Papers*, No. 2013/05. https://doi.org/10.1787/5k41t69f6f6d-en
11. Botta E, Koźluk T. 2014. Measuring Environmental Policy Stringency in OECD Countries: A Composite Index Approach. *OECD Economics Department Working Papers*, No. 1177. https://doi.org/10.1787/5jxrjnc45gvg-en
12. OECD/European Union/Joint Research Centre. Handbook on Constructing Composite Indicators: Methodology and User Guide. Paris: OECD Publishing; 2008. https://doi.org/10.1787/9789264043466-en.
13. Rey-Álvarez B, Sánchez-Montañés B, Silvestre E. Harmonizing indoor air quality standards across Europe: A comparative analysis framework for building material regulations and public health protection. Build Environ. 2026;288:113967. https://doi.org/10.1016/j.buildenv.2025.113967.
14. Kang S, Hong J. Configurational driving mechanisms of local environmental governance under the institutional pressure–organizational capacity framework: evidence from China. Front Environ Sci. 2026. https://doi.org/10.3389/fenvs.2026.1806129.

Figures

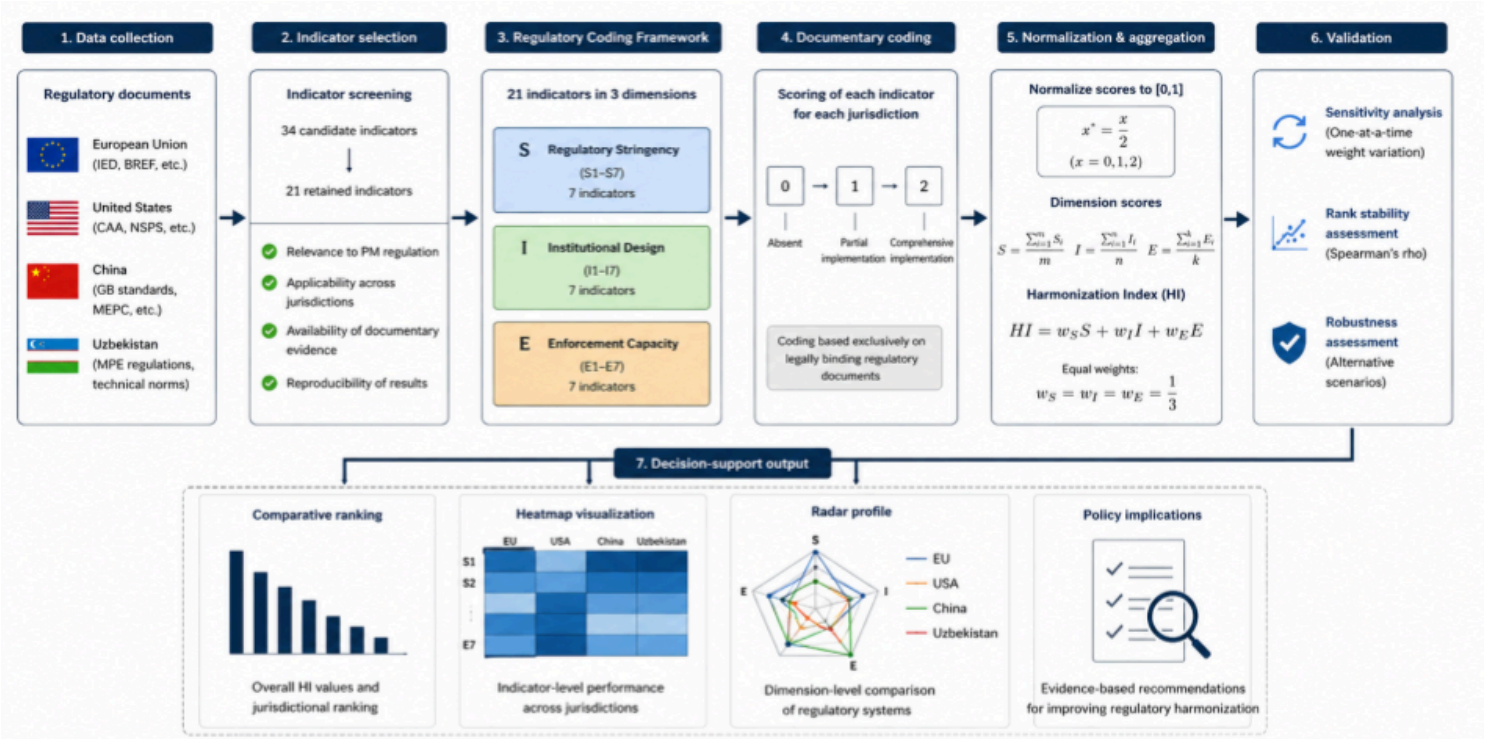


Figure 4. Methodological workflow for construction and validation of the proposed Harmonization Index.

Figure 1

Methodological workflow for construction and validation of the proposed Harmonization Index.

Dimension	Code	Indicator	Jurisdiction			
			European Union (EU)	United States (USA)	China (CHN)	Uzbekistan (UZB)
Regulatory Stringency (S1–S7)	S1	Sector-specific emission limit values	2	2	2	1
	S2	Technology-based regulation (BAT/MACT equivalent)	2	2	1	0
	S3	Coverage of PM fractions (TSP, PM_{10}, $PM_{2.5}$)	2	2	1	1
	S4	Periodic revision of emission standards	2	2	2	1
	S5	Standardized measurement methods	2	2	2	1
	S6	Standard reference conditions	2	2	2	1
	S7	Sectoral applicability	2	2	2	1
Institutional Design (I1–I7)	I1	Integrated environmental permitting	2	1	1	1
	I2	Mandatory operating permit	2	2	2	2
	I3	Permit renewal mechanism	2	2	1	1
	I4	Mandatory environmental reporting	2	2	2	1
	I5	Public accessibility of regulatory information	2	2	1	1
	I6	Digital environmental management	2	2	2	1
	I7	Institutional coordination	2	2	2	1
Enforcement Capacity (E1–E7)	E1	Mandatory continuous emission monitoring (CEMS)	2	2	2	1
	E2	Performance testing	2	2	2	1
	E3	Regulatory inspection programme	2	2	2	1
	E4	Independent verification	2	2	1	0
	E5	Administrative sanctions	2	2	2	2
	E6	Operational suspension authority	2	2	2	1
	E7	Mandatory corrective actions	2	2	2	1

Coding score: 0 Absent; 1 Partially implemented or limited; 2 Comprehensively implemented

Figure 2

Heatmap of the raw regulatory coding scores for the 21 Harmonization Index indicators across the European Union, the United States, China, and Uzbekistan.

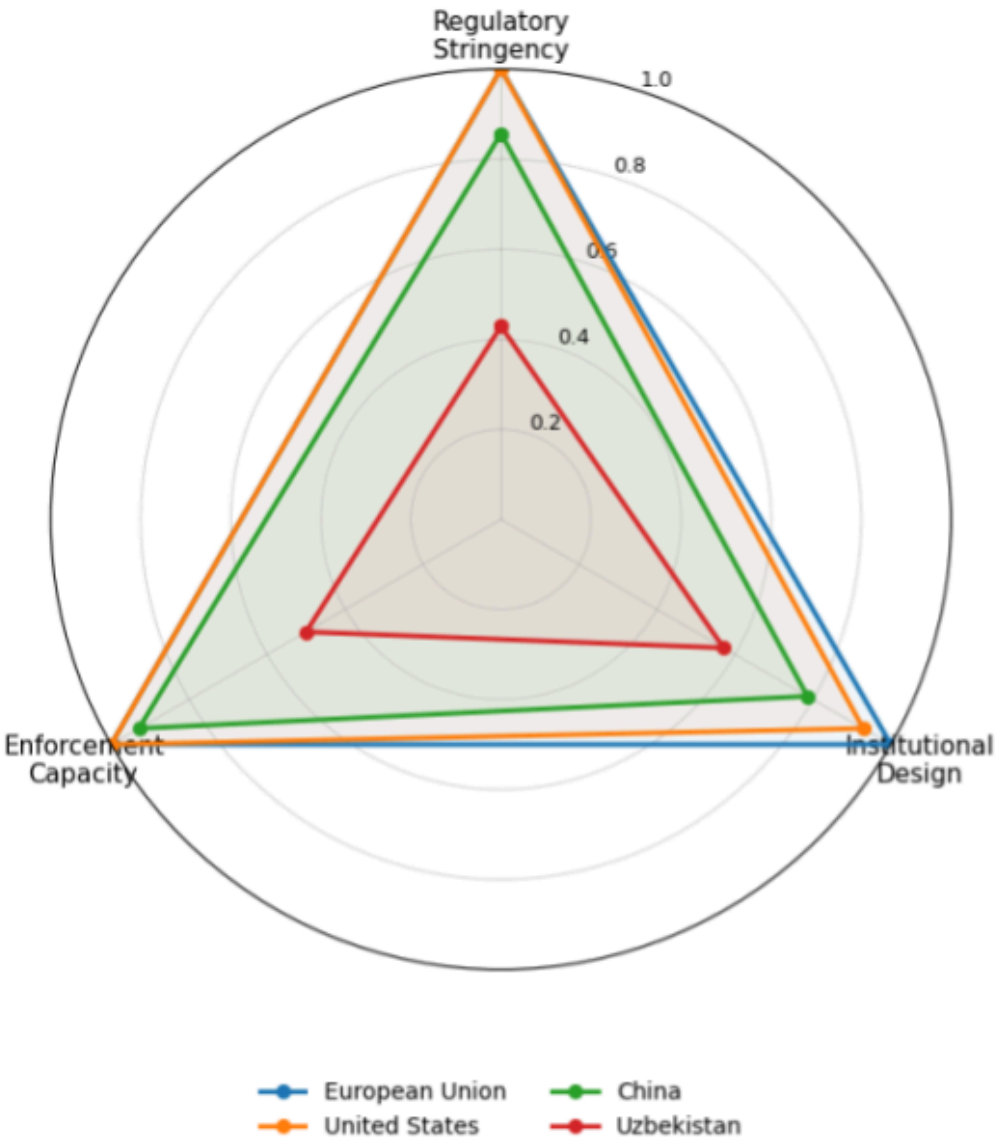


Figure 3

Radar-chart comparison of Regulatory Stringency, Institutional Design, and Enforcement Capacity scores across the European Union, the United States, China, and Uzbekistan.

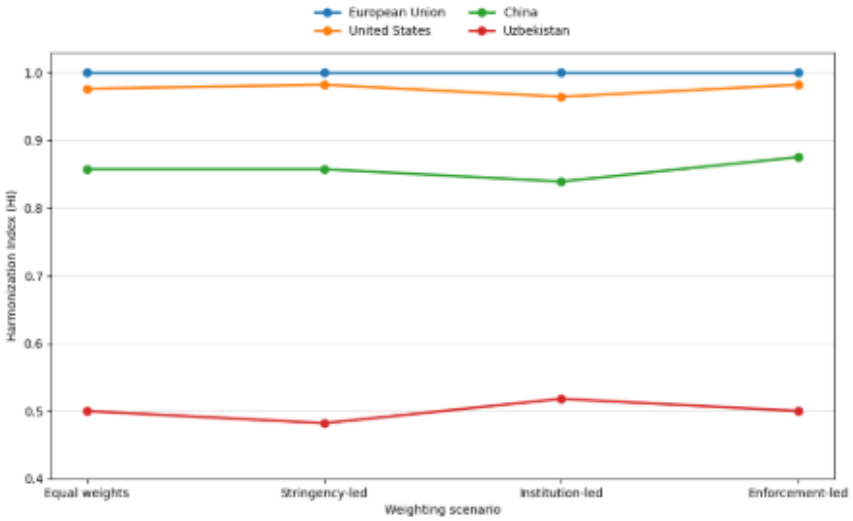


Figure 4

Sensitivity of jurisdictional Harmonization Index values to alternative dimension-weighting scenarios.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryTableS1.docx
- SupplementaryTableS2.docx
- SupplementaryTableS3.docx
- SupplementaryTableS4.docx