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Environmental Impact of Produced Water: A Comparative Review of Regulatory Frameworks and Ecotoxicological Assessment

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Abstract. Petroleum processing generates significant volumes of 'produced water' during extraction. Due to its complex composition, this effluent poses substantial environmental, technical, and economic risks when discharged. Evaluating the contamination potential through ecotoxicological assessments is therefore essential for sustainable management. This study provides a comprehensive review and critical analysis of environmental regulations across various jurisdictions regarding the treatment, disposal, and ecotoxicological assessment of produced water. By synthesizing data on marine organisms from different trophic levels - typically algae (producers), crustaceans (primary consumers), and fish (secondary/tertiary consumers) - the research analyzes the effects of conventional and alternative reagents used in physicochemical treatment processes reported in the scientific and regulatory literature. A comparative analysis of Brazilian, American, and European standards reveals distinct regulatory philosophies. While Brazil emphasizes specific pollutant monitoring and toxicity, Europe focuses on achieving 'good water status' through best practices, and the USA integrates comprehensive toxicity assessments. Ultimately, a multispecies approach is identified as crucial for identifying toxicity patterns and variability in organism sensitivity, providing a robust framework for developing effective global regulations and mitigating ecosystem-wide impacts.

Key words. Produced Water; Environmental Regulations; Ecotoxicological Assessment; Toxicity Tests; Oil Industry.

1. Introduction

From its remote uses by ancient civilizations to its consolidation in the modern global economy, oil has become the most valuable energy source and the engine of energy development in contemporary society [1]. Currently, about 90% of the world's oil is consumed in energy generation, while the remaining 10% serves as raw material for various industries, supplying 60% of global industrial inputs [2].

Although it initially played a crucial role in public lighting, it was with subsequent technological development that the applications of oil and its derivatives multiplied, establishing the industry as a fundamental pillar for both energy generation and the supply of industrial inputs on a global scale [3],[4].

In its trajectory of constant growth, the oil industry faced its first major setback in 1973 with the crisis triggered by the oil embargo imposed by the Organization of Arab Petroleum Exporting Countries (OAPEC) in response to the Yom Kippur War [5].

This landmark event, by exposing the vulnerability of dependence on fossil fuels and the instability of oil supply, not only shook the global economy but also acted as a catalyst for the development and discussion of environmental issues, highlighting the finiteness of natural resources and the need for more sustainable development models.

The growing environmental awareness, driven in part by the impacts of the 1973 crisis, directed attention to the negative externalities of oil activity. This movement added to important warnings already raised in the 1960s, such as the publication of Rachel Carson's "Silent Spring," which exposed the dangers of pesticides and, more broadly, the fragility of ecosystems in the face of industrial pollution [6].

Among these externalities, the management of produced water emerges as a significant challenge. This effluent, generated in large volumes during oil and gas extraction, carries a complex mixture of components that demand adequate treatment and disposal, under penalty of causing serious damage to aquatic and terrestrial ecosystems. The search for sustainable solutions for the management of produced water has therefore become a crucial point in the evolution of the industry, reflecting the increasing pressure for more responsible practices aligned with environmental preservation.

Faced with the growing environmental concern driven by the externalities of the oil industry, the management of produced water emerges as a critical challenge due to its complex composition and potential ecotoxicity. In this context, it becomes crucial to comparatively analyse the different regulatory approaches and guidelines adopted in important oil industry hubs, such as Brazil, Europe, and the United States, with regard to the assessment and control of the ecotoxicity of this effluent.

2. Petroleum Processing

Oil processing is carried out in two stages: primary processing, done at the extraction stage, and secondary processing, done at the refinery. Only primary treatment will be addressed, as it is at this stage that produced water is obtained.

A. Primary Processing

In addition to the oil and gas phases, an oil field typically produces water after a certain period of operation, either because it is initially present in the reservoir or due to its injection in a process aimed at increasing oil recovery. This water is called production water or produced water.

Figure 1 shows a schematic with the main steps of the primary processing that occurs in the oil-producing region, in offshore facilities (at sea). The entire oil production system begins at the wellhead, through equipment consisting of a set of valves called a Christmas tree, whose purpose is to control the production of fluids. When two or more wells are aligned for the same surface facility, the use of equipment known as a production manifold is indicated. This manifold gathers all the fluids and equalizes the feed pressure of the primary processing facility [3].

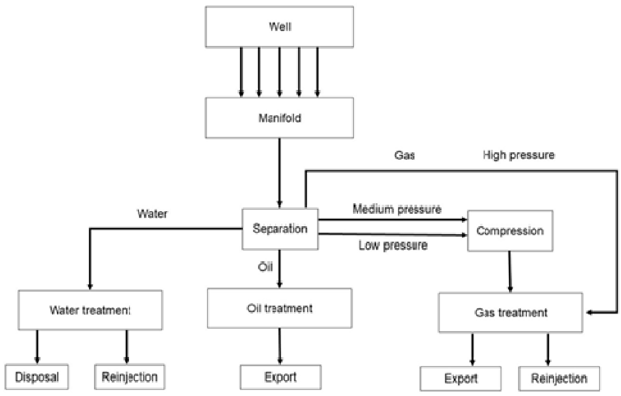

Fig.1. Scheme of the main stages of primary processing, adapted according to [3]

Primary processing allows the oil to meet the specifications required by refining, which are:

a) A minimum of lighter components (the gases);

b) A salt content below 300 mg/L of oil;

c) A water and sediment content below 1% (of the oil volume).

B. Produced Water

Produced Water (PW), also called Production Water, whose composition is shown in Figure 2, is the water generated as a byproduct of oil and gas production and includes:

d) Formation water: consists of seawater or freshwater that remained trapped for millions of years along with oil and natural gas within a geological reservoir. It is brought to the surface together with oil and gas during the production activities of these fluids;

e) Injection water: corresponds to water that was previously injected to pressurize the reservoir and thus enhance oil and gas recovery;

f) Various chemicals added during the oil and water production and separation processes.

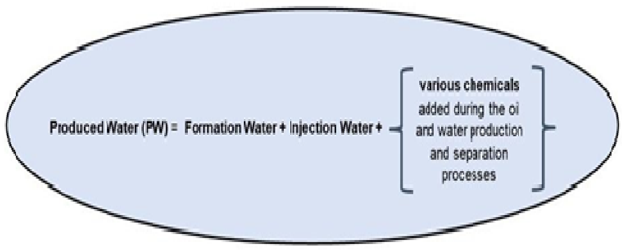

Fig.2. Composition of Produced Water

Produced Water can constitute 2% to 98% of the gross fluid production in a well. In the initial phase of well exploration, the volume of water is relatively small, but over time, the amount of produced water exceeds the production of hydrocarbons.

Globally, it is estimated that the generation of produced water results in a water-oil ratio of 3:1 (average value), while in Brazil this ratio is on average less than 1 [7],[8]. When oil is accompanied by large quantities of water, the field is considered mature because its production is declining as a consequence of the advanced stage of its productive life. In this case, the well must employ more advanced recovery techniques aimed at conserving production or even reversing its decline. Thus, the volume of this effluent generally increases over time. Depending on the useful life of the well, that is, in mature fields, the amount of water can reach up to 10 times that of the oil produced.

In both onshore and offshore activities, the volume of this effluent can be very large, being considered the largest waste generated by the oil industry.

3. Ecotoxicology

Ecotoxicology is dedicated to the study of the ways in which the environment is contaminated by pollutants, whether natural or synthetic, originating from human activities. Its central objective is to understand the mechanisms of action of these pollutants and their effects on the set of living beings that inhabit the biosphere [9].

It becomes evident, therefore, that ecotoxicology investigates the effects of pollutants on organisms and how these interact with their habitats. This perspective of ecotoxicology as the science that studies the effects of pollutants on organisms and their environmental interactions is also presented in the diagram as illustrated in Figure 3 [10].

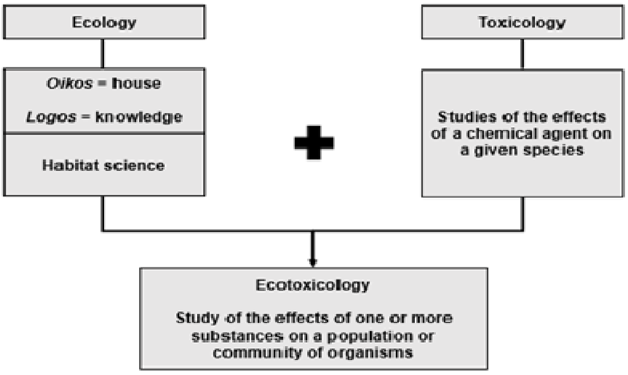

Fig.3. Conceptualization of Ecotoxicology, adapted according to [10]

A. Toxicity test

Formerly called bioassays or biological assays, toxicity tests aim to evaluate the effects caused to representative test species of the environment. In these tests, organisms are exposed to various concentrations of one or more substances, or to environmental factors, for a determined period of time. For a more complete assessment of a substance's toxicity, it is fundamental to conduct tests on diverse organisms, encompassing different trophic levels. This approach allows for the identification of toxic effects at different levels of organization, from individual organisms to communities and ecosystems. By comparing the responses of distinct organisms, it is possible to identify patterns of toxicity and the natural variability of organism sensitivity [11].

This multispecies and multidisciplinary approach provides a more robust understanding of environmental risks and the substance's impacts on the ecosystem as a whole. Several authors in the literature suggest the use of at least three species: an alga, representing the producers; a crustacean, representing the primary and/or secondary consumers; and a fish, representing the consumers and/or tertiary consumers [12]. Depending on the chemical composition, some effluents are toxic only to fish, others only to crustaceans (primary consumer), and others to both organisms. Algae (producer organisms), for example, can be more sensitive than the other tested species [13].

In the description of the deleterious effects of a toxic agent, the terms "acute effect" and "chronic effect" are used. The
parameters presented below, LC_{50} and EC_{50}, are used to describe acute effects, while the parameters NOEC and LOEC are used for chronic effects. These parameters are frequently used in ecotoxicology and are normalized according to the environment in which the organisms are exposed.

B. Acute Toxicity Assay

The acute effect represents a rapid and severe response of aquatic organisms to a stimulus, generally manifesting within a period of up to 96 hours. Lethality is the most common effect, but it can be preceded by other manifestations, such as the immobility observed in some microcrustaceans.

To evaluate the acute effects of toxic agents in toxicity tests, the Lethal Concentration (LC_{50}) or the Effective Concentration (EC_{50}) are frequently used, both referring to the concentration that affects 50% of the tested organisms. This response is considered the most significant for extrapolation to a population [14].

Specifically, the Lethal Concentration (LC_{50}) indicates the nominal concentration of the sample capable of causing mortality in 50% of the organisms during the exposure period and under the test conditions. In turn, the Effective Concentration (EC_{50}) refers to the nominal concentration of the sample that induces an acute effect, such as immobility, in 50% of the organisms under the same conditions.

C. Chronic Toxicity Assay

The chronic effect manifests as a response to prolonged exposure, generally extending for part or the entirety of the organisms' life cycle. Unlike acute effects, chronic consequences develop over time, reflecting continuous exposure to a particular agent.

These effects are predominantly sublethal and occur in situations where the concentrations of the toxic agent allow the organism's survival, although they compromise one or more of its biological functions. Among the affected functions, reproduction, egg development, growth, and maturation stand out. The evaluation of these effects is carried out through chronic toxicity tests, in which the No Observed Effect Concentration (NOEC) and the Lowest Observed Effect Concentration (LOEC) are determined [14].

The No Observed Effect Concentration (NOEC) represents the highest concentration of a toxic agent that does not induce statistically significant deleterious effects in the organisms during the exposure period and under the test conditions. In contrast, the Lowest Observed Effect Concentration (LOEC) corresponds to the lowest concentration of the toxic agent capable of causing statistically significant deleterious effects in the organisms under the same time and exposure conditions.

4. Regulations and Regulatory Overview

The following examines the environmental legislations that regulate the ecotoxicological aspects of produced water in the oil industry in Brazil, Europe, and the USA. The approaches of each region to the treatment and disposal of this effluent will be presented, highlighting the similarities, differences, and challenges for environmentally effective management.

A. Brazil

In Brazil, the Conselho Nacional do Meio Ambiente (CONAMA) its activities in 1981 with the promulgation of Law No. 6,938, which established the National Environmental Policy. This law represented a fundamental milestone in the institutionalization of the environmental issue in Brazil, recognizing the need for a collegiate body to deliberate on the guidelines and standards related to the environment. CONAMA emerged as the highest instance of the Sistema Nacional do Meio Ambiente (SISNAMA), with the responsibility of formulating and approving environmental resolutions, norms, and standards at the national level. Its creation reflected a growing concern with environmental degradation and the search for more effective management mechanisms.

CONAMA Resolutions No. 357/2005, No. 393/2007, and No. 430/2011 form an essential regulatory framework for the environmental management of the oil industry in Brazil, focusing on produced water and the assessment of its toxicity, as well as the conditions and standards for effluent discharge.

CONAMA Resolution No. 357/2005 establishes the classification of water bodies and the conditions and standards for the discharge of effluents in general. Crucially, in its Article 34, it determines that the discharge of effluents must observe standards, including the performance of toxicity tests defined by the competent environmental agency. This legal provision establishes the fundamental principle of the need to assess the potential toxic effects of any effluent discharged into water bodies [15].

CONAMA Resolution No. 393/2007, in turn, is more specific to the oil industry, regulating the continuous discharge of process or production water from offshore platforms. In Article 3, saline waters in the area where offshore platforms are located, while there is no specific classification, will be considered Class 1 Saline Waters, according to the definition in CONAMA Resolution No. 357, of March 17, 2005. This resolution also, in Article 10, sets limits for the discharge of oils and greases and requires regular monitoring of various physicochemical parameters in produced water, such as heavy metals, BTEX, phenols, and chronic toxicity of produced water determined through a standardized ecotoxicological method with marine organisms. Although it does not detail the toxicity test methods to be applied, it falls within the context of Article 18 of Resolution No. 357/2005, which defines the quality standards for Class 1 Saline Waters, specifically requiring the absence of chronic toxic effects as verified by standardized ecotoxicological assays [16].

CONAMA Resolution No. 430/2011 provides for the conditions and standards for the discharge of effluents, complementing and amending Resolution No. 357, of March 17, 2005. In its Article 18, the resolution establishes that the effluent must not cause or have the potential to cause toxic effects to aquatic organisms in the receiving water body, according to the ecotoxicity criteria established by the 1 competent environmental agency. This article reinforces the need for prior treatment of industrial effluents, including those from the oil industry, before their discharge, in accordance with the principles of environmental protection established by Resolutions No. 357/2005 and No. 393/2007 [17].

Therefore, these three resolutions complement each other. Resolution No. 357/2005 establishes the general guideline for the assessment of effluent toxicity, Resolution No. 393/2007 focuses on the specific characteristics of produced water from the oil industry, and Resolution No. 430/2011 reinforces the requirement for prior treatment before discharge. The environmental assessment of produced water, according to Resolution No. 393/2007, must therefore consider not only the concentration limits of chemical parameters but also the need to perform toxicity tests, as recommended by Resolution No. 357/2005, and the appropriate treatment before discharge, in accordance with Resolution No. 430/2011 and any complementary requirements of state environmental agencies, to ensure the protection of aquatic ecosystems.

B. Europe / European Union

In Europe, the management of produced water from the oil industry is primarily governed by the Water Framework Directive (2000/60/EC), which seeks to protect the quality of all waters and control industrial pollution. The European Environment Agency (EEA) plays a crucial role in providing data and assessments on the state of water in Europe, including pollution from industrial sources, supporting the implementation of this directive [18]. The Industrial Emissions Directive (2010/75/EU) also applies, requiring the Best Available Techniques (BAT) to minimize emissions, including those from the oil and gas sector, with the EEA monitoring the impacts of these emissions on the environment [19].

Toxicity tests, although not detailed in a specific directive for produced water, are influenced by the need to assess the risks of chemical substances, according to REACH (Regulation (EC) No 1907/2006), whose acronym stands for Registration, Evaluation, Authorisation and Restriction of Chemicals. The EEA uses the data generated by REACH to assess the impact of these substances on the aquatic environment, informing water quality-related policies. The objective of the Water Framework Directive to monitor hazardous substances also reinforces the importance of ecotoxicity tests, with the EEA providing information that supports this assessment [20].

For the offshore oil industry, the Offshore Oil and Gas Operations Safety Directive (2013/30/EU) focuses on safety and the prevention of marine pollution, which includes the proper management of produced water. The EEA monitors the environmental impacts of offshore oil and gas activities, providing data that can assist in evaluating the effectiveness of this directive [21]. The Environmental Impact Assessment Directive (2011/92/EU) concerning the assessment of the effects of certain public and private projects on the environment is applicable to oil and gas extraction projects, requiring the prior assessment of their environmental impacts, which would include the management of produced water [22].

The OSPAR Convention (Convention for the Protection of the Marine Environment of the North-East Atlantic) complements EU legislation in the North-East Atlantic region. The EEA collaborates with OSPAR, providing data and analysis on the marine environment, which informs the guidelines and best practices for the environmental management of the offshore industry, including produced water and the need for toxicity tests.

C. United States

In the United States, the management of produced water from the oil industry is strongly influenced by the Environmental Protection Agency (EPA). This federal agency is central to establishing regulations and guidelines to protect human health and the environment. The EPA administers crucial programs related to produced water, grounded in important federal laws.

The Clean Water Act (CWA), overseen by the EPA, establishes the framework to prevent and control water pollution. Although the direct discharge of produced water into continental surface waters is generally restricted, the National Pollutant Discharge Elimination System (NPDES), a program under the CWA, may issue permits for specific activities. For the offshore sector, these permits are based on the Critical Dilution Factor (CDF), which defines acceptable limits to ensure the effluent does not present toxicity at the discharge sites [23],[24].

Complementarily, the management of chemical substances used in the oil industry is governed by the Toxic Substances Control Act (TSCA) of 1976 [25]. This framework was significantly updated and strengthened by the Frank R. Lautenberg Chemical Safety for the 21st Century Act (LCSA) in 2016 [26]. Through this modern legislation, the EPA enhanced risk assessment criteria for persistent and bioaccumulative substances, allowing for stricter control over the chemical lifecycle of additives before they are even discharged as part of the produced water effluent.

The Safe Drinking Water Act (SDWA), also administered by the EPA, aims to protect drinking water sources. The Underground Injection Control (UIC) Program, established by the SDWA and implemented by the EPA and the states, regulates the underground injection of fluids, including produced water disposed of in disposal wells. The EPA sets the requirements for the construction, operation, and monitoring of these wells to prevent the contamination of aquifers [25].

Regarding toxicity testing, the EPA uses Whole Effluent Toxicity (WET) methods under the CWA to assess the toxic potential of effluents, including produced water, on aquatic organisms. These tests are crucial for determining discharge limits and evaluating the effectiveness of treatment processes. The EPA provides detailed guidelines on testing procedures.

For the offshore oil industry, the EPA has specific regulations to prevent marine pollution, covering the management of produced water. NPDES permits for offshore platforms establish discharge limits and treatment requirements. The EPA also requires environmental impact assessments for new offshore activities, including the management of produced water.

In addition to the federal role of the EPA, states have an important role in regulating produced water, establishing specific requirements and administering their own UIC and NPDES programs under the EPA's oversight.

5. Results and Discussion

The comparative analysis of environmental legislations for produced water in the oil industry in Brazil, Europe, and the United States reveals a fundamental concern shared regarding the presence of pollutants such as oils and greases and heavy metals, with Brazil also focusing on BTEX and phenols. However, the regulatory strategies to mitigate the risks associated with these pollutants and to assess the toxicity of produced water as a whole present important qualitative difference that extend beyond the monitored parameters.

In Brazil, CONAMA Resolution No. 393/2007, while specifying the monitoring of priority pollutants for offshore activity, also establishes guidelines for the treatment of produced water before disposal, often involving oil-water separation and solids removal processes. However, the apparent lower emphasis on systematic ecotoxicological testing may indicate a more focused approach on the chemical analysis of specific pollutants. Brazilian legislation also addresses disposal restrictions in sensitive areas, demonstrating a concern for the protection of vulnerable ecosystems [16].

CONAMA Resolution No. 357/2005 establishes the classification of water bodies and the conditions and standards for the discharge of effluents in general. In its Article 18, Class 1 saline waters must observe the following conditions and standards [15]:

I - Water quality conditions:

a) No verification of chronic toxic effects on organisms, according to the criteria established by the competent environmental agency, or, in its absence, by renowned national or international institutions, proven by the performance of a standardized ecotoxicological test or other scientifically recognized method;

b) Floating materials virtually absent;

c) Oils and greases: virtually absent;

d) Substances that produce odor and turbidity: virtually absent;

e) Dyes from anthropogenic sources: virtually absent;

f) Objectionable solid waste: virtually absent;

g) Thermotolerant coliforms: for primary contact recreation use, CONAMA Resolution No. 274, of 2000, must be observed. For other uses, a limit of 1000 thermotolerant coliforms per 100 millilitres should not be exceeded in 80% or more of at least 6 samples collected during a one-year period, with a bimonthly frequency. E. Coli may be determined as a substitute for the thermotolerant coliforms parameter according to limits established by the competent environmental agency;

h) Total organic carbon up to 3 mg/L, as C;

i) DO, in any sample, not less than 6 mg/L O_2; and

j) pH: 6.5 to 8.5, with no change in natural pH greater than 0.2 units.

Tables I presents a comparison between the parameters required in Brazil with Europe and the USA.

Table I. - Limits of TOC, DO, and pH

Parameter	**Brazil (CONAMA Resolution No. 357/2005)**	**Europe / European Union**	**United States**
Total Organic Carbon	Up to 3 mg/L (as C)	No directly comparable generic value. Concentrations in coastal waters vary but can be in the same order of magnitude in unpolluted areas.	No directly comparable generic value. Concentrations depend on water quality and pollution sources.
Dissolved Oxygen	Not less than 6 mg/L O□	Minimum limits for good ecological status generally in the same order of magnitude (e.g., ≥ 4 mg/L to protect marine life).	State minimum limits for aquatic life protection generally in the same order of magnitude (e.g., ≥ 4 mg/L).
pH	6.5 to 8.5 (variation < 0.2)	Range for good ecological status generally similar (e.g., 6.5 - 8.5). Concern about natural pH variation is also relevant.	State range for aquatic life protection generally similar (e.g., 6.5 - 8.5). Limits on pH variation are also considered to protect ecosystems.

In Europe (European Union), the pursuit of "good status" of waters under the Water Framework Directive drives the adoption of Best Available Techniques (BAT), which encompass not only the limitation of pollutants but also the optimization of processes to reduce effluent generation and its toxicity. There is a trend towards considering the reuse of produced water as a sustainable practice, although implementation may vary among Member States. Responsibility for pollution prevention and remediation is generally well-defined, aligned with the polluter-pays principle [18].

In the United States, the increasing incorporation of toxicity assessment by the EPA, complementing the concentration limits of the NPDES, reflects a recognition of the complexity of the effects of produced water on aquatic ecosystems. NPDES permits frequently specify treatment technologies to be implemented. The Underground Injection Control (UIC) Program regulates the common practice of reinjection of produced water, with requirements to protect underground aquifers. American legislation also establishes clear responsibilities for contamination and requires remediation actions.

In summary, the regulatory approaches demonstrate different priorities and mechanisms. Brazil focuses on the monitoring of specific pollutants, Europe seeks integrated management with a focus on "good status" of waters and best practices, and the United States combines concentration limits with an increasing emphasis on toxicity assessment and the control of reinjection. A more detailed analysis of treatment requirements, reuse practices, continuous monitoring, liability in case of contamination, and the influence of international agreements is necessary to further improve and enrich this qualitative comparison.

6. Conclusions

The trajectory of the oil industry, from an energy pillar to a focus of environmental concerns, highlights the increasing importance of produced water management. The comparative analysis of regulations in Brazil, Europe, and the USA reveals distinct approaches: Brazil with specific monitoring of pollutants and toxicity; Europe seeking "good status" of waters via best practices; and the USA integrating toxicity assessment.

These differences reflect the complexity of reconciling oil exploration with environmental protection, driven by increasing awareness of the impacts of pollution. The evolution of regulations points to a need to go beyond chemical analysis, considering ecotoxicological effects and seeking sustainable solutions such as reuse and advanced treatment technologies.

Ultimately, the effectiveness of environmental protection will depend on the robustness of enforcement, the clarity of responsibilities, and the encouragement of innovation. The continuous evolution of regulations, informed by science and best practices, will be crucial for an oil industry more aligned with environmental preservation. A more detailed analysis of treatment requirements, reuse practices, continuous monitoring, liability in case of contamination, and the influence of international agreements is necessary to further improve and enrich this qualitative comparison.

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