

COMPARATIVE REVIEW OF INTERNATIONAL WATER REUSE POLICIES FROM A RISK MANAGEMENT PERSPECTIVE

ÉTUDE COMPARATIVE DES POLITIQUES INTERNATIONALES DE RÉUTILISATION DE L'EAU DU POINT DE VUE DE LA GESTION DES RISQUES

Ignacio Gómez-Lucena¹, Nassim Ait-Mouheb², Emilio Camacho¹
and Juan Antonio Rodríguez-Díaz¹

ABSTRACT

Agricultural water reuse is increasingly promoted as a strategic response to water scarcity, population growth, and pressure on freshwater resources. Reclaimed wastewater for agricultural irrigation offers environmental, economic, and social benefits, including reduced abstraction from surface and groundwater bodies, improved drought resilience, and enhanced water security for agricultural production. However, agricultural water reuse also presents environmental and public health risks related to pathogen exposure, chemical contaminants, and long-term soil and ecosystem impacts. Managing these risks requires regulatory frameworks adapted to different socio-economic conditions in order to balance safety objectives with technical and economic feasibility.

As agricultural water reuse policies have expanded globally, regulatory approaches to risk management have evolved differently across countries. These differences reflect variations in water scarcity, institutional capacity, and economic development. Consequently, substantial diversity exists worldwide in treatment requirements, water quality standards, monitoring obligations, and restrictions on reuse practices. Understanding how underlying risk management paradigms shape regulatory design is therefore essential for evaluating the effectiveness and practicality of water reuse policies.

This review compares recent versions of nine internationally influential agricultural water reuse policies, including guidelines, standards, and regulations from organizations and jurisdictions such as the WHO, FAO, US EPA, ISO, the European Union, Jordan, Israel, and California. It examines how regulatory structures are shaped by hazard-based, risk-based, and hybrid approaches. Hazard-based frameworks rely on fixed treatment and quality thresholds, whereas risk-based approaches emphasize site-specific exposure assessment and multiple-barrier strategies. Hybrid frameworks combine baseline quality standards with flexible, risk-informed management measures.

The analysis shows that regulatory outcomes are shaped not only by scientific evidence, but also by prevailing risk management philosophies and socio-economic realities. Recent policies demonstrate a gradual convergence toward hybrid regulatory frameworks that seek to balance safety goals with practical implementation and local feasibility.

Keywords: Agricultural water reuse; Technical and economic feasibility; Water quality standards; Regulatory outcomes; Multiple-barrier strategies.

RÉSUMÉ

La réutilisation de l'eau agricole est de plus en plus encouragée comme réponse stratégique à la pénurie d'eau, à la croissance démographique et à la pression exercée sur les ressources en eau douce. L'utilisation d'eaux usées traitées pour l'irrigation agricole offre des avantages environnementaux, économiques et sociaux, notamment une réduction des prélèvements dans les eaux de surface et

¹ Department of Agronomy, Universidad de Córdoba, Campus de Rabanales, Spain Email: igomezlucena@uco.es

² UMR G-EAU, INRAE, University of Montpellier, France Email: nassim.ait-mouheb@inrae.fr

souterraines, une meilleure résilience face à la sécheresse et une sécurité hydrique renforcée pour la production agricole. Cependant, la réutilisation de l'eau agricole présente également des risques pour l'environnement et la santé publique liés à l'exposition aux agents pathogènes, aux contaminants chimiques et aux impacts à long terme sur les sols et les écosystèmes. La gestion de ces risques nécessite des cadres réglementaires adaptés aux différentes conditions socio-économiques afin de concilier les objectifs de sécurité avec la faisabilité technique et économique.

À mesure que les politiques de réutilisation de l'eau à des fins agricoles se sont développées à l'échelle mondiale, les approches réglementaires en matière de gestion des risques ont évolué différemment d'un pays à l'autre. Ces différences reflètent les variations en termes de pénurie d'eau, de capacités institutionnelles et de développement économique. Par conséquent, il existe une grande diversité à l'échelle mondiale en ce qui concerne les exigences de traitement, les normes de qualité de l'eau, les obligations de surveillance et les restrictions relatives aux pratiques de réutilisation. Il est donc essentiel de comprendre comment les paradigmes sous-jacents de gestion des risques façonnent la conception réglementaire pour évaluer l'efficacité et la faisabilité des politiques de réutilisation de l'eau.

Cette étude comparative examine les versions récentes de neuf politiques de réutilisation de l'eau à des fins agricoles ayant une influence internationale, notamment les lignes directrices, normes et réglementations émanant d'organisations et de juridictions telles que l'OMS, la FAO, l'EPA américaine, l'ISO, l'Union européenne, la Jordanie, Israël et la Californie. Elle examine comment les structures réglementaires sont façonnées par des approches fondées sur les dangers, sur les risques et hybrides. Les cadres fondés sur les aléas s'appuient sur des seuils fixes de traitement et de qualité, tandis que les approches fondées sur les risques mettent l'accent sur l'évaluation de l'exposition spécifique au site et sur des stratégies à barrières multiples. Les cadres hybrides combinent des normes de qualité de base avec des mesures de gestion flexibles et fondées sur les risques.

L'analyse montre que les résultats réglementaires sont façonnés non seulement par les preuves scientifiques, mais aussi par les philosophies dominantes en matière de gestion des risques et les réalités socio-économiques. Les politiques récentes témoignent d'une convergence progressive vers des cadres réglementaires hybrides qui cherchent à concilier les objectifs de sécurité avec la mise en œuvre pratique et la faisabilité locale.

Mots-clés : Réutilisation de l'eau agricole; Faisabilité technique et économique; Normes de qualité de l'eau; Résultats réglementaires; Stratégies à barrières multiples.

1. INTRODUCTION

Current water scarcity and the forecasted climate change scenarios are progressively driving the adoption of water reuse practices worldwide (UNESCO, 2017; United Nations, 2023a; Winpenny et al., 2010). Accounting for 70% of global freshwater consumption, agricultural irrigation also represents the largest application of wastewater (WW) reuse. It is estimated that 36 million hectares worldwide are irrigated with some kind of WW, however, only 15% of this WW is properly treated under formal, planned reuse schemes, where the quality and the volume of reclaimed WW (RWW) are typically monitored (Ait-Mouheb et al., 2020; Jones et al., 2021).

2. POLICY FRAMEWORK FOR AGRICULTURAL WATER REUSE

Despite conveying multiple benefits (stable supply, climate-resilience resource, nutrient recycling, circular economy), agricultural WW reuse conveys potential risks that should be properly managed to protect both human and environmental health. Therefore, since the early 20th century, governments and international institutions have developed numerous regulations to establish a legal framework for WW reuse and mitigate its associated risks.

When dealing with policies on irrigation with RWW, a clear distinction between the terms 'hazard' and 'risk' should be made. These two interrelated concepts are often used interchangeably despite conveying different meanings. According to the European Food Safety Agency (2016), a hazard is any

physical, chemical or biological agent that has the potential to harm people, whereas risk refers to the likelihood of any identified hazard causing harm in a specified timeframe, including the severity of the consequences. The way policies address reuse-related risks (i.e., the risk management approach) is what primarily characterizes them. There are two main contrasting philosophies on risk management: the 'risk-based' and the 'hazard-based' approach (Barlow et al., 2015) (Table 1).

Table 1. Main features of hazard-based and risk-based policies (adapted from Barlow et al., 2015)

Hazard-based approach	Risk-based approach
The presence of a potentially harmful agent is used as a basis for legislation.	Policies are based on health-performance targets (e.g., Disability-Adjusted Life Years, number of infections per year).
Prescriptive standards (treatment specifications, quality thresholds, monitoring requirements). Treatment-driven safety.	Based on human exposure to identified hazards and dose-response models. Includes uncertainty.
Fixed requirements for RWW quality.	More flexible requirements for RWW quality.
Low pathogen concentration in RWW (even absence) (e.g., total coliform bacteria < 2.2 MPN ³ /100 mL).	Higher pathogen concentration in RWW (e.g., <i>E. coli</i> < 1000 CFU ⁴ /100 mL).
Unrestricted irrigation; wider range of allowed purposes.	Restricted irrigation (need of multiple barriers); low-exposure uses are encouraged.
Binary logic for RWW quality (i.e., RWW is either suitable or not for a given purpose).	The use of RWW is adapted based on its quality and the implementation of barriers.
Need for intensive treatment and appropriate technology (e.g., UV disinfection).	Extensive treatments are valid for treating WW (e.g., constructed wetlands, stabilization ponds).
Low stakeholder involvement. The water utility (usually the WWTP) is responsible for mitigating risks through treatment and monitoring.	High stakeholder involvement. Risk is managed throughout all actors involved in the RWW value chain (i.e., WWTP operators, farmers, consumers). Shared liability.
High-quality RWW reduces consumer's reluctance to food products.	Consumer may feel reluctant to eat products irrigated with RWW due to disgust biases ('yuck factor').
Policies are easier to regulate and enforce through end-of-pipe quality verification. Compliance is checked at a single point (WWTP outlet).	More difficult to verify compliance due to high stakeholder involvement and reliance on multiple, independent barriers.
Example: California Water Recycling Criteria (2000).	Example: WHO guidelines for the safe use of wastewater, excreta and greywater (2006).

Table 1 summarizes the main features of the two contrasting risk management paradigms shaping agricultural reuse policies. The hazard-based framework prioritizes public health protection by reducing or even eliminating pathogens and other contaminants directly at the source through fixed, prescriptive standards, including specific compulsory treatment and rigid quality thresholds. Operating under a binary pass/fail logic, these policies consider irrigation with RWW safe as long as the effluent complies with the quality standards. For this reason, these policies are generally considered risk-averse, due to their treatment-driven safety. In contrast, the risk-based approach seeks to balance safety and technical and economic feasibility by assessing and managing human exposure pathways along the entire RWW chain. Risk-based policies are based on specific health-performance targets, and implement the 'fit-for-

3 Most Probable NumberForming Units

4 Colony Forming Units

purpose' and the 'multi-barrier' concepts not to rely solely on water quality improvement via treatment (WHO, 2006). The ultimate objective of risk-based policies is to determine whether residual risks are tolerable or if further mitigation measures are required (Barlow et al., 2015). As will be discussed in the following sections, both regulatory approaches show strengths and drawbacks.

Policy reviews

Over the past decade, numerous comparative analyses have evaluated the effectiveness of global wastewater reuse policies (Berbel et al., 2023; McLennan et al., 2024; Shoushtarian & Negahban-Azar, 2020; Zhao et al., 2022). However, most existing reviews remain geographically constrained to single nations or specific continents (Goyal & Kumar, 2022; Paranychianakis et al., 2015). International-level studies often focus strictly on threshold comparisons, without analyzing crucial dimensions such as risk management, implementation feasibility, and field compliance. To date, no study has systematically examined international agricultural water reuse policies from an explicit risk management perspective. This paper addresses this gap by conducting a comprehensive, up-to-date comparative analysis of nine highly influential regulatory instruments, evaluating how their structural design is shaped by their underlying risk management philosophies.

3. METHODS

Selection of regulatory frameworks

Nine policies on agricultural water reuse were selected for performing the comparative analysis based on international relevance, regulatory maturity, paradigm representation, and geographical/economic diversity. The selection includes guidelines, national and international standards, and binding regulations:

- WHO Guidelines (2006): Guidelines for the Safe Use of Wastewater, Excreta and Greywater. Landmark risk-based model.
- FAO Guidelines (1992): Irrigation and Drainage Paper No. 47 (Pescod, 1992). Focus on agronomic feasibility and field management.
- AGWR (2006): Australian Guidelines for Water Recycling. Advanced risk-based paradigm with health targets.
- EPA Guidelines (2012): U.S. Environmental Protection Agency Guidelines for Water Reuse. Highly influential technical reference.
- ISO 16075 (2020-2025): Guidelines for treated wastewater use for irrigation projects. Comprehensive international standard.
- JS 893/2021: Jordanian Standard for treated wastewater, representing strict binding limits in hyper-arid regions.
- CWRC (2000): California Water Recycling Criteria (Title 22). The pioneer and archetype of hazard-based, prescriptive regulations.
- Israel 5770-2010: Effluent quality standards and rules for sewage treatment. Integrated mandatory water recycling framework.
- EU 2020/741: Regulation on minimum requirements for water reuse. A hybrid model establishing rigid classes but requiring risk management plans.

Analytical framework and comparative procedure

A comparative policy analysis was conducted in three stages: (1) Categorization: classifying each policy into hazard-based, risk-based, or hybrid paradigms based on compliance locations and barrier reliance;

(2) Comparative Analysis: systematically evaluating quality categories, treatment mandates, microbiological thresholds, physical-chemical thresholds, and monitoring frequencies; and (3) Contextual Synthesis: contrasting technical data with socio-economic and environmental parameters like infrastructure capacity and water scarcity.

4. RESULTS

Classification of regulatory frameworks

The comparative analysis shows that while all frameworks share the core structure of defining distinct water quality categories adapted to specific crop types and irrigation methods, their underlying philosophies differ significantly. For instance, JS 893/2021 is classified as hazard-based due to its strict binding nature and fixed end-of-pipe thresholds, yet it lacks specific prescriptive treatment requirements. Conversely, risk-based models like the WHO guidelines emphasize flexible, multi-barrier field strategies rather than advanced engineering controls.

Table 2. Comparison of the selected reuse policies

Framework	Dominant paradigm		Treatment intensity	Key strengths	Main limitations
WHO Guidelines	Risk-based	Multi-barrier and health-based targets	Flexible	Adaptable and affordable	Difficult enforcement
FAO Guidelines	Risk-based	Agronomic and environmental protection	Flexible	Practical for developing regions	Weak microbiological control
Australian Guidelines	Risk-based	Preventive risk management through health-based targets and validation monitoring	Moderate	Comprehensive risk assessment framework	High technical and organizational complexity
EPA Guidelines	Hybrid	Treatment reliability combined with risk management	High	Strong technical guidance and operational robustness	High infrastructure and monitoring costs
ISO 16075	Hybrid	Flexible risk management	Moderate	International applicability	Non-binding nature
EU 2020/741	Hybrid	Minimum standards + risk management plans	Moderate–high	Balance between safety and flexibility	Administrative complexity
California Water Recycling Criteria	Hazard-based	Treatment-driven safety	Very high	Strong public health protection	High operational cost
Israel standards 5770-2010	Hazard-based	Integrated national reuse planning	High	Very high reuse rates	Infrastructure-dependent
Jordanian Standard 893/2021	Hazard-based	Conservative public health protection	High	Clear enforceability	Limited flexibility

Comparison of regulatory requirements

Treatment requirements and microbiological quality

Quality requirements typically rely on Fecal Indicator Bacteria (FIB)—such as *E. coli*, thermotolerant coliforms, or total coliforms—and intestinal nematodes, since monitoring specific pathogens directly is too costly and complex. *E. coli* serves as the benchmark FIB in most of modern frameworks.

Discrepancies for high-risk uses (e.g., irrigation of crops consumed raw) are stark: risk-based models (WHO, FAO) allow up to 1,000 units/100 mL by assuming field barriers will attenuate exposure, whereas

hazard-based frameworks (CWRC, EPA, JS 893/2021) demand near-complete absence, mandating advanced secondary filtration and intensive disinfection (e.g., UV or chlorine). For intestinal nematodes, there is a strong consensus among frameworks that include them (WHO, FAO, ISO, JS, EU) on a strict threshold of ≤ 1 egg/L to control helminth infections, which are prevalent in tropical countries where WW is poorly treated and widely used for agricultural irrigation.

Physical-chemical quality of RWW

Organic load (BOD₅), Total Suspended Solids (TSS), and turbidity represent the standard physical-chemical parameters. WHO guidelines omit physical-chemical monitoring completely, focusing entirely on microbiology. Integrated frameworks that rule WW treatment and reuse like Israel 5770-2010 and JS 893/2021 monitor extensive parameters (36 and 39 respectively), tracking Chemical Oxygen Demand (COD), heavy metals, and nutrients. Agronomic-environmental safeguards such as Electrical Conductivity (EC) and Sodium Adsorption Ratio (SAR), which are essential for soil stability and crop yield protection, are notably ignored by most policies, appearing exclusively in FAO guidelines, JS 893/2021, and Israel 5770-2010.

Monitoring requirements

Monitoring protocols vary from comprehensive structures in AGWR (baseline, validation, operational, and verification monitoring) to strict routine frequencies in EPA and CWRC (mandating daily FIB testing). Frameworks enforcing advanced disinfection typically link microbial compliance with continuous operational monitoring of turbidity and residual chlorine. In contrast, hazard-based models like JS 893/2021 enforce rigid monitoring frequencies uniformly across all RWW categories, failing to reduce burdens for lower-risk applications.

5. DISCUSSION

Convergence toward hybrid models

Recent frameworks, such as Regulation (EU) 2020/741 and the ISO 16075 standards, reflect an emerging global transition toward hybrid governance models that combine prescriptive minimum quality requirements with flexible risk management principles. These hybrid approaches aim to bridge the gap between contrasting regulatory philosophies by strategically capitalizing on the strengths of each. From hazard-based paradigms, they incorporate strict safety benchmarks and mandatory quality monitoring, which are essential for maintaining clear enforceability and increasing public trust in water reuse schemes. Simultaneously, they integrate the core tenets of risk-based frameworks by assessing real-world exposure pathways through "fit-for-purpose" and "multi-barrier" philosophies.

This integration is key to reconciling rigorous sanitary safety with economic viability and operational practicality, as it avoids relying exclusively on energy-intensive water quality improvements at the treatment plant level. Ultimately, these recent policies demonstrate that the most viable pathway for modern water governance lies in hybrid frameworks that establish multiple, distinct quality classes. This structural design provides clear, legally enforceable thresholds while maintaining the site-specific flexibility necessary to make agricultural water reuse both economically feasible and safe.

Economic considerations

While risk-based approaches appear cheaper on paper by avoiding capital-intensive treatments, they generate substantial administrative burdens. Developing a Risk Management Plan (as mandated by EU 2020/741) demands specialized expertise to model exposure pathways and dose-response dynamics. Logistically, centralized hazard-based models verify compliance at a single point (WWTP outlet), whereas risk-based multi-barrier models require field inspectors to verify distributed farming practices across hundreds of decentralized agricultural plots, making field enforcement exceptionally resource-intensive. Furthermore, rigid 'one-size-fits-all' limits disproportionately penalize small WWTPs (< 5,000

population equivalents), where compliance and sampling costs (ranging from 6,000 € to 18,000 €/year for Class A in the EU) lack the benefit of economies of scale, rendering reuse economically unfeasible.

Limitations of the ‘fit-for-purpose’ and ‘multi-barrier’ approaches

The practical deployment of fit-for-purpose irrigation faces a major operational constraint: it requires homogeneous crop landscapes. Real agricultural schemes typically consist of seasonal crop mosaics. Consequently, water utilities are forced to treat water to meet the most stringent required category at all times, losing the economic and technical advantages of the fit-for-purpose approach. Similarly, monitoring the implementation of multiple independent barriers at field level introduces high organizational costs that may offset treatment savings.

Governance challenges

Water reuse regulations do not operate isolated; since they interact closely with other policies that rule other aspects of the water cycle (e.g., sanitation). In the EU, Regulation 2020/741 is heavily influenced by Urban Wastewater Treatment Directive 2024/3019. The mandatory tightening of baseline effluent standards (extending tertiary and quaternary treatment across municipal plants) is expected to minimize additional reclamation costs, internalizing the reclamation costs in the urban water cycle. Alternatively, integrated approaches in hyper-arid countries like Israel and Jordan merge sanitation and reuse standards under a single instrument, achieving extreme recycling rates (~90% of treated effluents) by streamlining bureaucratic and physical infrastructure. This highlights that separate regulations increase environmental safety but can inadvertently create administrative friction that dampens agricultural adoption.

6. CONCLUSION

Agricultural water reuse is becoming an essential strategy for improving water security and adapting agriculture to climate change in water-scarce regions. However, the success of reuse programs depends largely on the regulatory frameworks governing RWW use. This comparative review demonstrates that reuse regulations are strongly shaped by their underlying risk management paradigm. Hazard-based frameworks prioritize treatment-driven safety through strict standards and centralized monitoring, whereas risk-based approaches focus on reducing exposure through fit-for-purpose and multi-barrier strategies. Both paradigms present important advantages and limitations regarding safety, enforceability, governance complexity, and economic feasibility. Recent regulations reflect a growing transition toward hybrid models that combine minimum quality requirements with flexible risk management tools. These frameworks seek to reconcile public health protection with operational practicality and economic viability. Future reuse policies should avoid excessively rigid approaches that may compromise the affordability and scalability of RWW projects. At the same time, fully decentralized risk-based systems may become administratively difficult to implement and enforce. Consequently, balanced hybrid frameworks appear to represent the most realistic pathway for expanding safe and sustainable agricultural water reuse. Ultimately, RWW should not be viewed solely as a threat to be managed, but as a strategic and reliable water resource capable of supporting agricultural resilience under increasing water scarcity and climate change pressures.

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