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PRÓ-REITORIA DE PESQUISA E PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO EM MANEJO DE SOLO E ÁGUA
DOUTORADO EM MANEJO DE SOLO E ÁGUA

CYDIANNE CAVALCANTE DA SILVA BATISTA

PRODUCED WATER FROM PETROLEUM FOR IRRIGATION USE: LITERATURE REVIEW AND POTENTIAL FOR ENERGY CROPS

MOSSORÓ
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Tese apresentada ao Programa de Pós-Graduação em Manejo de Solo e Água da Universidade Federal Rural do Semi-Árido como requisito para obtenção do título de Doutora em Manejo de Solo e Água.

Linha de Pesquisa: Tratamento e uso de resíduos e seus impactos no solo e na água.

Orientador: Prof. Dr. Daniel Valadão Silva.

Coorientador: Prof. Dr. Frederico Ribeiro do Carmo.

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GENERAL SUMMARY

Water scarcity in semi-arid regions, coupled with the global shift toward low-carbon policies, has intensified interest in unconventional water sources for agricultural use. Among these, produced water (PW) from the oil industry emerges as a promising yet underutilized resource in Brazil, constrained by technical, environmental, and regulatory challenges. This study aimed to assess the potential of PW as a sustainable alternative for irrigating bioenergy crops through an integrated approach combining comprehensive literature analysis and experimental evaluation. Chapter I presents a bibliometric assessment of wastewater reuse in agriculture, revealing a recent surge in scientific publications predominantly concentrated in the Middle East and North America. The analysis also highlights critical gaps in Brazilian legislation, the standardization of treatment technologies, and environmental monitoring, as well as the urgent need for further research on energy crops adapted to saline conditions. Chapter II delves into the technical and scientific discussion of the chemical composition of produced water (PW), the challenges of its management in Brazil, and the potential for reuse in irrigation. It also highlights that PW treatment technologies have been tested with positive results, and its agricultural reuse can promote synergies between the energy and agriculture sectors, contributing to the Sustainable Development Goals (SDGs). Chapter III reports the results of a greenhouse experiment with three bioenergy species—sorghum, elephant grass, and cotton—irrigated with PW dilutions. Soil physicochemical parameters and plant biometric variables were evaluated. The results indicated that PW irrigation increased soil salinity and sodium concentrations, especially at higher effluent concentrations. Despite this, sorghum and elephant grass showed good vegetative performance under moderate dilutions, indicating greater salt tolerance compared to cotton. The use of PW in irrigation proved viable, provided appropriate salinity management practices are observed. The results of this work demonstrate that PW, when properly treated and managed, can be strategically incorporated into irrigated agriculture, contributing to water resilience and productive sustainability in semiarid environments.

Keywords: Unconventional water resources; Energy crops; Resilient agriculture.

RESUMO GERAL

A escassez de água nas regiões semiáridas e o avanço das políticas voltadas à economia de baixo carbono têm incentivado o uso de fontes não convencionais de água para fins agrícolas. Dentre elas, a água produzida (AP) oriunda da indústria do petróleo destaca-se como um recurso promissor, embora ainda subutilizado no Brasil devido às barreiras técnicas, ambientais e normativas. Assim, objetivou-se com a presente pesquisa avaliar o potencial da AP como alternativa sustentável para irrigação de cultivos bioenergéticos, por meio de uma abordagem integrada entre revisão teórica e experimentação prática. O Capítulo I apresenta uma análise bibliométrica de conteúdo sobre o uso agrícola de águas residuárias. Foi observado um crescimento recente nas publicações científicas sobre o tema, concentrados majoritariamente em países do Oriente Médio e América do Norte. Identificaram-se lacunas na legislação brasileira, na padronização de métodos de tratamento e no monitoramento ambiental, além da necessidade de mais estudos com culturas energéticas adaptadas às condições de salinidade. O Capítulo II aprofunda a discussão técnico-científica sobre a composição química da AP, os desafios de sua gestão no Brasil e o potencial de reúso na irrigação. Também destacou que as tecnologias de tratamento de AP vêm sendo testadas com bons resultados e seu reaproveitamento agrícola pode promover sinergias entre os setores de energia e agricultura, contribuindo para os Objetivos do Desenvolvimento Sustentável (ODS). O Capítulo III relata os resultados de experimento em casa de vegetação com três espécies bioenergéticas — sorgo, capim-elefante e algodão — irrigadas com diluições de AP. Foram avaliados parâmetros físico-químicos do solo e variáveis biométricas das plantas. Os resultados indicaram que a irrigação com AP provocou aumento da salinidade e da concentração de sódio no solo, especialmente nas maiores concentrações do efluente. Apesar disso, sorgo e capim-elefante apresentaram bom desempenho vegetativo sob diluições moderadas, indicando maior tolerância aos sais em comparação ao algodão. O uso da AP na irrigação se mostrou viável, desde que observadas práticas adequadas de manejo da salinidade. Os resultados deste trabalho demonstram que a AP, quando adequadamente tratada e manejada, pode ser incorporada de forma estratégica à agricultura irrigada, contribuindo para a resiliência hídrica e a sustentabilidade produtiva em ambientes semiáridos.

Palavras-chave: Recursos hídricos não convencionais; Culturas energéticas; Agricultura resiliente.

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LIST OF ABBREVIATIONS AND ACRONYMS

WS	Water supply
ANOVA	Analysis of variance
ANP	National Petroleum, Natural Gas and Biofuels Agency
PW	Water produced
boe	Barrel of oil equivalent
PDA	Potato Dextrose Agar
BTEX	Volatile hydrocarbons (benzene, toluene, ethylbenzene and xylene)
CAERN	Water and Sewage Company of Rio Grande do Norte
CE	Ceará
CEi	Electrical conductivity
CEes	Electrical conductivity of soil saturation extract
CEa	Electrical conductivity of water
COEMA	State Environment Council
CONAMA	National Environmental Council
DBC	Randomized block design
EMBRAPA	Brazilian Agricultural Research Corporation
et al	And others
FAO	Food and Agriculture Organization
PAHs	Polycyclic aromatic hydrocarbons
GW	Gigawatt
SEMACE	State Environmental Superintendence
MMA	Ministry of the Environment
MAP	Monoammonium phosphate
OM	Organic matter
NA	Nutrient agar
NORMs	Naturally occurring radioactive materials
SDG	Sustainable Development Goals
PATEN	Energy Transition Acceleration Program
pH	Hydrogen potential
PNPB	National Program for the Production and Use of Biodiesel
ESP	Exchangeable sodium Percentage

Proalcohol	National Alcohol Program
PVC	Polyvinyl chloride
SAR	Sodium adsorption ratio
RN	Rio Grande do Norte
TDS	Total dissolved solids
EU	Experimental units
CFU	Colony forming units
UFC	Federal University of Ceará
UFERSA	Federal Rural University of the Semi-Arid

LIST OF SYMBOLS

Al^{+3}	Aluminum cation
Ag	Silver
As	Arsenic
B	Boron
Ba	Barium
Br	Bromide
Ca^{2+}	Calcium
$CaCl_2$	Calcium chloride
Cd	Cadmium
Co	Cobalt
Cr	Chromium
CEC	Cation exchange capacity
Cu	Copper
ºC	Degrees Celsius
Cl	Chlorine
cm	Centimeter
CO_2	Carbon dioxide
cmolc	Centimol load
$dS\ m^{-1}$	Decisiemens per meter
ETc	Crop evapotranspiration
Fe	Iron
g	Grams
HCO_3^{-}	Bicarbonate
Hg	Mercury
K^{+}	Potassium
Mg^{+2}	Magnesium cation
$mg\ dm^3$	Milligram per cubic decimeter
$mm\ day^{-1}$	Millimeter per day
m	Aluminum saturation
m^3	Cubic meters
Mo	Molybdenum

mg/L	Milligrams per liter
mL	Milliliter
Mn	Manganese
mmolc	Millimol of charge per liter
L^{-1}	Liter
N	Nitrogen
Na^{+}	Sodium
NaCl	Sodium chloride
Ni	Nickel
NO_3^{-}	Nitrate
No. º	Number
P	Phosphorus
Pb	Lead
Sb	Antimony
SB	Sum of bases
Se	Selenium
SO_4^{2-}	Sulphate
BS	Base saturation
T	Effective cation exchange capacity
USD m^{-3}	One US dollar per cubic meter
V	Vanadium
Zn	Zinc
%	Percent
µL	Microliter
µS cm^{-1}	Microsiemens per centimeter
pCi L^{-1}	Picocuries per liter
~	Approximately

SUMMARY

GENERAL INTRODUCTION

Oil production in Brazil ranks among the largest in the world (Surrey, 1987; Anjos; Sombra; Spadini, 2024). The country currently extracts oil from both onshore fields, located on the continent, and offshore fields. During extraction, significant volumes of water, known as "produced water," are generated (Clark; Veil, 2009). This is the main liquid waste produced by the oil and gas industry (Echchelh; Hess; Sakrabani, 2020), with millions of liters generated annually in Brazil. Because it originates from the geological formation of reservoirs, produced water (PW) has a variable and complex composition, containing high levels of salts, metals, hydrocarbons, radioactive materials, and additives used in exploration processes (McLaughlin *et al.*, 2020). Its volume and characteristics vary according to the location, age of the well, and the extraction technique employed.

In certain regions, especially those with semi-arid climates, the volume of PW generated is sufficient to be considered an alternative water source for agriculture (McLaughlin *et al.*, 2020). The search for unconventional water sources has intensified in response to water scarcity, prolonged drought, and the need to preserve freshwater reserves for priority uses (Echchelh; Hess; Sakrabani, 2020; Ali *et al.*, 2022). However, one of the main challenges to PW reuse is its high salinity, which can reduce agricultural productivity and complicate soil management. Even after dilution with freshwater, concerns regarding PW toxicity persist (Sedlacko *et al.*, 2022), necessitating rigorous monitoring of soil conditions.

The agricultural use of PW requires special attention to soil properties, particularly salinity and sodicity, which can be significantly altered by the application of this effluent (Burkhardt *et al.*, 2015). The presence of recalcitrant organic matter, toxic organic compounds, and salts such as carbonates, bicarbonates, and heavy metals must also be considered, as they affect groundwater quality and soil fertility (Aslam *et al.*, 2024). Nevertheless, technological advances have enabled the treatment of wastewater, including PW, making its use viable and safe for agricultural irrigation, especially in semi-arid regions (Echchelh *et al.*, 2019a). The reuse of PW thus represents a sustainable alternative for water resource management, contributing to environmental conservation and the circular economy.

The growing global demand for raw materials for biofuel production poses an additional challenge to food security, especially in countries like Brazil, where the most fertile areas are devoted to food production. In this context, the semi-arid Northeast region is emerging as a new strategic agricultural frontier for the cultivation of bioenergy crops in areas of low agricultural potential. The use of drought- and salinity-tolerant species such as sorghum, elephant grass, and cotton, irrigated with unconventional water resources such as PW, represents a promising opportunity to expand the national renewable energy matrix without competing with land designated for food production.

Choosing plants adapted to salinity conditions is essential when using lower-quality water for irrigation (Soltanbeigi *et al.*, 2021). Selecting tolerant or resistant species is a key consideration in production systems that use PW as a water resource. Among oilseeds, cotton (*Gossypium hirsutum* L.) has stood out for its ability to adapt to semi-arid environments and its moderate tolerance to salinity.

Cotton is an economically important crop in Brazil and exhibits good resistance to water and saline stress (Soares *et al.*, 2020; An *et al.*, 2025), although productivity can be affected by high saline concentrations depending on the species. Other cultivars can maintain good production characteristics even under saline irrigation (Rehman; Iqbal, 2022). Furthermore, both crops generate value-added products, such as oils used in industry and in the production of biofuels, which makes them attractive to regions seeking sustainable production alternatives (Del Gatto *et al.*, 2015).

Another relevant group consists of species specific to biomass production, such as sorghum (*Sorghum bicolor* L. Moench) and elephant grass (*Pennisetum purpureum*). Sorghum stands out for its tolerance to drought and salinity, making it an excellent option for saline soils or soils irrigated with poor-quality water, enabling its development in semi-arid environments (Mwamahonje *et al.*, 2021; Xin *et al.*, 2022), in addition to its potential for bioenergy generation (Rooney *et al.*, 2007; Mullet *et al.*, 2014; Appiah-Nkansah *et al.*, 2019). Elephant grass, in turn, is a fast-growing plant with a high biomass yield, adaptable to poor-quality soils and water. Both species possess physiological and morphological mechanisms that favor their survival under saline stress and are recommended for use with PW in strategies for the recovery of degraded areas and sustainable production.

The use of PW in agriculture must comply with current legislation. At the national level, CONAMA Resolution No. 357/2005 establishes criteria for the discharge of effluents into water bodies, while Resolution No. 393/2007 specifically addresses the disposal of PW on offshore platforms (MMA, 2005; MMA, 2007). At the state level, as in Ceará, COEMA Resolution No. 02/2017 defines parameters and limits for the reuse of liquid effluents, ensuring that water quality is compatible with agricultural use (CEARÁ, 2017).

Given this context, it is imperative that traditionally high-emitting sectors, such as oil and gas, develop strategies aligned with climate goals. Reusing produced water (PW) in agricultural systems for biomass and biofuel production represents a promising alternative while also offering a new business opportunity for oil companies. Considering the progressive depletion of oil reserves, diversifying activities through sustainable initiatives can ensure future competitiveness, meet regulatory requirements, and contribute to international climate mitigation commitments.

Oil-producing companies play a central role in the energy transition agenda, particularly through initiatives that involve the valorization of byproducts from the extraction process, such as PW. Using PW as an agricultural input for the cultivation of bioenergy species not only enables the reuse of a difficult-to-dispose effluent but also contributes to integrated emissions offsetting and carbon sequestration projects. The cultivation of plant biomass irrigated with PW can thus be seen as a strategy aligned with climate neutrality and circular economy policies, in addition to fostering carbon credit initiatives in partnership with the agricultural sector.

Thus, this work is structured around complementary approaches: two comprehensive reviews on global and national PW production, its strategic role in the context of the Brazilian energy transition and as an alternative source of irrigation, highlighting its environmental challenges, agricultural potential, and contribution to sustainability and decarbonization; and an experimental study evaluating the feasibility of using treated PW and its dilutions for irrigating plant species, focusing on the effects on plant growth and soil salinity. By integrating theoretical and practical knowledge, the proposal aims to provide support for the safe and efficient reuse of PW in agriculture, contributing to water resource management in semi-arid regions and the advancement of sustainable solutions aligned with the circular economy and bioenergy generation.

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CHAPTER I

GLOBAL RESEARCH TRENDS ON WASTEWATER REUSE AND ENVIRONMENTAL SUSTAINABILITY: A BIBLIOMETRIC ANALYSIS (2010-2025)

Abstract - This bibliometric study analyzed scientific production related to wastewater reuse with a focus on environmental sustainability, from 2010 to 2025, based on data from the Web of Science. Searches were performed using the terms wastewater, reuse and environmental sustainability, and the data were processed with the support of the VOSviewer® and Bibliometrix tools. The results indicated a significant growth in publications from 2016 onwards, with emphasis on countries such as China, the United States, India and Brazil. The evaluation of thematic clusters and co-occurrence and co-authorship networks revealed the consolidation of themes such as reuse in irrigation, application of bioadsorbents, use of membranes and use of microalgae in effluent treatment. On the other hand, emerging themes evidence the advancement of waste valorization, bioenergy production and the integration between water reuse and climate neutrality strategies. One of the main insights obtained was the identification of water produced by the oil industry as a strategic vector that is still underexploited, with the potential to irrigate bioenergy crops, contributing to the reduction of emissions and insertion in carbon credit markets. This gap represents a promising opportunity for the development of interdisciplinary research aimed at the decarbonization of water-intensive sectors. Thus, the bibliometric study not only maps the evolution and main actors of scientific production, but also signals future perspectives and priority areas for further study.

Keywords: Wastewater; Reuse; Environmental sustainability.

1 INTRODUCTION

The growing scarcity of water resources, aggravated by the effects of climate change, has driven the adoption of more sustainable water management strategies (Hasan *et al.*, 2023) . In this context, the use of treated wastewater has emerged as an effective alternative for mitigating environmental impacts, increasing water resilience and conserving natural water bodies, especially in regions with water scarcity (Kandou *et al.*, 2023)

Reuse practices cover a variety of sources, including: (i) treated domestic effluents (Ayaz *et al.*, 2015), (ii) graywater from non-contaminating uses (Elhegazy; Eid, 2020), (iii) treated industrial effluents and (iv) urban rainwater (Pochwat, 2022). Each of these streams has different physical, chemical and microbiological compositions, requiring different combinations of treatments depending on the intended final destination.

Treatment processes involve physical, chemical and biological steps and, when necessary, advanced technologies such as membrane filtration (Aziz *et al.*, 2024; Ullah *et al.*, 2020), ozonation (Cheng *et al.*, 2024) and ultraviolet radiation (Guo *et al.*, 2022; Sun *et al.*, 2023). Depending on the efficiency of the process, the treated water becomes suitable for strategic non-potable uses, such as recharging aquifers, industrial cooling, washing public roads, dust control in mining areas and sanitary uses in buildings (Ma *et al.*, 2022).

The choice of end use depends on technical, regulatory and economic criteria, taking into account the required quality standards, associated health risks and the cost-benefit of treatment (Tzanakakis; Capodaglio; Angelakis, 2023; Urkiaga *et al.*, 2008). Consolidated applications include agricultural irrigation, especially in semi-arid regions where water scarcity compromises productivity and food security (Xing; Wang, 2024). Studies indicate that agricultural reuse can, in addition to providing water, supply essential nutrients to plants, such as nitrogen and phosphorus, contributing to agricultural practices integrated with the logic of the circular economy (Saliu; Oladoja, 2021).

In this scenario, the reuse of so-called produced water, the effluent generated during oil and gas extraction activities (Feder, 2020; Nath; Chowdhury; Rhaman, 2023). In mature fields, the volumes of water extracted often exceed the volumes of oil, turning this by-product into a significant environmental liability. With its high salinity, presence of hydrocarbons, heavy metals and toxic organic compounds, produced water has traditionally been considered difficult to manage. However, recent technological advances have boosted studies into its treatment and revalorization (Fito; Van Hulle, 2021).

Among the possible routes of utilization is the use of produced water as an alternative source for agricultural irrigation (Echchelh; Hess; Sakrabani, 2018; Kondash *et al.*, 2020; Sedlacko *et al.*, 2020). The viability of this practice often depends on the application of advanced purification technologies in order to reduce contaminants to acceptable levels while ensuring safety for the soil, crops and human health. This approach has aroused interest in arid and semi-arid regions, where oil production and water scarcity coincide, as is the case in areas of the Middle East, North America and the Brazilian Northeast (Marangon *et al.*, 2020; Rahman *et al.*, 2024).

Given this panorama, it is important to understand how the scientific literature has approached water reuse and, in particular, produced water. Bibliometric analyses are robust methodological tools for mapping the state of the art of a field of knowledge (Lazarides; Lazaridou; Papanas, 2023; Pessin; Yamane; Siman, 2022), identifying the main research centers, reference authors, consolidated themes and emerging lines (Kipper *et al.*, 2020; Oktavio; Harsono, 2024).

This study therefore proposes a bibliometric analysis of the scientific literature on the subject, based on the key terms Wastewater, Reuse and "Environmental Sustainability". The aim of this analysis is to identify whether the use of water produced by the oil industry for irrigation is an incipient or consolidated line of research, as well as pointing out gaps in knowledge and subsidizing future research.

2. METHODOLOGY

This bibliometric review was conducted using a systematic approach, with the aim of mapping international scientific production related to the use of wastewater and its interface with environmental sustainability. The methodological design adopted follows models consolidated in the literature (Martins *et al.*, 2024; Melo *et al.*, 2024, 2025) widely used to analyze scientific networks, collaboration patterns and identify emerging trends.

The methodological structure used is based on recognized databases, with clear eligibility criteria, and combines the use of robust analytical tools with standardized network visualization and interpretation strategies. By adopting this approach, the aim is to ensure reproducibility, transparency and adherence to the good methodological practices observed in the main scientific journals focused on mapping knowledge. Figure 1 illustrates the stages of bibliometric research.

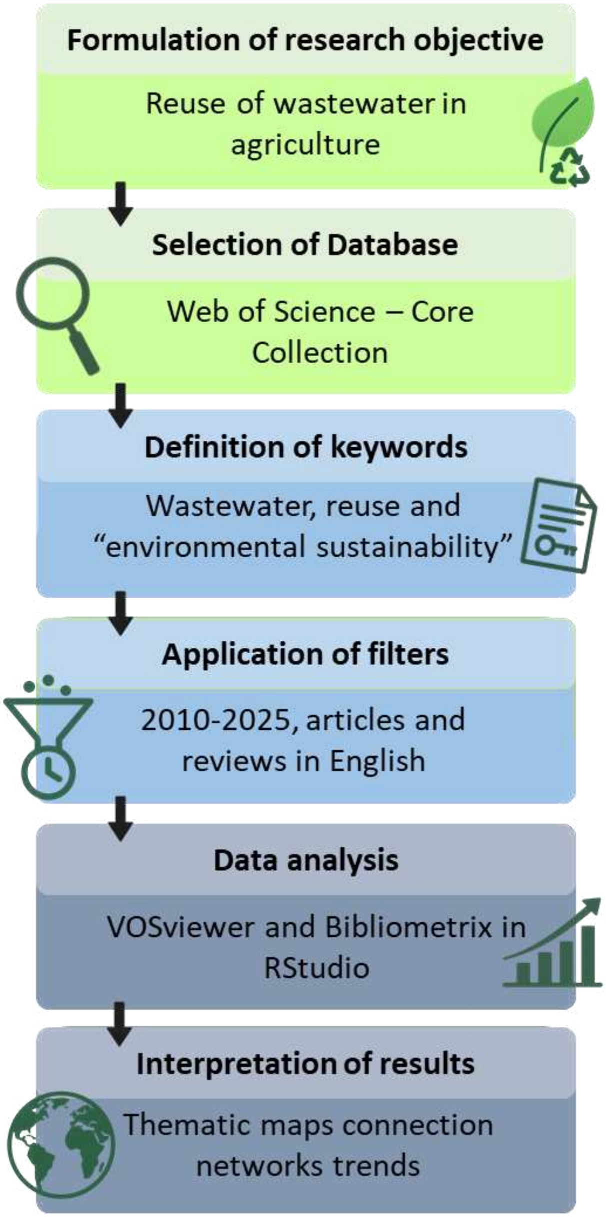


Figure 1. Bibliometric methodology for research on water reuse.

2.1 Source and search criteria

The database used was the Web of Science - Core Collection, recognized for its multidisciplinary scope and reliability in scientific impact analyses. The search strategy used a combination of the key terms: "wastewater", "reuse" and "environmental sustainability", applied to all indexed fields (title, abstract, keywords and associated fields). The time frame covered the period from 2010 to 2025, limited to the English language and the document types "article" and "review", in accordance with the established bibliometric eligibility criteria.

2.2 Data collection and processing

The bibliographic records were exported directly from the Web of Science in formats compatible with the software used (.txt and .csv). In a preliminary stage, the data was organized and checked in Microsoft Excel®to check, clean duplicates and verify the consistency of the metadata (year, title, authors, country, institution, journal, keywords, among others). After this stage, the files were processed in the analysis software.

2.3 Analysis and visualization tools

Two complementary environments were used for the quantitative and structural analyses:

- VOSviewer® (version 1.6.20): used to build network maps related to the co-occurrence of keywords, co-authorship between authors, institutions and countries, co-citation of journals and Total Link Strength (TLS). The tool made it possible to identify thematic groupings (clusters), as well as emerging trends based on the density and interconnectivity of the terms.
- Bibliometrix (version 3), operated in the R language using the RStudio®environment: used to generate statistical graphs, productivity tables (by author, journal and country), thematic analysis by strategic clusters and the temporal evolution of publications. This tool enabled a robust descriptive analysis of the corpus, helping to identify research fronts, emerging keywords and priority areas.

2.4 Analysis strategy

The analyses carried out covered quantitative and structural aspects of the literature, such as the evolution of the number of publications over the years, the identification of the authors, institutions and countries with the greatest scientific contribution, and the most relevant journals on the subject. Co-authorship networks, co-citation and co-occurrence of terms were also examined, with a focus on forming thematic clusters and identifying research gaps. The software parameters were adjusted based on minimum frequencies of occurrence (n ≥ X, depending on the metric) and strength of linkage (TLS) between the elements, in order to ensure the robustness of the visualizations and the statistical relevance of the thematic groupings identified.

3. RESULTS AND DISCUSSION

3.1 General overview of scientific production (2010-2025)

The query carried out on the Web of Science (WoS) database, using the combined descriptors ("wastewater", "reuse" and "environmental sustainability") resulted in a total of 212.546 publications with the term "wastewater". By refining the search to the intersection with "reuse", the number was reduced to 20.224 articles. Finally, the simultaneous combination of the three terms restricted the set to just 183 records from 2010 to 2025, as shown in Figure 2.

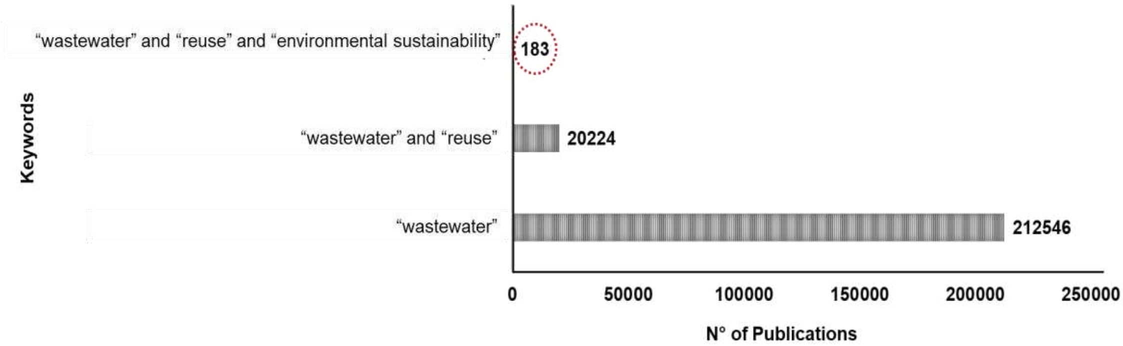


Figure 2. Publications by keyword combination in Web of Science (2010-2025).

This progressive reduction highlights the broad scope of the "wastewater" field, but also reveals that only a fraction of the literature explicitly contextualizes reuse within the scope of environmental sustainability. This gap is significant, since wastewater use involves variables that go beyond treatment efficiency, including economic, environmental, regulatory and social aspects (Ma *et al.*, 2022; Silva *et al.*, 2022). According to Kumar; Goyal (2020) and Torkayesh *et al.* (2022) the advancement of sustainable reuse strategies requires integrated approaches, based on tools such as life cycle assessment, water governance and multi-criteria analysis.

The evolutionary analysis of the number of publications over time indicates that scientific production on the three themes combined has grown significantly since 2015, in line with the intensification of water crises in regions such as the Middle East, North Africa, South Asia and Latin America. This growth also reflects the consolidation of regulatory frameworks for reuse, policies to encourage the circular economy and advances in clean technologies in countries such as China, India, Spain and Australia (Yánez *et al.*, 2024).

Among the 183 articles found, approaches focusing on:

- Use of constructed wetlands as natural treatment systems (Vymazal, 2022);
- Integration of reuse with bioenergy production and nutrient recovery (Martins *et al.*, 2024);
- Development of natural adsorbents and functional nanomaterials for selective purification (Melo *et al.*, 2024);
- Agricultural applications of treated wastewater, with an emphasis on safe irrigation (Mishra; Kumar; Kumar, 2023; Ofori *et al.*, 2021);

Figure 3 shows the evolution of the number of publications related to the terms "wastewater", "reuse" and "environmental sustainability" from 2010 to 2025, based on data from the Web of Science. There is a clear upward trend in scientific production over the last 15 years, with a significant increase from 2020 onwards.

During the initial years (2010-2015), production was negligible, with a maximum of three articles per year, reflecting the embryonic stage of research integrating wastewater use with the theme of environmental sustainability. However, from 2016 onwards, there was more consistent growth, culminating in a significant leap from 2020, when 17 articles were published, almost triple the number recorded in 2019.

The peak occurred in 2024, with 36 publications, indicating the height of scientific interest in the topic. This increase may be associated with the intensification of global policies aimed at the circular economy, water security and countries' commitments to the Sustainable Development Goals (SDGs), especially SDGs 6, 12 and 13.

In 2025, even though the data was still partial at the time of analysis, the number of publications already equaled the 2022 total (23 articles), suggesting that interest in the subject remains high. This growth reveals not only a quantitative increase, but also a maturing of the area, as will be discussed in the following sections based on the analysis of keywords, collaboration networks and strategic themes.

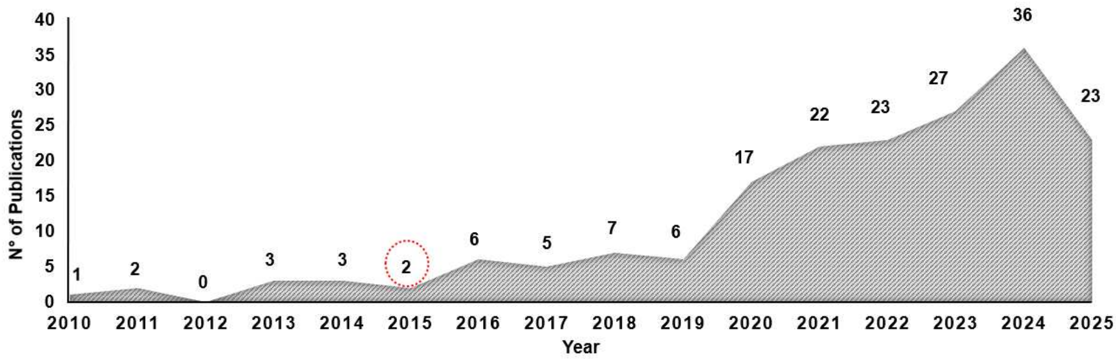


Figure 3. Annual publication output for selected keyword combinations (Web of Science, 2010-2025).

These works show that, although the document base is limited, it concentrates advanced, diverse and interdisciplinary initiatives that contribute directly to strengthening water reuse as an environmental sustainability strategy. Based on this bibliographic base, this study will outline the main thematic axes and discuss their evolution and interconnections, with a view to identifying opportunities for expansion and innovation.

3.2 Main authors, journals, institutions and countries

Table 1 shows the ranking of the 10 authors, journals, institutions and countries with the highest number of publications on water reuse with an emphasis on sustainability, between 2010 and 2025. The data shows the significant and diverse scientific contribution of different regions and authors in consolidating this interdisciplinary field.

Table 1. Ranking of the 10 main authors, journals, institutions and countries with the most publications on the use of wastewater with an emphasis on sustainability in the last 15 years.

RANKING		NP	NC	AC
	AUTHORS			
1	Du, Hongbo	3	51	17.00
2	Fatima, Faryal	3	51	17.00
3	Kommalapati, Raghava R.	2	45	22.50
4	Liu, Junxin	2	95	47.50
5	Silva, Jorge Alejandro	2	155	77.50
6	Wang, Xu	2	95	47.50
7	Zhang, Qiong	2	103	51.50
8	Asamoah, George Adu	1	1	1.00
9	Asmatulu, Eylem	1	3	3.00
10	Baffoe, Janet	1	1	1.00
	JOURNALS			
1	Journal of Cleaner Production	19	701	36.89
2	Journal of Environmental Management	11	347	31.55
3	Science of The Total Environment	9	221	24.56
4	Water	7	84	12.00
5	Separation and Purification Technology	6	59	9.83
6	Sustainability	6	169	28.17
7	Chemical Engineering Journal	5	24	4.80
8	Journal of Water Process Engineering	5	225	45.00
9	Desalination and Water Treatment	4	20	5.00
10	Agricultural Water Management	3	99	33.00
	INSTITUTIONS			
1	Chinese Academy of Sciences	5	168	33.60
2	University of Chinese Academy of Sciences	4	92	23.00
3	Indian Institutes of Technology	3	110	36.67
4	King Saud University	3	7	2.33
5	Lebanese Amer University	3	134	44.67
6	Prairie View A&M University	3	51	17.00
7	Saveetha Institute of Medical and Technical Sciences	3	145	48.33
8	Tsinghua University	3	92	30.67
9	University of Catania	3	74	24.67
10	University of Johannesburg	3	128	42.67
	COUNTRIES			
1	USA	33	619	34.00
2	China	29	778	10.00
3	India	24	866	9.00
4	Italy	18	283	6.00
5	Saudi Arabia	12	200	3.00
6	Saudi Arabia	11	170	2.00
7	Malaysia	10	582	4.00
8	Egypt	8	125	2.00
9	Iran	7	192	1.00
10	Spain	7	70	0.00

Note: NP = number of publications; NC = number of citations; AC = average number of citations (NC/NP).

Among the authors, Du, Hongbo and Fatima, Faryal lead the way with three publications each, accumulating 51 citations and an average of 17 citations per article. However, the highlight in terms of average impact belongs to Silva, Jorge Alejandro, with 77.5 citations per article, despite having only two publications on the subject. These figures indicate that, in addition to productivity, there are authors whose specific contributions are highly relevant to the scientific community.

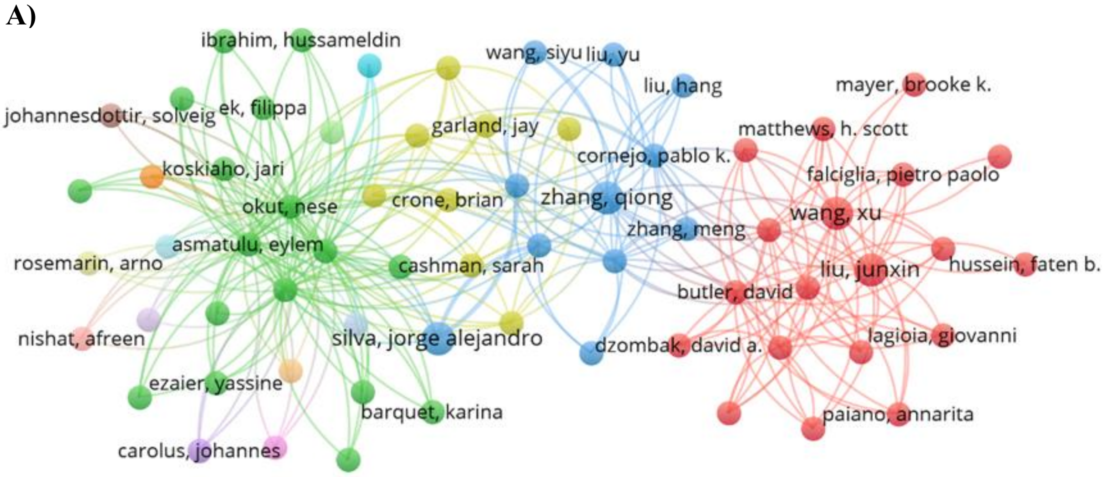
With regard to journals, the Journal of Cleaner Production stands out as the most productive, with 19 published articles and 701 citations, resulting in an average citation index (AC) of 36.89. This was followed by the Journal of Environmental Management and Science of The Total Environment, confirming the relevance of these journals in the debate on environmental sustainability and water reuse. The Journal of Water Process Engineering, despite having only five articles, has a high average citation index (45.00), which reinforces its impact in the area.

In terms of institutions, the Chinese Academy of Sciences appears to be the most productive, with five articles and an AC of 33.6. The Saveetha Institute of Medical and Technical Sciences, although it has the same number of publications as other institutions (three), obtained the highest AC, with 48.33, suggesting the high quality and impact of its contributions. The institutions Tsinghua University, University of Johannesburg and Lebanese American University also stand out for their volume of citations and balanced productivity.

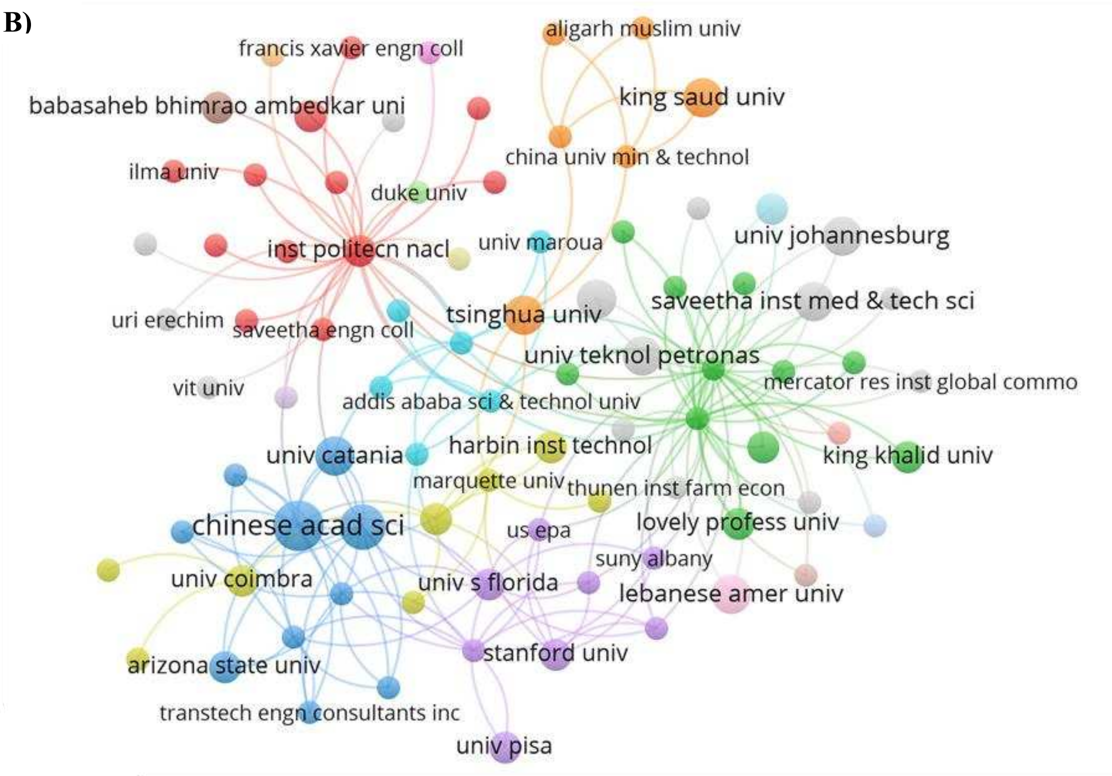
Among the countries, the United States leads in number of publications (33) and maintains a relevant AC of 34.00. However, China, with 29 articles, obtained the highest absolute number of citations (778), albeit with an AC of only 10.00. India, Italy and Brazil complete the list of the most active countries, especially Brazil which, despite having 11 publications, has a low AC (2.00), indicating room to increase the impact of national research on the subject. These quantitative results serve as the basis for the visual analyses presented in the following figures, which detail the collaboration networks between authors, institutions and countries, as well as highlighting the central journals in the dissemination of knowledge on the use of wastewater with a sustainable approach.

The analysis of co-authorship and collaboration networks is a fundamental component of bibliometrics, as it makes it possible to understand the organization of knowledge, the main agents producing science and the dynamics of the dissemination of ideas and technologies. Figure 4 shows the most relevant clusters of authors, institutions, journals and countries in the literature on the use of wastewater with a focus on environmental sustainability.

A)



B)



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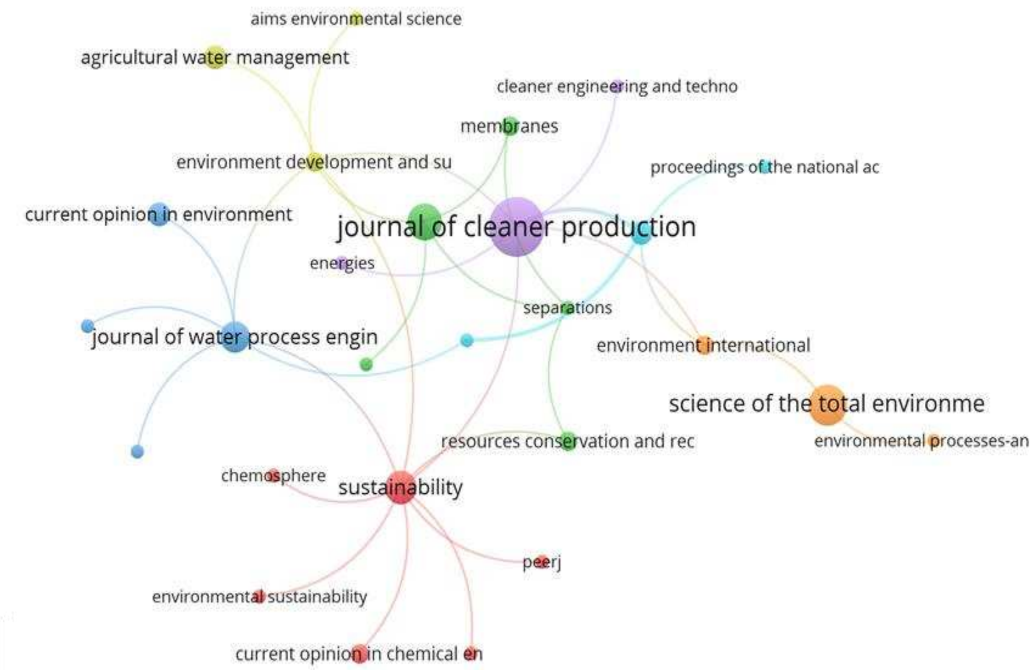


D)

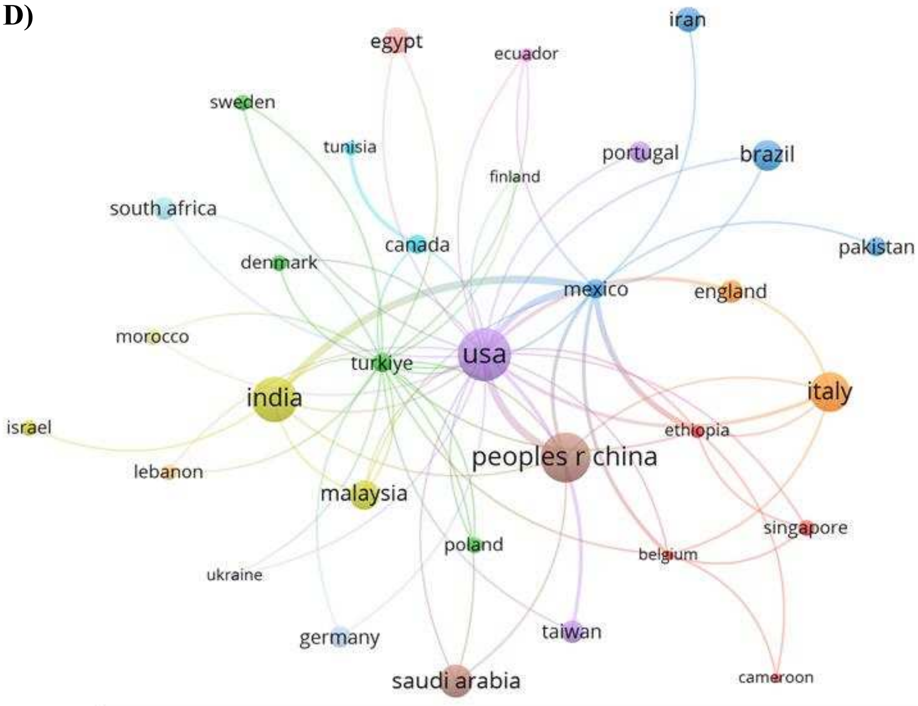


Figure 4 Scientific collaboration networks on wastewater reuse and sustainability research: A) authors, B) institutions, C) journals and D) countries.

Figure 4A shows the collaboration network between the main authors based on co-authorship. It shows five large groups (clusters), each with strong internal connections and occasional relationships between clusters. The largest of these is led by Wang, Xu and Liu, Jun Xin, who make up a relevant axis of research concentrated in China, with strong production on the removal of contaminants, the use of adsorbents and membrane technologies (Yang. *et al.*, 2021). This cluster is strongly focused on technical and experimental applications.

Another prominent cluster is centered on researchers such as Cashman, Sarah, Garland, Jay and Okut, who have strong ties to the US Environmental Protection Agency and US institutions. This group takes a more interdisciplinary approach, focusing on life cycle assessment (LCA), multi-criteria decision making and public perception of water reuse (Opher; Friedler; Shapira, 2019; Opher; Shapira; Friedler, 2018).

The presence of authors such as Silva, Jorge Alejandro and Asmatulu, Eylem (Table 2) also indicates the active participation of Latin American and Middle Eastern groups in international networks. The link between clusters reinforces that, although there is geographical polarization, international collaborations are intensifying.

Figure 4B shows the institutional co-authorship clusters. In it, the Chinese Academy of Sciences emerges as an important pillar of the network, both in terms of production and articulation with other Asian institutions, such as Tsinghua University and Harbin Institute of Technology, which lead cutting-edge technological research into membranes, nanomaterials and resource recovery (Ge *et al.*, 2024; Guo *et al.*, 2021).

The Saveetha Institute of Medical and Technical Sciences and the Universiti Teknologi Petronas also occupy central positions, with emphasis on their joint work with researchers from Malaysia and India. These institutions have been consolidating themselves as emerging research centers applied to water reuse in tropical and industrial contexts (Kumar; Goyal, 2020).

European and American institutions, such as the University of South Florida, Stanford University and again the Chinese Academy of Sciences, also appear as hubs, but with a greater focus on sustainability and water governance. It is important to note that some Latin American institutions, such as the Integrated Regional University of Alto Uruguay and the Missions, Erechim campus (Brazil) and the University of Catania, also appear in the network, albeit in peripheral positions. This institutional analysis reveals the multipolar configuration of water reuse research, with a strong Asian role and the growth of research centers in Africa and Latin America with bilateral collaborations.

Figure 4C shows the main scientific journals by their co-citation network. The Journal of Cleaner Production stands out as the most central journal, acting as a bridge between technical, environmental and social approaches to water reuse. Its central position demonstrates its role in integrating different areas, including environmental engineering, sustainable management and public policies (Almeida *et al.*, 2017).

Other highly relevant journals are:

- Science of the Total Environment, focusing on interdisciplinary studies on contamination and remediation;
- Sustainability, with an emphasis on circular models, environmental impacts and reuse policies;
- Journal of Water Process Engineering, which focuses on experimental and technological approaches to purification and treatment;
- Environment International, with a growing emphasis on risk assessments and public health.

The presence of journals from different areas, such as engineering, environmental chemistry, management and public policy, reinforces the interdisciplinary nature of the field. The network shows that the literature on water reuse is not limited to sanitary engineering, but is strongly connected to the principles of sustainability, governance and the circular economy (Capodaglio; Angelakis; Tzanakakis, 2023; Fernandes; Marques, 2023; Smeets *et al.*, 2020).

Figure 4D shows an analysis of the collaboration networks between countries, highlighting the geographical distribution and international links in scientific production. The United States and China stand out as central nodes, with a high density of connections. The United States establishes significant collaborations with countries in Western Europe (England, Italy, Germany), Latin America (Brazil, Mexico) and Asia (India, Malaysia, Taiwan), reflecting its traditional role as a global articulator of research into water sustainability (Adetoro *et al.*, 2021).

China, in turn, shows strong integration with Asian and African countries such as Malaysia, Turkey and Ethiopia, consolidating a hub of technical and experimental innovation. India has emerged as a link between the Middle East and Southeast Asia, reinforcing a regional configuration around issues applied to agricultural and urban water reuse.

In Europe, Italy appears as an important hub for connections with countries in Africa and Asia, such as Ethiopia, Singapore and Belgium, broadening the scope of European research in tropical contexts. Countries such as Brazil, Iran, Egypt and South Africa occupy intermediate positions, acting as strategic bridges between consolidated research centers and regions with critical needs for sustainable water management solutions (Santos; Carvalho; Martins, 2023).

This international network shows a deconcentration of scientific production, with the emergence of South-South collaborations and the strengthening of new scientific centers, especially in developing countries. This reinforces the importance of global funding and scientific cooperation strategies to tackle contemporary water challenges.

3.3 Most cited articles

An analysis of the most cited articles in the bibliometric database reveals the main conceptual and methodological vectors that structure the field of wastewater use with a focus on environmental sustainability. The 15 articles with the highest number of citations between 2010 and 2025 (Table 2) were published in high impact factor journals such as the Journal of Cleaner Production, Environmental Science & Technology, Science of the Total Environment, Green Chemistry and Proceedings of the National Academy of Sciences of the United States of America. These journals occupy prominent positions in the co-citation networks discussed above (Figure 4C), reinforcing their centrality in the scientific consolidation of the topic.

Table 2. 15 most cited articles on wastewater reuse and environmental sustainability (2010-2025).

RANKING	TITLE OF ARTICLE	FIRST AUTHOR	MAGAZINE	YEAR	CITATIONS	REFERENCES
1	Role of electrocoagulation in wastewater treatment: A developmental review	Amina Tahreen	Journal of Water Process Engineering	2020	208	Tahreen; Jami; Ali, 2020)
2	Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature Review	Jorge Alejandro Silva	Sustainability	2023	140	(Silva, 2023)
3	Applications of fluidized bed reactors in wastewater treatment: A review of the major design and operational parameters	Mustapha Mohammed Bello	Journal of Cleaner Production	2017	140	(Bello; Abdul Raman; Purushothaman, 2017)
4	Analysis of the polyester clothing value chain to identify key intervention points for sustainability	Cristina Palacios-Mateo	Environmental Science Europe	2021	132	(Palacios-Mateo; van der Meer; Seide, 2021)
5	Algae biotechnology for industrial wastewater treatment, bioenergy production, and high-value bioproducts	Ashfaq Ahmad	Science of the Total Environment	2022	119	(Ahmad *et al.*, 2022)
6	Performance of various catalysts on treatment of refractory pollutants in industrial wastewater by catalytic wet air oxidation: A review	Sushma Yadav	Journal of Environmental Management	2018	108	(Sushma; Kumari; Saroha, 2018)
7	Environmental technology and wastewater treatment: Strategies to achieve environmental Sustainability	Syed Abdul Rehman Khan	Chemosphere	2022	107	(Khan *et al.*, 2022)
8	Low carbon hydrogen production from a waste-based biorefinery system and environmental sustainability assessment	Omprakash Sarkar	Green Chemistry	2021	104	(Sarkar; Katakojwala; Mohan, 2021)
9	How Does Scale of Implementation Impact the Environmental Sustainability of Wastewater Treatment Integrated with Resource Recovery?	Pablo Cornejo	Environmental Science & Technology	2016	91	(Cornejo; Zhang; Mihelcic, 2016)
10	The innovative Osmotic Membrane Bioreactor (OMBR) for reuse of wastewater	Emile Cornelissen	Water Science & Technology	2011	91	(Cornelissen *et al.*, 2011)
11	Wastewater reclamation and reuse potentials in agriculture: towards environmental sustainability	Jemal Fito	Environment, Development and Sustainability	2021	85	(Fito; Van Hulle, 2021)
12	Magnesiation roasting-acid leaching: A zero-discharge method for vanadium extraction from vanadium slag	Hong-Yi Li	Journal of Cleaner Production	2020	85	(Li *et al.*, 2020)
13	Probabilistic evaluation of integrating resource recovery into wastewater treatment to improve environmental sustainability	Xu Wang	Proceedings of the National Academy of Sciences of the United States of America	2015	76	(Wang *et al.*, 2015)
14	Wastewater treatment: A short assessment on available techniques	Afreen Nishat	Alexandria Engineering Journal	2023	74	(Nishat *et al.*, 2023)
15	Are view on sustainable reuse applications of Fentons ludge During wastewater treatment	Lihui Gao	Frontiers of Environmental Science & Engineering	2022	73	(Gao *et al.*, 2022)

Noteworthy works include that by Tahreen, Jami and Ali (2020), with 208 citations, which offers a critical review of the use of electrocoagulation in wastewater treatment. The article combines a technological approach with a feasibility analysis for application in developing countries, reinforcing the importance of affordable solutions with a low environmental impact.

Another highlight is the article by Silva (2023), which presents a systematic review of water reuse and sustainable management, based on more than 140 studies. Its high citation rate, despite being recent, indicates adherence to a contemporary debate on water security and the circular economy, with a strong focus on public policies and integrated water resource management.

The recurring presence of articles aimed at evaluating emerging technologies, such as fluidized bed reactors (Bello; Abdul Raman; Purushothaman, 2017), catalytic processes (Sushma; Kumari; Saroha, 2018) and bioenergy from effluents (Ahmad *et al.*, 2022; Sarkar; Katakojwala; Mohan, 2021), highlights the central role of technological innovation in advancing the field. These studies focus on improving process efficiency, reducing the carbon footprint and using waste energy, themes also identified in institutional co-authorship networks (Figure 4B) and collaborations between countries with semi-arid climates and growing industrialization (Figure 5).

The contribution of authors such as Khan *et al.* (2022) and Wang *et al.* (2015) represents the intersection between sustainability and the probabilistic assessment of environmental impacts. The article by Wang *et al.* (2015) for example, integrates statistical modeling and probabilistic scenarios to measure the net benefits of resource recovery in sewage treatment plants, and is exemplary in the use of sustainability indicators on a large scale. This approach has been especially relevant in formulating guidelines for implementing solutions in developing countries, as reinforced by Ahmad *et al.* (2022).

It is worth noting that the majority of the most cited articles adopt interdisciplinary approaches, combining environmental engineering, life cycle assessment (LCA), green chemistry, public policies and resource economics. This confirms the cross-cutting nature of the subject, as pointed out in the co-citation analyses and in the journals mapped. In addition, there is a rise in authors from countries such as India, China, Iran and Brazil, indicating the expansion of qualified scientific production beyond the traditional centers of the Global North.

These articles represent not only the state of the art of research in the area, but also point the way to future investigations. Issues such as the feasibility of low-cost solutions, energy integration, regional adaptation of technologies and social and economic sustainability metrics remain central to new research agendas.

3.4 International and institutional collaboration

The analysis of institutional and international collaborations reveals the building of a robust and diverse global network in the field of wastewater use with a focus on environmental sustainability. This expansion of international scientific connections complements the findings in Figure 4, showing a growing multipolarity in the global knowledge production system.

Figure 5A shows a world map of collaborations by country, in which we see strong links between the United States and China, which reaffirm their role as technical and scientific leaders. India also occupies a prominent position, articulating intense collaborations with countries in Southeast Asia, the Middle East and the United States itself. In addition, there is a dense network of interactions involving European countries such as Germany, Spain, Italy and England, consolidating Europe as a strategic hub for scientific articulation with a focus on water governance and sustainability.

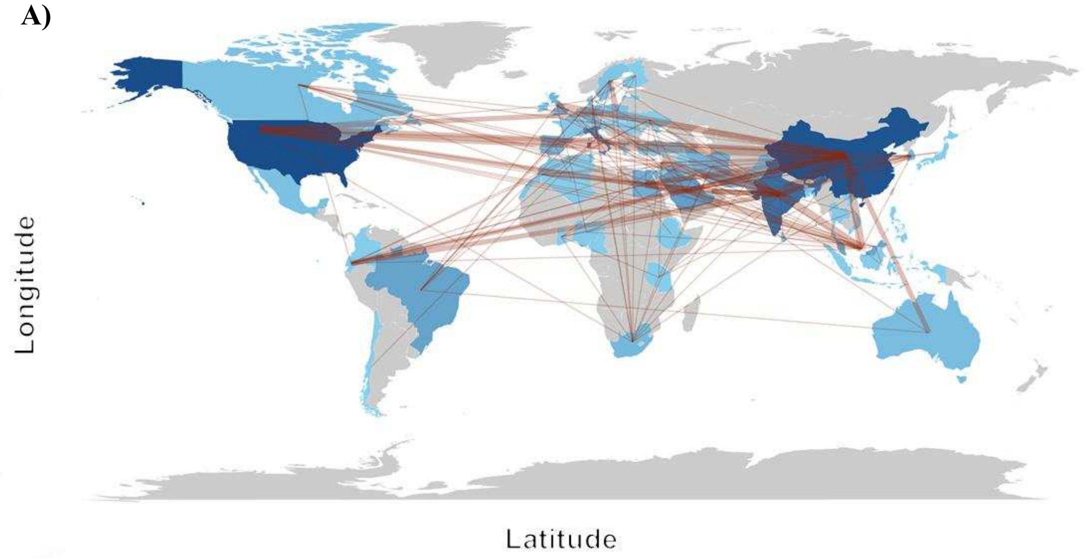
Brazil, although in a less central position, shows consistent growth in scientific interactions, with collaborations directed towards Western Europe and Latin America. This intermediate position is evidence of a continuous effort towards international integration, especially in areas related to agricultural reuse, such as fertigation with treated effluents, constructed wetlands and low-cost technologies - critical areas for tropical and semi-arid regions, as pointed out by Ahmad *et al.* (2022).

Figure 5A deepens this analysis by integrating geographical, institutional and thematic dimensions, revealing how authors, institutions and countries articulate around common scientific agendas. It can be seen that researchers such as Kumar V., Kommalapati R.R. and Du H.B. act as links between centers of excellence in the United States, China, India and Malaysia, with emphasis on institutions such as the Texas A&M University System, Prairie View A&M University and the Saveetha Institute of Medical and Technical Sciences. These connections not only illustrate the intensification of science diplomacy, but also highlight the role of technical universities and emerging institutes in advancing solutions applied to water reuse in urban and agricultural environments.

Institutions with a strong experimental base, such as the Chinese Academy of Sciences and the University of Tehran, have taken a leading role in multilateral projects, while centers such as the Consejo Superior de Investigaciones Científicas in Spain and the Federal University of Rio Grande do Norte in Brazil have stood out for incorporating sustainability and governance metrics into technological projects. These arrangements reflect an ongoing effort to transdiscipline and regionalize solutions, aligning science, policy and innovation to tackle global water challenges.

Therefore, the integration between the co-authorship maps (Figure 4), geographical links (Figure 5A) and institutional flows (Figure 5B) confirms the trend towards internationalization of water reuse research, with a strong Asian centrality, consolidation of South-South networks and appreciation of collaborations that prioritize technology transfer adapted to vulnerable socio-environmental contexts.

A)



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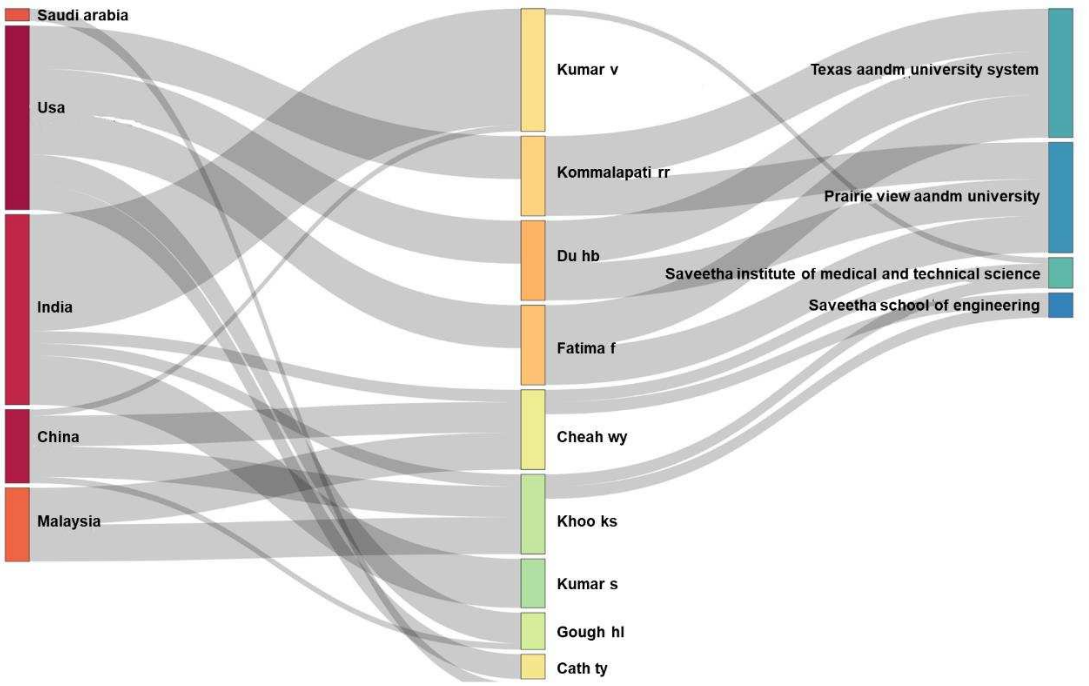


Figure 5. International collaborations and thematic research structure: A) Global map of co-authorships between countries; B) Network of countries, institutions and thematic areas.

3.5 Main keywords and their evolution over time

Based on the publications indexed between 2010 and 2025, visualizations were generated using VOSviewer®and Bibliometrix software, which made it possible to map the patterns of keyword competition. The resulting figures helped to identify five main thematic axes, whose characterization is presented below. These axes reflect the current state of the field and point to promising directions for scientific and technological development.

Figure 6A shows the most recurrent terms, such as "reuse", "removal", "environmental sustainability", "wastewater reuse", "circular economy", "adsorption" and "life cycle assessment". The red and orange hues indicate a high density of occurrences and a strong thematic connection, reflecting the concentration of research into treatment technologies, environmental assessment and reuse strategies. Terms associated with specific technologies also stand out, such as "reverse osmosis", "ultrafiltration", "membrane fouling", "anaerobic digestion" and "adsorbent". The presence of terms such as "bioremediation", "activated carbon", "nanoparticles" and "kinetics" points to technical advances in sustainable solutions applied to wastewater treatment.

Figure 6B complements this analysis by illustrating the temporal overlap of the main terms used, highlighting the emergence and persistence of themes over time. It can be seen that terms such as "treatment", "performance", "effluent" and "sustainability" are long-lasting and highly relevant, consolidating themselves as conceptual foundations of the field. In contrast, more recent words such as "nanoparticles", "biochar", "composites" and "desalination" emerge in the final years of the series, reflecting the technical sophistication of more current approaches. This visualization makes it possible to clearly identify the transition from a focus on treatment efficiency to more integrated approaches to sustainability and the circular economy.

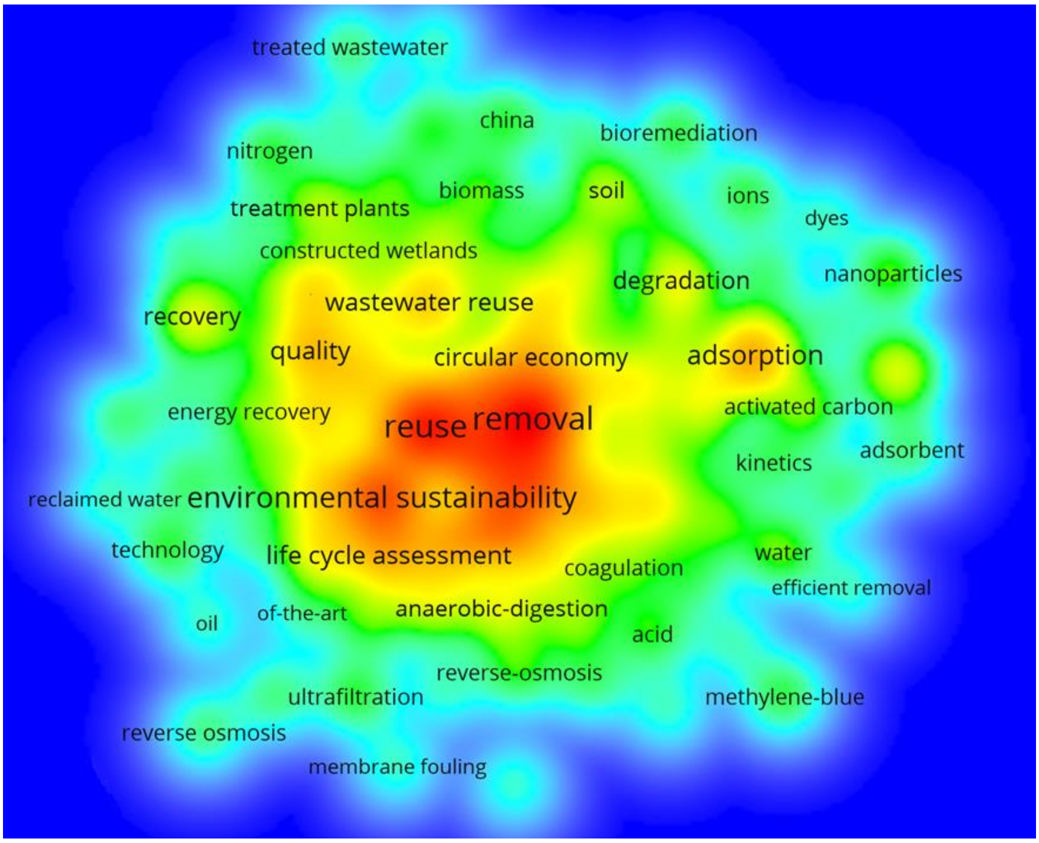
Figure 6C shows the thematic groupings structured based on the co-occurrence of keywords. It shows the formation of conceptual clusters around "treatment", "performance", "recycling" and "effluent", suggesting that these themes form the consolidated foundation of the literature. These terms are often associated with the efficiency of technologies, the quality of treated water and the suitability of reuse in applications such as irrigation, aquifer recharge and industrial uses.

The term "performance", strongly correlated with "treatment" and "effluent" in the previous visualizations, highlights the interest in quantitative indicators of effectiveness, such as the removal of nutrients, pathogens and emerging contaminants. Studies such as those by Agarwal; Singh (2022) and Bhave; Naik; Salunkhe (2020) explore these relationships using constructed wetlands, membrane bioreactors and moving bed biofilm reactors integrated with UV and electrochemical disinfection systems.

Figure 6D complements this analysis by illustrating the temporal evolution of the keywords using a Sankey chart, dividing the most frequent terms into four intervals (2010-2020, 2021-2022, 2023-2024 and 2025-2025). It can be seen that in the initial years, generic terms such as "reuse" and "performance" predominated. From 2021 onwards, more technical and specialized terms became more prominent, such as "heavy-metals", "nanofiltration", "methylene-blue" and "energy". In more recent years (2023-2025), there is a rise in terms such as "reclamation", "composites", "aqueous solution" and "desalination", indicating greater sophistication in reuse approaches in the face of the complexity of contaminants.

These data demonstrate not only the consolidation of the field, but also its interdisciplinary evolution, encompassing aspects of environmental chemistry, process engineering, energy, agriculture and policy formulation. The permanence of the terms "reuse" and "removal" throughout the time series reinforces their role as structuring axes in the scientific debate on the use of wastewater.

A)



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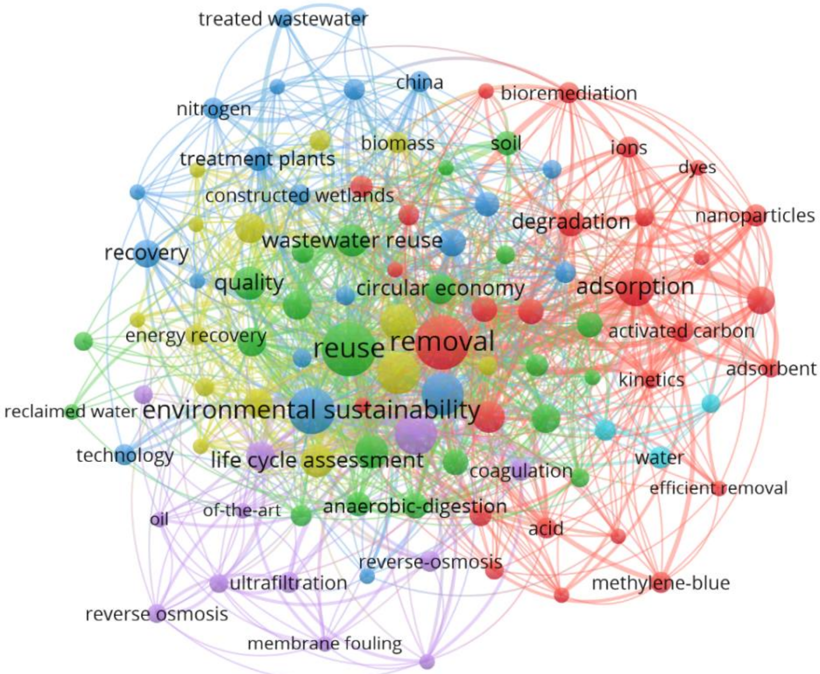

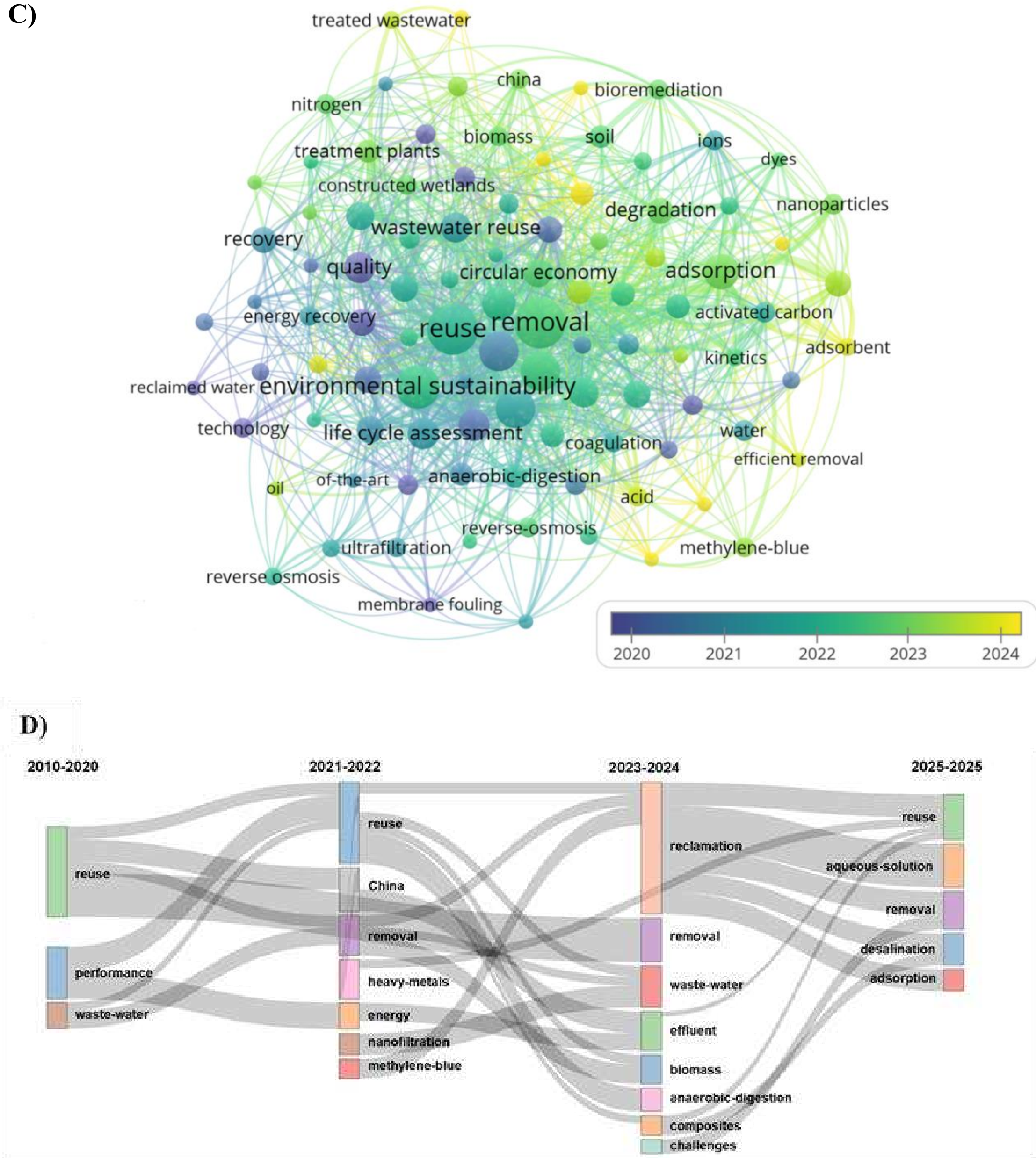

Figure 6. Bibliometric analysis of keywords related to wastewater reuse (2010-2025): A) Density map highlighting the most frequently occurring terms; B) Temporal overlay map showing keyword trends; C) Cluster map of thematic structures based on keyword relationships; and D) Temporal evolution of the main keywords

3.6 Emerging and rising themes

Figure 7 shows a thematic map built from the co-occurrence of keywords, based on a matrix normalized by cosine similarity and clustering via the Louvain algorithm. The clusters are distributed along two axes: centrality, which indicates the relevance of the topic in the scientific field, and density, which reflects its degree of internal development.

This visualization makes it possible to identify consolidated, emerging or peripheral themes in the area analyzed (Su; Lee, 2010).

The chronological analysis of the keywords shows a transition in the literature on wastewater use: from the traditional focus on treatment efficiency and pollutant removal to a more systemic and interdisciplinary approach. An agenda aimed at integrating concepts such as bioenergy, irrigation, resource recovery and the circular economy is gaining prominence, indicating the maturing of circular models in which water reuse is no longer a final solution but becomes part of sustainable production chains.

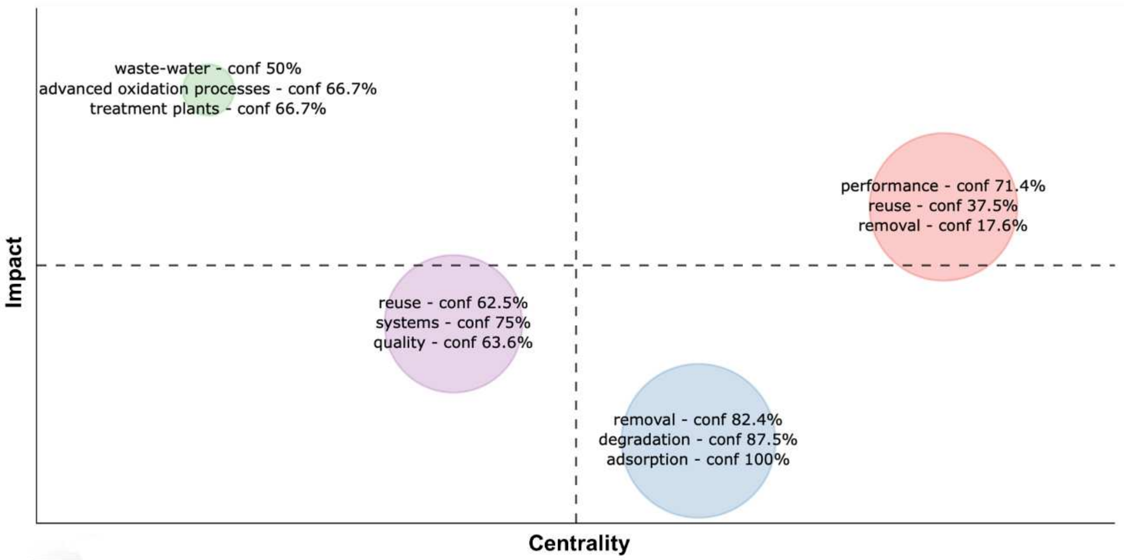

Figure 7. Temporal evolution and co-occurrence map of emerging topics in wastewater reuse research (2010-2025).

This trend is illustrated by studies such as that by Martins *et al.* (2024) investigating the use of agricultural and industrial waste in bioreactors to produce biohydrogen, integrating wastewater treatment with clean energy generation. The growing use of membrane bioreactors reinforces this integrated approach, promoting highly efficient hybrid processes that combine purification and energy use, as discussed by Kujawa, Giwa and Dindi (2019).

Another highlight is the advance of technologies based on constructed wetlands. Works such as those by Hendy *et al.* (2023) and Singh *et al.* (2021) demonstrate their technical and economic viability for domestic treatment and agricultural irrigation, especially in semi-arid regions. These solutions are particularly relevant from the perspective of water resilience, as they enable the recovery of biomass and the agricultural use of treated water.

The growth in the use of the terms "reuse in agriculture", "constructed wetlands", "sorption", "membrane bioreactors" and "life cycle assessment" after 2017 suggests a deeper technical and environmental evaluation of reuse systems. Opher and Friedler (2016) , for example, apply life cycle assessment to different scales of urban reuse, demonstrating the operational and environmental advantages of decentralized models.

Also noteworthy is the incorporation of resource recovery approaches, which go beyond water reuse to include the production of fertilizers, biogas, green hydrogen and phosphorus recovery through processes such as struvite precipitation and anaerobic digestion.

This paradigm shift is also reflected in the scientific questions that have come to guide the field, such as:

- What are the net environmental impacts of reuse in different contexts?
- Which technologies offer the greatest synergy between purification, recovery and value generation?
- How can water reuse be integrated into agro-ecological and energy planning?

These directions have significantly expanded the scope of the field, signaling a new generation of wastewater solutions based on the multifunctionality of effluents as strategic inputs.

3.7 Specific themes under development

The thematic map generated in Bibliometrix (Figure 8) allows recurring topics to be classified according to two axes: centrality (relevance in the field) and density (degree of conceptual maturity). This organization results in four quadrants with distinct characteristics:

- Top right quadrant - Driving themes: these include widely developed and central topics such as "wastewater treatment", "reuse", "performance" and "activated sludge". They are pillars of the literature, underpinning conventional technical practices with a high degree of consolidation.
- Upper left quadrant - Well-developed niche themes: these represent areas such as "sorption" and "membranes", with a high technical level, but little integration with other themes.

- Lower right quadrant - Emerging or transitional themes: these cover topics such as "bioenergy", "constructed wetlands", "irrigation" and "resource recovery", which stand out for their potential for productive integration.
- Lower left quadrant - Declining or still incipient themes: these include "industrial wastewater" and "UV disinfection", whose application has been replaced by hybrid approaches.

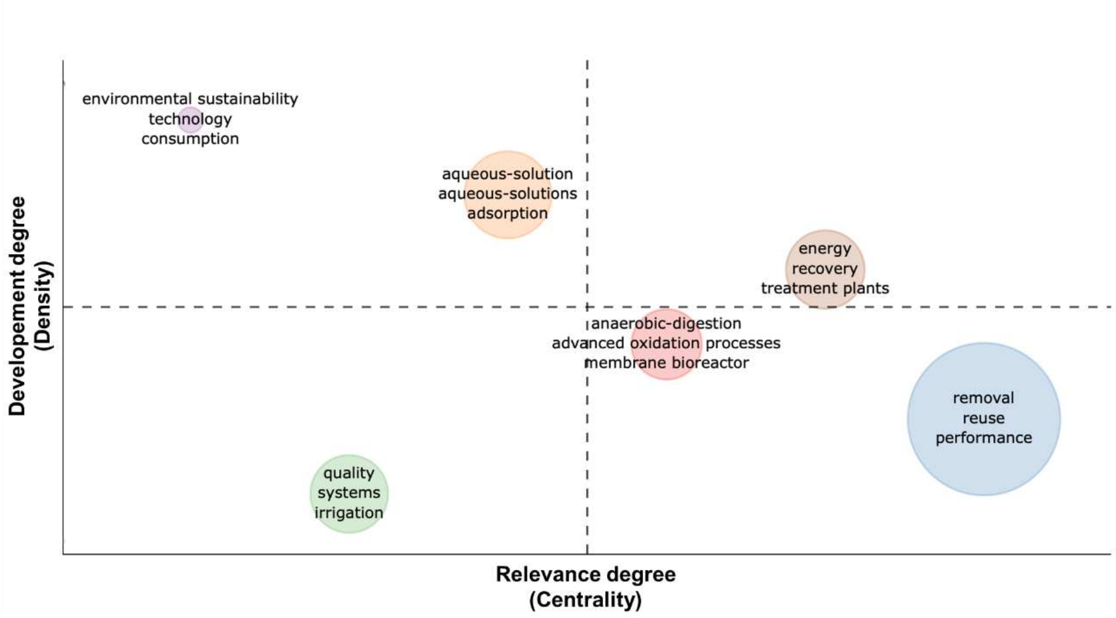

Figure 8. Strategic thematic map: Centrality and density of central, niche and transition themes in wastewater reuse.

These classifications reveal that although certain topics located in the lower left quadrant of the thematic map have low centrality and density, they should not be considered marginal. On the contrary, topics such as "quality", "systems" and "irrigation" point to emerging niches of great potential, especially when analyzed in the light of contemporary challenges such as water scarcity and pressure on agricultural production.

For example, irrigation practices with reused water are increasingly being studied as viable and sustainable alternatives in semi-arid regions and intensive agriculture, requiring customized approaches for monitoring water quality, phytosanitary safety and agronomic efficiency. The use of constructed wetlands with ornamental or forage plants, as investigated by Alemán-Chang *et al.* (2018) illustrates solutions that can be adapted to the peri-urban context, combining ecological and productive benefits.

Similarly, technologies such as membrane bioreactors, activated carbon and modified zeolites continue to be explored for wastewater treatment with a focus on removing emerging contaminants and compacting systems. Despite challenges such as operating costs and the formation of by-products, these technologies have potential for application in controlled irrigation systems, especially where water quality needs to be rigorously adjusted to the type of crop.

3.8 Integration between technical and strategic topics

The convergence between technical topics (such as adsorption, membrane filtration and anaerobic digestion) and strategic topics (such as sustainability, policy, governance and life cycle assessment) is one of the most significant transformations in the field of wastewater use. This trend is visible in the semantic groupings in Figure 7 and in the positioning of themes on the thematic map in Figure 8.

Khan *et al.*(2022) is an example of a researcher who argues that the expansion of safe reuse depends on technical robustness combined with public acceptance, clear regulations and transparency in the processes. A study by Hendy *et al.* (2023) shows that decentralized urban reuse systems can surpass traditional models, provided they are aligned with public policies and environmental education actions.

Local governments and public institutions play a strategic role in making reuse viable. Initiatives such as that of the city of Sant Cugat del Vallès (Spain), with economic incentives and clear regulatory frameworks, illustrate the impact of governance. Conceptual models such as those addressed by Kaya, Pintossi and Dane (2021) show that factors such as risk perception, consumer behavior and environmental trade-offs need to be considered in public policies.

This rapprochement between engineering, environmental economics and the social sciences represents an important turning point: reuse is now understood as a complex practice that requires multisectoral coordination for its acceptance and long-term viability.

3.9 Future trends and frontiers of knowledge

Figure 9 shows a co-occurrence map of keywords generated by multiple correspondence analysis (MCA). Based on a co-occurrence matrix, the terms are projected onto a two-dimensional space, where the proximity between them reflects semantic similarity. The clusters, defined by clustering algorithms (such as k-means), indicate cohesive thematic groups. This approach makes it possible to visualize the conceptual structure of the literature and identify central, emerging or peripheral areas in the field of study.

In this sense, the analysis of thematic clusters (Figure 9), combined with the strategic maps of centrality and impact (Figure 8), allows us to visualize the intellectual structure of the area of wastewater treatment with a focus on environmental sustainability, revealing recurring conceptual and technological groupings in publications between 2010 and 2025. These clusters reflect the different strands of scientific development and offer concrete clues for consolidating future agendas.

3.9.1 Red cluster - wastewater treatment and conventional technologies

This cluster concentrates keywords such as "removal", "performance", "effluent" and "pollution", reflecting the traditional focus on treatment efficiency. Studies highlight the evolution of systems based on converting activated sludge into biochar as an adsorbent for removing contaminants from water (Nancharaiah; Sarvajith, 2021) as well as the removal of nitrogen and phosphorus (Liu *et al.*, 2023). The high semantic density of this cluster reveals its maturity, but also its limited integration with broader sustainability approaches.

3.9.2 Green cluster - adsorption and advanced materials

This cluster is characterized by terms such as "Adsorption", "nanoparticles", "activated carbon" and "biochar", indicating advances in the use of synthetic and natural adsorbents. The review by Melo *et al.* (2024) highlights the use of nanocomposites based on enzymes (such as immobilized lipases) and hybrid materials (graphene, metal oxides) with high selectivity for emerging contaminants. In addition, recent studies point to strategies for in situ regeneration and the reuse of adsorbents in agriculture as soil conditioners.

3.9.3 Yellow cluster - sustainability and life cycle assessment

This cluster connects terms such as "life cycle assessment" and "circular economy", representing the effort to integrate environmental, energy and social metrics into reuse decisions. Khan *et al.* (2022) point to the growing incorporation of life cycle analysis, including water, energy and carbon footprint indicators, as well as multi-criteria approaches for strategic decisions in public policy. Although this cluster is dense, it has moderate centrality, which indicates that it has the potential to become a thematic driving force in the coming years.

3.9.4 Purple cluster - resource recovery and energy production

Terms such as "biogas", "biohydrogen" and "resource recovery" predominate here. The studies in this group, such as the one by Martins *et al.* (2024) use hybrid digesters to produce biohydrogen and stand out as a promising technological frontier. The interconnection between wastewater treatment, energy generation and nutrient recovery (such as struvite) reinforces the integration with the principles of the circular bioeconomy.

3.9.5 Blue cluster - agricultural reuse and irrigation

With keywords such as "irrigation", "quality", "salinity", "drip irrigation", "fertigation", this cluster represents a rapidly growing line of research and points to the growth of literature on the application of treated effluents in agriculture, especially in semi-arid areas. The interface between agronomic safety and water efficiency makes this cluster particularly strategic for semi-arid regions, as highlighted in the study by Xing and Wang (2024). In addition, emerging technologies, such as the use of produced water from the oil industry applied to agriculture, are gaining prominence and appear as promising alternatives in different regions of the world.

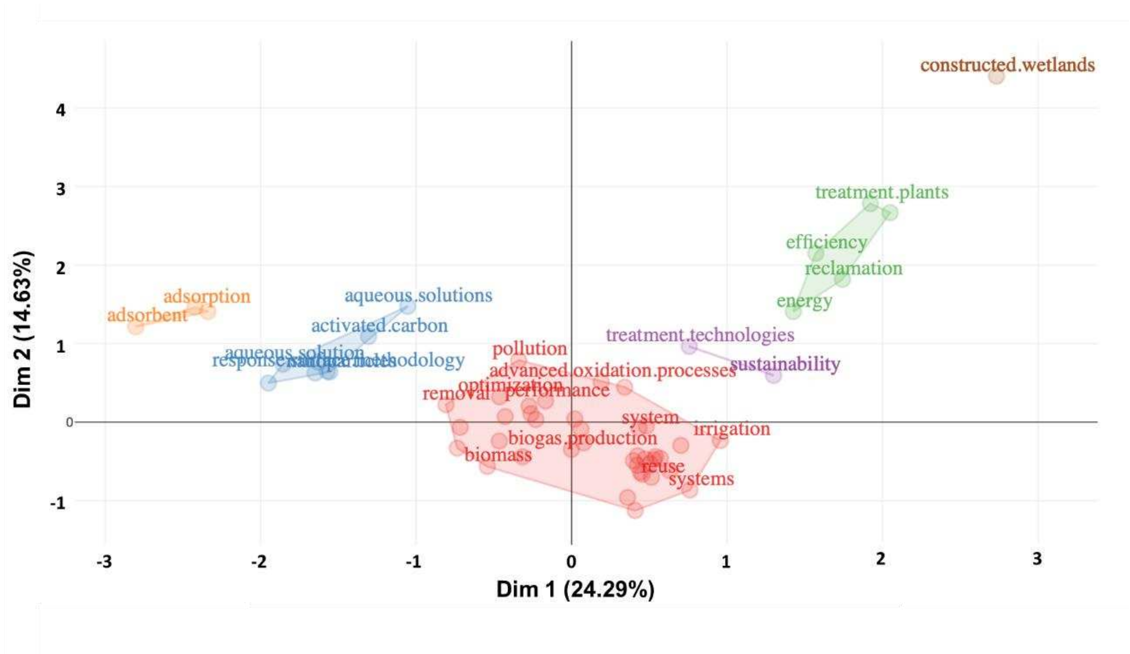

Figure 9. Keyword grouping and thematic grouping in wastewater reuse and environmental sustainability.

3.10. Thematic expansion: the keyword "produced-water" as an emerging insight

Once the emerging insight of the keyword "produced water" had been identified, a complementary scientometric search was carried out on the Web of Science database, using the same methodological approach adopted in this study. The combination of the terms "produced water", wastewater, reuse and "environmental sustainability", for the period 2010 to 2025, resulted in only 4 indexed documents (2 articles and 2 reviews), all in English. This small number shows that, although the term is present in the literature, there is not yet enough critical mass for a structured quantitative bibliometric analysis. Figure 10 shows the networks generated from these few results.

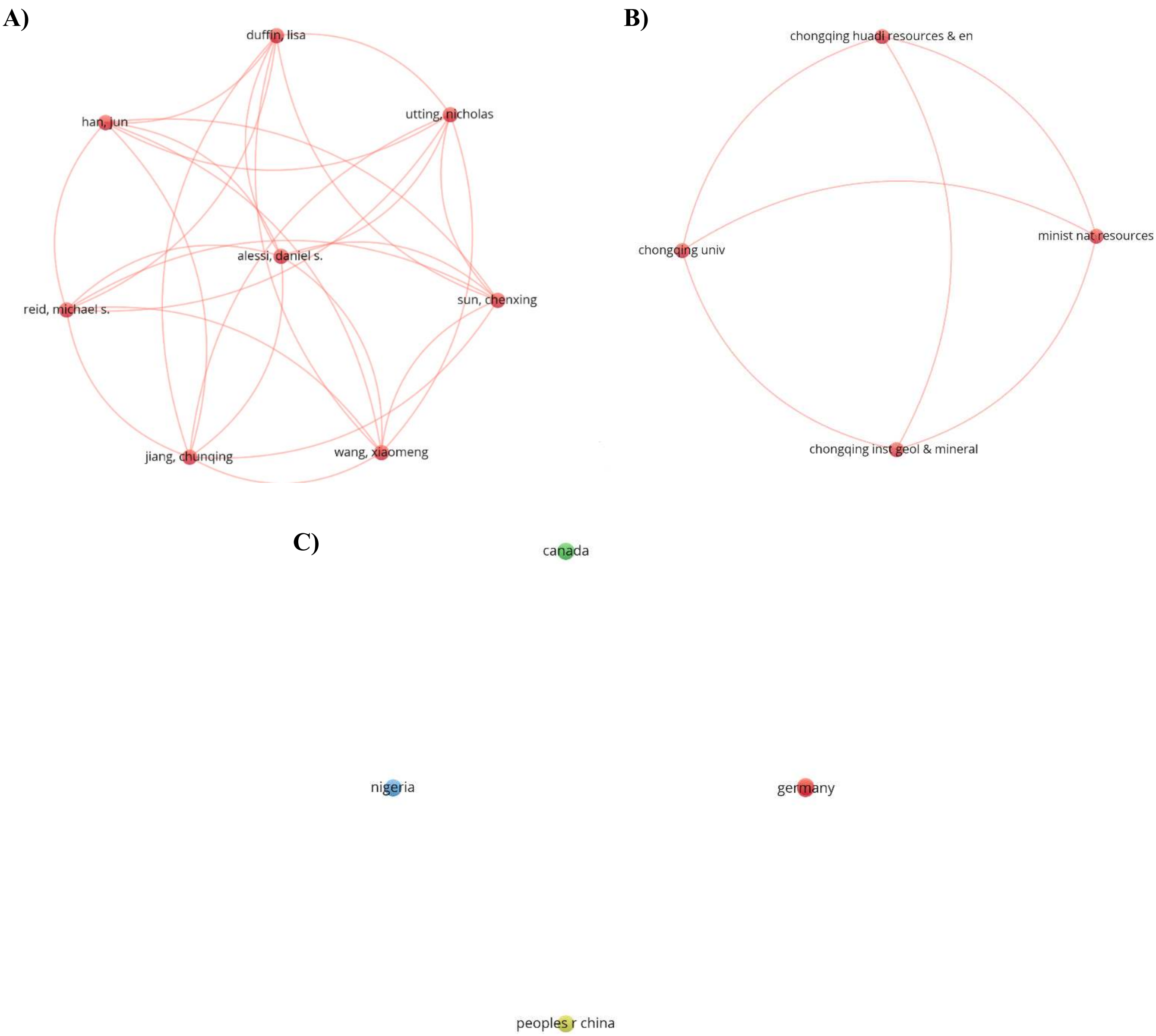

Figure 10. Networks based on the Web of Science keyword "produced water" (2010-2025): A) Author co-authorship network; B) Co-authorship network of institutions; C) Country co-authorship network.

The co-authorship network between authors (Figure 10) shows a restricted collaborative nucleus, led by Daniel Alessi and collaborators, with connections concentrated on studies on hydrocarbons and environmental impacts. However, the network of institutions (Figure 10B) is made up exclusively of Chinese institutions, with low geographical diversity, which reinforces the limitation of the internationalization of the theme in this specific context. The network of countries (Figure 10D) reveals an even more dispersed pattern: only five countries appear (China, Canada, Germany, the United States and Nigeria), without the formation of strong international links.

In terms of keyword co-occurrence analysis (Figure 11), it can be seen that "produced water" is associated with technical terms such as "wastewater", "organic compounds", "hydraulic fracturing", "natural gas" and "drinking water", signaling a thematic axis focused on the oil and gas industry, but still with a low density structure and no independent clusters. Despite the limitations found, the data reinforces that "produced water" is on the rise conceptually, being frequently mentioned in the body of the texts, although not formally registered as a keyword in several articles.

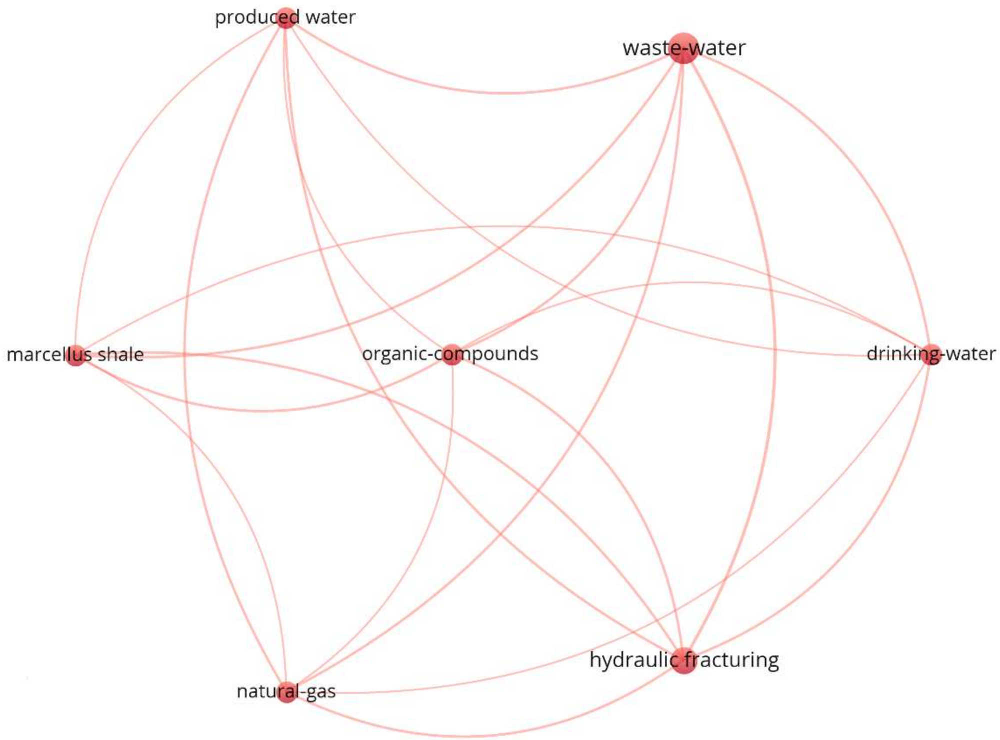

Figure 11. Keyword co-occurrence network obtained from the analysis of articles related to the expression "produced water", indexed in the Web of Science database (2010-2025).

3.11. Integration of clusters and "Insights" for the future

Despite the thematic segmentation between the clusters identified, there is a growing interconnectivity between the groups related to conventional wastewater treatment, adsorption and agricultural reuse. This convergence suggests a transition from the "pollutant removal" paradigm to an "effluent valorization" approach, especially relevant in the context of the circular economy.

This integration is even more strategic when considering the introduction of a new technological frontier: the reuse of "produced water" co-produced during the extraction of oil and natural gas. This is a large-volume industrial effluent with a complex composition (highly saline, with hydrocarbons, heavy metals and persistent organic compounds), which has historically been treated as waste, but is now beginning to be approached as a strategic resource in agricultural and energy contexts.

One study revealed that the available annual supply of produced water in the Permian Basin has been estimated at more than 45 million m^3 (Sabie; Pillsbury; Xu, 2022). Volumes generated by some wells in the United States produce 13 times more water than oil in mature fields, such as the Permian (Scanlon *et al.*, 2017). In Brazil, official data from the National Agency of Petroleum, Natural Gas and Biofuels (ANP, 2023) indicate that mature fields in the Recôncavo, Potiguar and Sergipe-Alagoas basins are still active, accounting for significant portions of total production. According to the ANP's Dynamic Production Panel, more than 80% of the water produced nationally comes from these mature fields, with volumes that often exceed those of extracted oil, requiring specific technological and logistical solutions for their management.

In addition to Brazil and the United States, countries such as Saudi Arabia, Iran, Algeria and China also face the challenge of managing produced water in advanced extraction fields. In Saudi Arabia, it is estimated that the ratio of water to oil in some fields exceeds 90%, making reinjection and strategic agricultural reuse a priority in arid regions. In Iran, public policies have encouraged controlled agricultural reuse, while in China pilot programs seek to integrate the reuse of this effluent with bioenergy chains and industrial reforestation.

The potential for reusing this water is especially associated with the irrigation of non-edible, salinity-tolerant crops (such as sorghum, elephant grass and halophytes), aimed at producing energy biomass. Technologies such as electrocoagulation (Tahreen; Jami; Ali, 2020), fluidized bed reactors (Bello; Abdul Raman; Purushothaman, 2017), advanced oxidative processes and bioremediation with microalgae (Ahmad *et al.*, 2022; Khan *et al.*, 2022) have shown promising results. In addition, studies point to the agronomic and environmental viability of systems that integrate partial desalination, bioadsorption and localized fertigation (Imbernón-Mulero *et al.*, 2023).

The application of microalgae stands out not only as a purification tool, but also as a producer of valuable biomass. Several studies have demonstrated their ability to metabolize toxic compounds, reduce heavy metals and generate raw materials for bioenergy and agricultural inputs (Christou *et al.*, 2024; Fito; Van Hulle, 2021; McLaughlin *et al.*, 2020).

This biomass can be converted into products such as briquettes and biochar - the latter widely recognized for its potential to sequester carbon and improve soil quality. Initiatives by startups such as Charm Industrial (United States), Qualterra (United States) and Varaha (India) have shown that the reuse of organic waste from biomass can be integrated into certified carbon credit markets (Karan *et al.*, 2023; Yang, Q. *et al.*, 2021).

This logic opens up space for an innovative model in which the oil industry itself, traditionally a generator of large volumes of wastewater, becomes a promoter of circular, low-carbon solutions. By using the water produced to cultivate fast-growing species with low nutritional requirements, a value chain is integrated that connects emissions mitigation, liability recovery and value generation.

Figure 12 illustrates the flow between the generation of produced water, its treatment and application in the irrigation of salinity-tolerant crops. These crops, such as sorghum, elephant grass and halophytes, are converted into biomass for the production of solid (briquettes), liquid (biodiesel) and gaseous (biogas) biofuels, as well as biochar for agricultural application. At the end of the cycle, this process generates measurable environmental benefits, including waste reduction, carbon sequestration and the generation of certified carbon credits.

This strategy is directly aligned with international commitments such as the Paris Agreement (IPCC, 2022; UNEP, 2023) and contributes directly to SDGs 6, 7 and 13. Organizations such as FAO, the Global Bioenergy Partnership (GBEP) and the International Renewable Energy Agency (IRENA) recognize the role of bioenergy integrated with water management as a resilient solution to climate change.

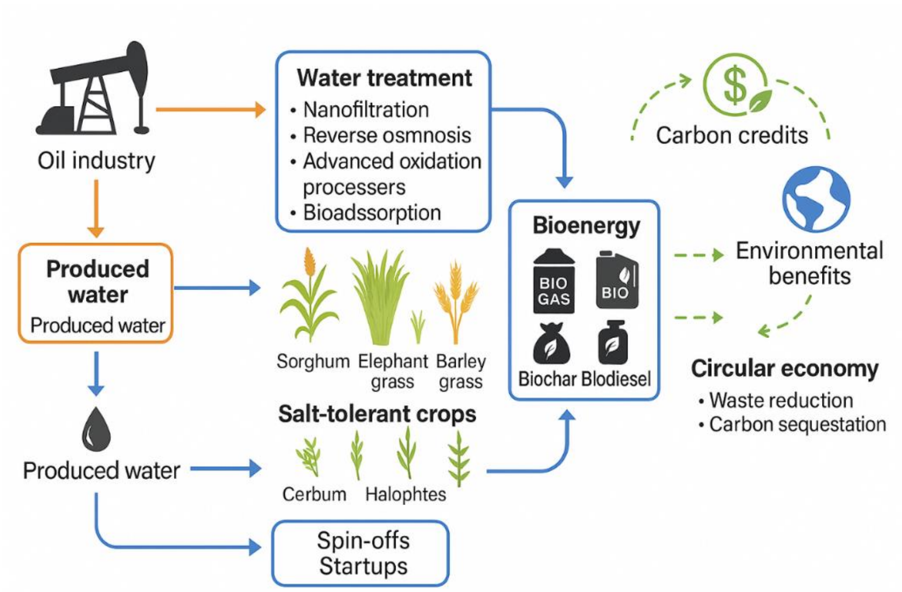

Figure 12. Conceptual framework for the agricultural reuse of produced water for bioenergy production and carbon circularity.

From a corporate point of view, the reuse of produced water represents a multifunctional strategy: it reduces operating costs with waste disposal, strengthens ESG (Environmental, Social and Governance) indicators and opens up opportunities for generating revenue with bioenergy and carbon credits (Cini; Ferrari, 2025). Major companies in the oil and energy sector, such as Shell, Equinor and Saudi Aramco, already highlight these guidelines in their sustainability reports, highlighting targets for reducing effluent disposal and increasing reuse in internal and external production chains. Such initiatives raise ESG scores and make companies more attractive to investors committed to sustainable criteria (GRESB, 2023).

From a commercial perspective, the systematization of these technological routes offers relevant subsidies for structuring new business models, validating spin-offs and formulating public and private policies that favour economically viable circular solutions. Faced with global commitments to carbon neutrality and water security, applied research and sectoral case studies will be decisive in guiding public and private managers to adopt resilient practices with a low environmental impact.

In the scientific field, the convergence between water reuse, energy agriculture and climate mitigation strategies forms an emerging and intersectoral agenda. The technical, environmental and economic viability of these systems still requires further investigation, especially in terms of the agronomic efficiency of crops irrigated with produced water, the behavior of contaminants in the soil and the indirect impacts on the water and carbon footprint (Ahmad *et al.*, 2022; McLaughlin *et al.*, 2020).

It is important to note that, in some contexts, the direct use of produced water, with minimal or no prior treatment, can be viable, especially for non-food crops grown in controlled or remote environments. This approach, while requiring rigorous ecotoxicological monitoring, can result in significant savings for extractive industries, especially where the costs of transportation and conventional water treatment are high.

This possibility is gaining momentum in arid regions with severe water scarcity and limited infrastructure, such as parts of Iran, Oman, Saudi Arabia and the Brazilian semi-arid region. In these scenarios, direct reuse, provided it is combined with safety protocols and adaptive management, can accelerate the implementation of circular models in industrial and agricultural chains (Danforth *et al.*, 2020; Helmecke; Fries; Schulte, 2020).

Thus, there is ample room for conceptual expansion and practical application of the reuse of produced water, particularly when associated with the production of bio-inputs and environmental valorization via carbon credits. In this context, new studies are essential for academic maturity and commercial innovation, promoting convergence between environmental engineering, agronomy, the circular economy and the energy transition. Bibliometrics is thus a strategic tool for mapping trends, identifying gaps and directing investments towards sustainability.

4. CONCLUSION

The bibliometric analysis carried out based on 183 publications indexed in the Web of Science between 2010 and 2025 made it possible to identify global trends, gaps and potential research directions related to wastewater, reuse and environmental sustainability. The annual evolution of publications revealed constant growth, with the years 2021 and 2023 standing out as having the highest number of published studies. China, the United States and India led the way in terms of volume of publications, while European countries such as Spain and Italy stood out for their higher average number of citations per article, indicating strong regional scientific influence. Chinese institutions such as the Chinese Academy of Sciences and Beijing Normal University were among the most productive, while the University of California system and the Consejo Superior de Investigaciones Científicas (Spain) had the greatest impact in terms of citations.

Among the most relevant journals were Science of The Total Environment, Journal of Cleaner Production and Water Research, all of which have a high impact factor and play a strategic role in scientific dissemination on the subject. The most frequent keywords reveal a technical and environmental approach, centered on the treatment, reuse and agricultural application of wastewater, reflecting the growing integration between water sustainability, food security and the circular economy. The thematic clusters indicate a consolidating field, with an emphasis on biological treatment, irrigation and energy.

An additional insight identified was the keyword "produced water", which, although not yet consolidated as a main descriptor, appeared in articles focused on industrial effluent management and environmental sustainability. A complementary search with this word, using the same methodological criteria, returned only four publications, an insufficient number for a robust bibliometric analysis. However, the co-occurrence networks formed indicated clusters related to the oil industry, hydraulic fracturing and environmental risks, suggesting an emerging and promising field.

Thus, the results provide a comprehensive overview of current scientific production on wastewater reuse and environmental sustainability, while highlighting opportunities for future research - especially on the use of produced water and its role in the energy transition and water security in vulnerable regions.

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CHAPTER II

WATER PRODUCED IN SUSTAINABLE AGRICULTURE: CHALLENGES AND OPPORTUNITIES IN THE BRAZILIAN ENERGY TRANSITION

Abstract - Produced water, the main effluent from the oil industry, constitutes one of the largest continuous flows of liquid waste in the global energy sector. Given the challenges related to water scarcity and the growing demand for sustainable solutions, the agricultural reuse of produced water emerges as a strategic alternative. It is estimated that global production of produced water reaches approximately 67 billion barrels per year. In Brazil, this volume corresponds to approximately 1.13 billion barrels per year, with the Potiguar Basin accounting for approximately 5.13% of this total, considering onshore and offshore operations. In this context, the revaluation of produced water for agricultural purposes, especially in semiarid regions with high demand for irrigation, can contribute to water security and the promotion of resilient production systems. This review article analyzes the main challenges and opportunities associated with the agricultural reuse of produced water in Brazil, with emphasis on its physical-chemical composition, potential risks associated with salinity, sodicity, and the presence of heavy metals and radionuclides, as well as available treatment technologies. Additionally, the study discusses gaps in national regulations and examines international experiences, such as those of the United States, especially Texas and New Mexico, where there are specific regulatory frameworks for the reuse of produced water in agriculture. The article also makes a comprehensive comparison between the Brazilian scenario and the international scenario, considering aspects such as generation volume, physical-chemical quality of produced water, regulatory maturity, and feasibility of agricultural reuse in different oil-producing regions. The results show that, with adequate treatment and management, produced water can be safely used for irrigation of non-food and bioenergy crops, such as sorghum, elephant grass, and cotton. The analysis also highlights the potential of this practice to generate carbon credits, reduce the water footprint of the oil industry and integrate circular economy principles, expanding environmental and economic benefits for the oil and gas sector.

Keywords: Bioenergy crops, Environmental management, Circular economy.

1 INTRODUCTION

Produced water (PW) is the main by-product of oil and gas extraction, constituting one of the largest continuous flows of industrial effluents in the world (Cooper *et al.*, 2021; Pichtel, 2016). Its generation, estimated at billions of cubic meters per year, is generally treated conventionally and reinjected or disposed of with minimal treatment (Fakhru'l-Razi *et al.*, 2009; Ibrahim *et al.*, 2023).

In mature fields, the water/oil ratio can exceed 3:1, raising management challenges (Assunção; Vieira; Almeida, 2018). The complex composition of PW, such as salts, hydrocarbons, metals and additives, requires advanced technologies to enable its safe reuse (Abdelhamid *et al.*, 2025; Echchelh; Hess; Sakrabani, 2020).

In recent years, the agricultural reuse of PW has been highlighted as a viable alternative, especially in arid and semi-arid regions. International studies demonstrate its safe use in the irrigation of non-food and bioenergy crops, reducing pressure on conventional water sources (Echchelh *et al.*, 2021; Pica *et al.*, 2017).

In Brazil, the Campos, Santos and Potiguar basins concentrate the largest volumes of PW, with monthly production exceeding 15 million m^3 (ANP, 2025). The proximity between onshore hubs and semi-arid agricultural areas, especially in the Northeast, favors agricultural reuse, in line with climate adaptation and water efficiency (Morais *et al.*, 2024; Oliveira *et al.*, 2022).

The reuse of PW can also integrate agro-energy models, irrigating salinity-tolerant crops such as sorghum, elephant grass and cotton, aimed at the production of biofuels (Chaganti *et al.*, 2020; Seleiman *et al.*, 2021). This strategy reduces competition with food crops, promotes circular economy and synergies between the energy, agriculture and water management sectors (Vazifedoust *et al.*, 2008; Yong; Wu, 2022).

This review article examines the state of the art on agricultural reuse of PW in Brazil, addressing: (i) treatment technologies; (ii) impacts on soil and crops; (iii) regulatory barriers and incentives; and (iv) connections with the energy transition and carbon credits. The analysis aims to subsidize public policies and research aimed at water and energy sustainability.

2. COMPOSITION OF PRODUCED WATER

2.1 Critical quality parameters of produced water

PW is a complex saline solution and its composition varies widely according to the geology of the reservoir, the production methods employed and the maturity of the fields. In mature formations, there is an increase in the volume of PW and the concentration of contaminants, which raises the challenges of management and reuse.

Total dissolved solids (TDS) vary globally between 10,000 and over 300,000 mg/L. Values higher than 150,000 mg/L are frequent in advanced offshore fields and in Middle Eastern basins (Al-Ghouti *et al.*, 2019; Dawoud *et al.*, 2024). In the United States, the Permian Basin records TDS between 129,000 and 137,000 mg/L, with a predominance of chlorides, sodium, high turbidity and significant organic load (Rodriguez *et al.*, 2020). In Brazil, the Potiguar Basin varies between 80,000 and 150,000 mg/L, with electrical conductivity above 5,500 µS/cm and salinity above 8,800 mg/L, showing a high salt load even in onshore operations.

Organic compounds include BTEX (benzene, toluene, ethylbenzene and xylenes) and PAHs (polycyclic aromatic hydrocarbons), whose concentrations can vary from 0.01 to 58 mg/L, as observed in countries such as Norway, Nigeria and Brazil. In Brazilian fields, BTEX levels vary between 8 mg/L (Sergipe-Alagoas) and 10 mg/L (values similar to those in San Joaquin, USA), which represents a phytotoxic risk even at low levels (Aguirre Hernandez, 2021).

Oil and grease levels in the PW range from 10 to 2,000 mg/L. In the Campos Basin, values can reach 386 mg/L (Gabardo *et al.*, 2011), affecting soil infiltration, root oxygenation and forming physical films that inhibit gas exchange (Jiménez et al., 2018).

With regard to trace metals, PW can contain elements such as Ba, Sr, Zn, Fe, Pb, Cd, Cu, As and Hg, at levels that depend on the geology and the time of interaction with the reservoir rocks. In the San Joaquin, barium reaches 2.6 mg/L, and in the Campos Basin, iron can reach 7.4 mg/L (Neff *et al.*, 2011). Records from the Potiguar Basin indicate the presence of Cd, Zn and Cu in concentrations compatible with ecotoxicological risk, which reinforces the need for monitoring to prevent bioaccumulation.

Naturally occurring radionuclides (NORMs), such as 226Ra and 228Ra, are also found. In the Permian, values range from 0.74 to 111 pCi/L (226Ra) and from 2.56 to 291 pCi/L (228Ra), often above the recommended limits for agricultural reuse (<5 pCi/L). These parameters require special attention and strict radiological control (Jiménez *et al.*, 2018; Rodriguez *et al.*, 2020).

Other relevant parameters include ammonia (NH_4^+), with values ranging from 70 to 432 mg/L, and sulphides (HS^-, S^{2-}), both with recognized phytotoxic potential. Ammonia above 70 mg/L, as observed in the Campos Basin, can damage germination and the absorption of essential nutrients. Sulphides, in addition to their smell and corrosiveness, can immobilize nutrients and compromise soil dynamics (Pichtel, 2016).

Table 1 summarizes the main chemical parameters of PW in different producing basins, including offshore and onshore formations in the USA, Norway, Nigeria and Brazil (Campos, Potiguar and Sergipe-Alagoas). The data show that offshore produced waters tend to concentrate greater organic complexity (BTEX, PAHs, oils and greases), while onshore waters, especially in arid regions and mature fields, have high levels of salts, metals and radionuclides.

In short, the composition of PW is highly variable and conditioned by geological and operational factors. This diversity poses distinct challenges for agricultural reuse, requiring detailed regional characterization, appropriate selection of treatment technologies and definition of specific technical criteria, taking into account environmental risks and regulatory requirements.

Table 1. Chemical parameters of produced water by region.

Country/State	Basin/Region/Company	Onshore/Offshore	Parameters	Reference
USA / California	San Joaquin Basin	Onshore	TDS: 10.000-40.000 mg/L; Ba: 2.6 mg/L; BTEX: up to 10 mg/L; PAHs: 5 mg/L	Neff *et al*. (2011)
USA / Colorado	Wattenberg Field	Onshore	pH: 8.9; TDS: 40.000 mg/L; TSS: 1.000 mg/L; Na^+: 12.000 mg/L	Cooper *et al*. (2021)
USA / Texas	Permian Basin	Onshore	pH: 7-7.5; TDS: 129-137 g/L; Cl^-: 65.000-67.000 mg/L; OG: 83-110 mg/L; Turbidity: 53-58 NTU; NH_4^+: 432 mg/L; Ba: 2.21 μg/L; Ra-226: 0.74-111 pCi/L; Ra-228: 2.56-291 pCi/L	Rodriguez *et al*. (2020)
Brazil / RJ	Campos Basin	Offshore	Toluene 1.065 mg/L; Xylene 0.135 mg/L; Naphthalene: 0.106 mg/L; Phenols: 4.3 mg/L; OG: 386 mg/L; NH_3: 70 mg/L; Ba: 1.3 mg/L; Fe: 7.4 mg/L; TPH: 28 mg/L	Gabardo *et al*. (2011)

Brazil / RN	Potiguar Basin	Onshore	pH: 6.6-8.2 Conductivity: 1.864-5.538 µS/cm Cl^-: 526-4.923 mg/L Salinity: 1.015-8.895 mg/L DO: 0.14-6.78 mg/L Nitrate: 12.6-19.3 mg/L Turbidity: 6.6-412 NTU OG: 38.8-97 mg/L TDS: 80.000-150.000 mg/L;	Figueredo *et al*. (2014); Costa *et al*. (2022)
Brazil / SE	Sergipe-Alagoas	Onshore	Cd: 0.09 µg/L; Cr: 24 µg/L; Cu: 1.3 µg/L; Ni: 8 µg/L; Pb: 3.5 µg/L; Zn: 140 µg/L; BTEX: 8 mg/L; PAHs: 6.5 mg/L	Dórea *et al*. (2007)
China	Sichuan Basin	Onshore (Shale)	pH: 6.45-8.29; TDS: 4.900-52.500 mg/L (average: 26,500); COD: 556-3.767 mg/L; Turbidity: 500-1.000 NTU	Zhang *et al*. (2019)
Russia	Various fields	Onshore	pH: 4.3-10; TDS: up to 400.000 mg/L; BTEX: 0.39-35 mg/L; COD: up to 120.000 mg/L; heavy metals: Ba, Sr, Fe, Zn, As, Pb, Cr, Cu	Costa *et al*. (2022)

Middle East	Abu Dhabi	Both	TDS: 233.000-292.500 mg/L; Ca^{2+}: 17.592-22.843 mg/L; COD: 1.686-7.937 mg/L; Oil: 186-6.802 mg/L; pH: 6.89-7.08; Turbidity: up to 671 NTU	Dawoud *et al*. (2024)
Norway	Norwegian Continental Shelf	Offshore	Oil: 11.7 mg/L; BTEX: 58 mg/L; PAHs: 1.5 mg/L; Ba: 1.100 mg/L; Fe: 75 mg/L	Bakke, Klungsøyr and Sanni (2013)
Nigeria	Niger Delta	Onshore	pH: 7.47-8.3; TDS: 3.200-7.000 mg/L; Ca^{2+}: 94-200 mg/L; Salinity: 2.700-4.400 mg/L; Turbidity: 10-79 NTU Zn: 0.68 mg/L; Cu: 0.05 mg/L; Fe: 0.89 mg/L;	Nwokoma and Dagde (2024)

Legend: pH - Hydrogen potential; Electrical conductivity (µS/cm) - Water's ability to conduct electricity, related to the concentration of ions; Salinity (mg/L) - Total concentration of dissolved salts; TDS - Total Dissolved Solids, in mg/L; TSS - Total Suspended Solids, in mg/L; COD/DQO - Chemical Oxygen Demand, in mg/L; DO - Dissolved Oxygen, in mg/L; NTU - Nephelometric Turbidity Units; Cl- - Chloride ion, in mg/L; Na^+ - Sodium ion, in mg/L; Ca^{2+} - Calcium ion, in mg/L; NH_4^+ - Ammonium ion, in mg/L; NH_3 - Free ammonia (non-ionized), in mg/L; Nitrate (NO_3-) - Soluble nitrogen form, in mg/L; Oil / Oils and Grease (OG) - Free or emulsified hydrocarbons, in mg/L; TPH - Total Petroleum Hydrocarbons, in mg/L; BTEX - Benzene, Toluene, Ethylbenzene and Xylenes, in mg/L; PAHs - Polycyclic Aromatic Hydrocarbons, in mg/L; Ra-226 and Ra-228 - Natural radionuclides radium-226 and radium-228, in picocuries per liter (pCi/L); Heavy metals: barium (Ba), strontium (Sr), zinc (Zn), copper (Cu), lead (Pb), cadmium (Cd), arsenic (As), iron (Fe), nickel (Ni), chromium (Cr).

2.2 Mature Fields: Profile and Particularities

The composition of PW varies substantially according to the stage of exploitation of the reservoirs. In fields considered young, in the early stages of oil production, the water/oil ratio (W/O) is usually less than 50%, resulting in reduced volumes of water generated. At this stage, PW tends to have a lower concentration of salts, trace metals and organic compounds, which makes it easier to manage and can make agricultural reuse feasible through simple quality adjustments (Aguirre Hernandez, 2021; Figueredo *et al.*, 2014).

On the other hand, in mature fields, usually at an advanced stage of production, the W/O ratio often exceeds 90%, accompanied by a significant increase in the volume of water extracted and the complexity of its composition. This worsening is related to the progressive depletion of reservoirs and the intensification of secondary recovery techniques, such as water injection, which mobilize salts, metals and contaminants from the geological matrix (Pichtel, 2016).

Table 2 summarizes the main differences between young and mature fields, based on criteria such as PW volume, total dissolved solids (TDS) content, presence of heavy metals, organic compounds (BTEX and PAHs), natural radionuclides (NORMs), estimated cost of treatment and feasibility of agricultural reuse. The data shows that although the mature fields concentrate the largest volumes of PW, their chemical characteristics impose additional restrictions on direct reuse, requiring more advanced and specific treatment technologies.

Table 2. Chemical parameters of produced water by type of field.

Criteria	Region	Young fields	Mature Fields	Reference
PW volume (barrels/year)	Permian (USA); Campos (Brazil)	10^6 - 10^7	>10^8	Cooper *et al.* (2021); GWPC (2023)
Water/oil ratio (W/O)	Mature fields in RN (Brazil)	<50%	>90%	Pichtel (2016); Figueredo *et al*. (2014)
TDS (mg/L)	Permian (USA); Middle East	10,000 – 50,000	80,000 – >200,000	Rodriguez *et al*. (2020); Dawoud *et al.* (2024)
Trace metals	Sergipe-Alagoas, Russia	Low/rare	Common: Ba, Pb, Cd, Hg, As	Costa *et al.* (2022) ; Jiménez *et al.* (2018)
Organic compounds (BTEX, PAHs)	Campos (Brazil), Norway	Rare or absent	Frequent; BTEX > 1 mg/L	Gabardo *et al*. (2011); Bakke et al. (2013)
NORMs (^{226}Ra, ^{228}Ra)	Middle East, Permian	Generally absent	Recurrent presence	Jiménez *et al*. (2018); Dawoud *et al*. (2024)
Cost of treatment	Permian (USA); Potiguar Basin	Moderate	High; requires multi-steps	Cooper *et al*. (2021); Veil *et al*. (2004)
Feasibility of agricultural reuse	Sergipe-Alagoas, Kuwait	High, after simple adjustments	Conditional on advanced treatment	Dórea *et al*. (2007); Aguirre Hernández (2021)

Legend: PW: Produced Water; W/O: Water/Oil Ratio; TSD: Total Dissolved Solids; BTEX: Benzene, Toluene, Ethylbenzene and Xylenes; PAHs: Polycyclic Aromatic Hydrocarbons; NORMs: Naturally Occurring Radioactive Materials; ^{226}Ra, ^{228}Ra: Radium Isotopes - Radium-226 and Radium-228.

In the United States, the Permian Basin stands out as one of the main producers of PW in the world, with annual volumes of over 1.6 billion barrels. Its waters have high salinity (TDS > 120,000 mg/L), the recurring presence of radionuclides (^226Ra and ^228Ra), heavy metals and volatile organic compounds such as BTEX and dissolved organic matter (Cooper *et al.*, 2021; Rodriguez *et al.*, 2020). These characteristics impose severe operational and environmental restrictions, requiring multi-stage treatment for any form of reuse.

A similar situation is observed in fields in the Middle East, especially in Saudi Arabia and Kuwait. With TDS often above 200,000 mg/L, as well as high levels of metals and radionuclides, these waters have sparked investments in advanced selective desalination technologies, making agricultural reuse feasible in contexts of extreme scarcity (Al-Ghouti *et al.*, 2019; Dawoud *et al.*, 2024).

In Brazil, the composition of PW varies according to the producing basin and the type of operation. In the Potiguar Basin, a mature onshore field in Rio Grande do Norte, TDS values range between 80,000 and 150,000 mg/L, with a significant concentration of metals and organic matter. Studies indicate the need for specific treatments to make it viable for agricultural irrigation (Figueredo *et al.*, 2014). The offshore Campos Basin has water with a high organic load (TPH, BTEX, ammonia) and metals such as iron and barium (Gabardo *et al.*, 2011). The Sergipe-Alagoas Basin, on the other hand, although less significant in volume, has significant concentrations of cadmium, chromium, zinc and PAHs, reinforcing the need for advanced removal technologies (Dórea *et al.*, 2007).

Comparing young and mature fields reveals a trend: as reservoirs age, PW becomes more saline, contaminated and complex, increasing treatment costs. Thus, agricultural reuse becomes dependent on the technical capacity to reduce salinity to levels compatible with irrigation (typically <2,000 mg/L), remove metals and toxic compounds, and control critical parameters such as ammonia and radionuclides (Jiménez *et al.*, 2018; Pichtel, 2016).

In the Brazilian context, this dynamic gains additional relevance. The coexistence of mature onshore fields in semi-arid regions, such as the Northeast, with high water demand and structural scarcity, creates a favorable scenario for the reuse of PW. However, its viability will require integrated efforts between science, technology, public policies and environmental regulation, taking into account the physical and chemical particularities of each basin and the agronomic requirements of local crops.

3. PRODUCED WATER: WORLD X BRAZIL

The water/oil ratio with field maintenance (water cut) can exceed 90%, which imposes growing operational and environmental challenges for the separation, treatment and final disposal of PW (Jiménez *et al.*, 2018). Recently, PW has been repositioned as an alternative water source, given the convergence between the energy transition, water scarcity and the promotion of the circular economy, which encourages its valorization, especially for agricultural uses in arid and semi-arid regions.

3.1 Global generation volumes

Global PW production varies between 100 and 300 billion barrels per year, depending on the methodological approach (GWI, 2022; Neff; Lee; DeBlois, 2011). Consolidated estimates put the volume at around 67.4 billion barrels/year, concentrated in the main producing regions (Cooper *et al.*, 2021; ANP, 2025).

The United States leads the ranking with 21.2 billion barrels/year, driven by unconventional basins such as the Permian, Bakken and Eagle Ford, where the water cut tends to be high from the start of production (Yang *et al.*, 2021). The Middle East comes next, with approximately 20 billion barrels/year, coming from mature and highly productive fields, such as Ghawar and Burgan (Al-Ghouti *et al.*, 2019). In China, there are around 9.4 billion barrels/year, mainly in the Songliao and Ordos basins, with growing investment in treatment technologies (Aguirre Hernandez, 2021). Russia (8.5 B bbl/year) and Canada (7.2 B bbl/year) also have significant production, with different regulatory and environmental approaches.

Countries such as Mexico, Venezuela, Nigeria and Algeria are not included in the consolidated data in Figure 1, but evidence points to fields with water cuts of over 95%, such as Maracaibo and Lagos, making PW management a critical challenge (Morais *et al.*, 2024; Jiménez *et al.*, 2018). In Brazil, annual production is estimated at 1.13 billion barrels, with the Campos, Santos and Potiguar basins standing out (ANP, 2025). Despite representing a smaller share of the global volume, the country has favorable climatic and geographical conditions for agricultural reuse, especially in the semi-arid regions of the Northeast.

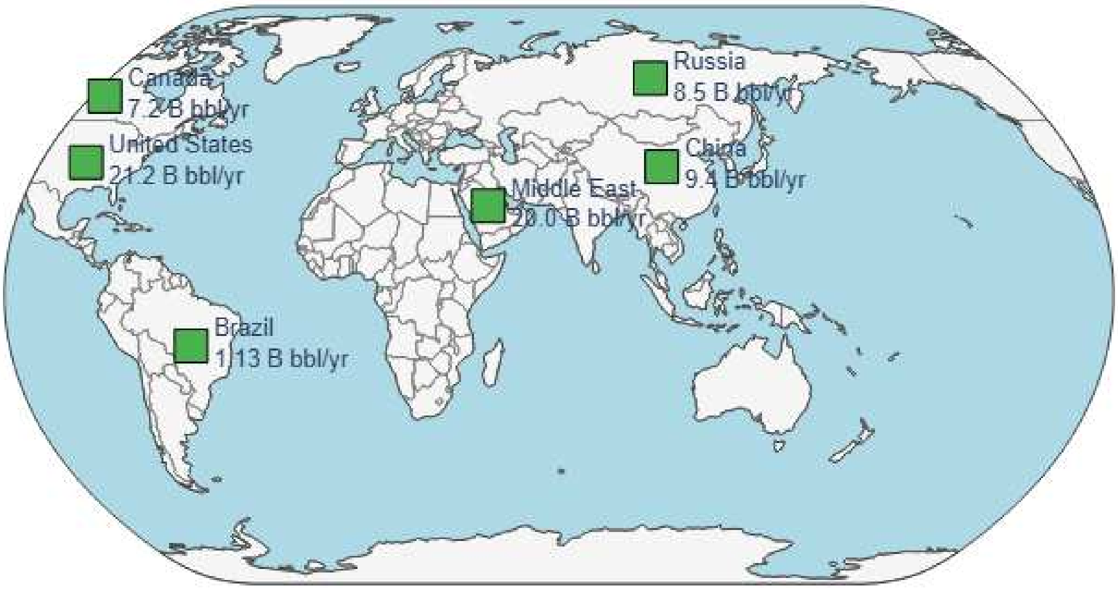

Figure 1. Global estimates of annual volumes of water produced by country/region (in billion barrels per year).

Source: GWPC (2015), Cooper *et al.* (2021), Al-Ghouti *et al.* (2019), Aguirre Hernández (2021), ANP (2025) and related sources.

3.2 The Brazilian PW production scenario

Brazil's PW production is structured into two operational domains: offshore, predominantly off the south-east coast, and onshore, concentrated in the north-east and north (Figure 2). Onshore wells stand out in the interior of Rio Grande do Norte, Bahia, Sergipe and Alagoas, while offshore fields are grouped together in Rio de Janeiro, Espírito Santo and São Paulo. This spatial division has direct implications for the logistics, cost and viability of PW reuse. Although more than 94% of national PW production takes place on offshore platforms, onshore operations offer greater potential for agricultural reuse, especially in semi-arid areas with unmet water demand.

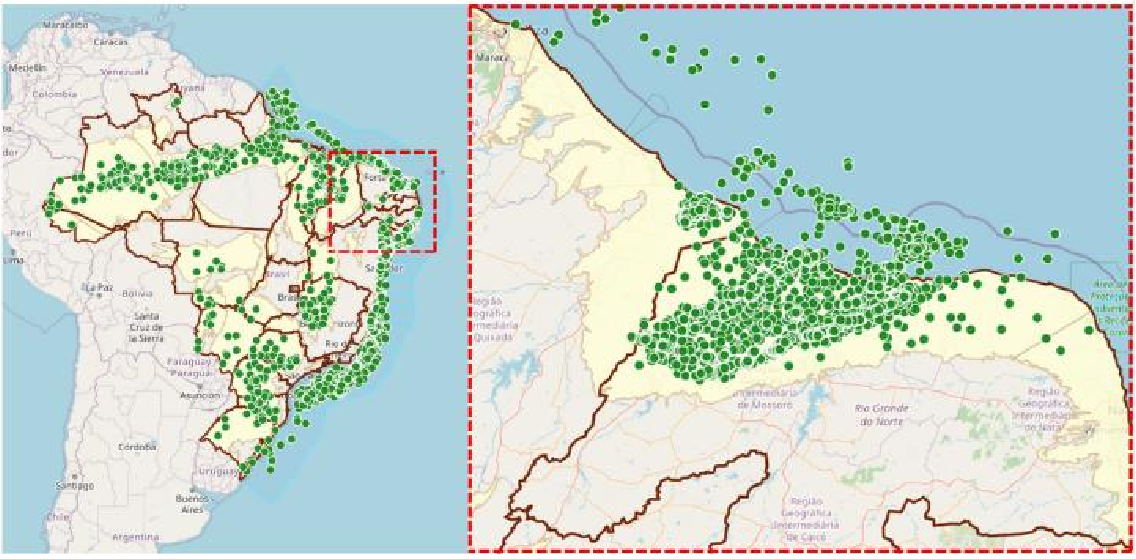

Figure 2. Distribution of Production Wells and Sedimentary Basins in Brazil: Onshore and Offshore Domains.

It is estimated that the country will produce around 1.13 billion barrels of PW/year (~180 million m³), in parallel with the extraction of 3.27 million barrels/day of oil and 931 thousand boe/day of natural gas (ANP, 2025). The Campos Basin, which is mature and highly productive, is home to fields such as Marlim, Albacora and Roncador, with high water cuts. However, offshore treatment faces operational and logistical restrictions, making agricultural reuse not very viable in this context (Pichtel, 2016).

The Santos Basin, in an intermediate stage of maturation, stands out for its pre-salt fields, such as Lula, Búzios and Sapinhoá, which tend to increase PW generation in the coming years, requiring new integrated solutions for their use. On the other hand, onshore basins such as Potiguar, Recôncavo and Sergipe-Alagoas offer the best conditions for direct agricultural reuse: proximity to agricultural areas, lower logistical costs and the presence of salinity-tolerant crops such as sorghum and elephant grass. These characteristics favor the implementation of decentralized pilot projects, with the potential for regional scaling.

3.3 Strategic potential of onshore operations

Although onshore operations account for only around 6% of the total volume of PW in Brazil, their strategic value is growing, especially in the context of integrated water resource management in semi-arid regions. Unlike the offshore environment, where high volumes of PW are generated on platforms far from the coast and agricultural zones, onshore fields are often located in water-deficit areas, where limited access to water compromises agricultural productivity and food security.

The Potiguar Basin is the main onshore producer of PW in the country, with an estimated volume of 979,000 barrels/day (ANP, 2025). Operating mostly in areas with a high water/oil ratio and close to rural territories, this basin has favorable characteristics for the local application of treated PW. Its consolidated infrastructure, with highways, pipelines and processing plants, facilitates the transportation and distribution of the effluent. The existence of ongoing agricultural reuse pilot projects reinforces the region's technical and institutional capacity, indicating the feasibility of scaling up.

According to criteria such as a minimum daily volume of over 100,000 barrels, access logistics, proximity to irrigable areas and operational maturity, Table 3 classifies the Potiguar Basin as having high potential for agricultural reuse. This position is even more relevant given the persistent water scarcity in the semi-arid northeast, which demands sustainable solutions for non-conventional water use.

Other land basins also stand out. The Recôncavo Basin, in Bahia, produces around 389,626 barrels of PW per day and is part of a diversified agricultural territory, with growing irrigated areas. The Sergipe-Alagoas Basin, with production of more than 156,000 barrels per day, has consolidated logistics, including road access and refining facilities, which facilitates the integration of reuse systems in the regional context. The Espírito Santo Basin, although a mixed operation (onshore/offshore), has significant onshore fields, with production estimated at 80,257 barrels per day, and proximity to small farms, making it classified as having medium potential for agricultural reuse.

On the other hand, basins such as Tucano Sul, Parnaíba and Barreirinhas have lower production volumes, as well as geographically dispersed wells and poor transportation and treatment infrastructure, resulting in low or very low potential for agricultural reuse, according to the same criteria evaluated.

Therefore, even though most of Brazil's PW comes from offshore operations, onshore fields concentrate the most favorable conditions for local agricultural reuse, especially in the Northeast. The convergence of PW availability, agricultural vocation and regional water vulnerability offers a window of opportunity for synergistic solutions between the energy and agriculture sectors. With regulatory and technological support, agricultural reuse of PW can generate environmental benefits, strengthen local economies and boost production practices in line with the circular economy.

Table 3. Potential for agricultural reuse of produced water in Brazilian oil basins.

Basin	Oil (bbl/d)	Crude oil (bbl/d)	Condensate (bbl/d)	Natural gas (boe/d)	Produced water (bbl/d)	Operation (predominance)	Agricultural Reuse Potential
Alagoas	2,595.83	2,167.61	428.23	6,977.19	8,681.70	Onshore	Middle
Amazonas	261.41	48.37	213.04	3,695.00	0.00	Onshore	----
Barrerinhas	33.09	33.09	0.00	7.94	4.16	Offshore	Very low
Camamu	123.67	0.02	123.65	8,966.16	58.53	Offshore	Offshore
Fields	718,929.50	718,929.49	0.00	76,002.37	1,349,942.26	Offshore	Very low
Ceará	0.00	0.00	0.00	0.00	0.00	Offshore (inactive)	----
Espírito Santo	13,383.41	13,248.28	135.12	4,131.83	80,257.16	Onshore/Offshore	Middle
Paraná	0.19	0.19	0.00	153.86	0.10	Onshore	Very low
Parnaíba	35.18	0.00	35.18	17,562.72	0.08	Onshore	Very low
Potiguar	**33,191.56**	**33,005.94**	**185.62**	**6,678.9**	**979,394.52**	**Onshore/Offshore**	**Upper**
Recôncavo	18,581.83	18,465.66	116.18	15,590.67	389,626.76	Onshore	High
Santos	2,472,830.27	2,470,276.59	2,553.62	705,423.78	235,145.11	Offshore	Very low
Sergipe	7,230.53	7,230.53	0.00	295.63	156,854.73	Onshore/Offshore	Upper
Solimões	12,049.24	8,632.24	3,417.00	85,195.41	21,028.76	Onshore	Low
Tucano South	6.94	0.00	6.94	619.56	11.75	Onshore	Very low
Total	3,279,252.65	3,272,038.01	7,214.58	931,301.02	3,221,005.62	----	----

Legend: Very low: PW< 100 bbl/d or offshore with no logistical viability; Low: 100 ≤ PW < 10,000 bbl/d and/or offshore with limited viability; Medium: 10,000 ≤ PW < 100,000 bbl/d, with partial onshore access or mixed logistics; High: PW ≥ 100,000 bbl/d and predominantly onshore with good access to agricultural areas.

3.4 Priority fields for agricultural reuse in the Potiguar Basin

The Potiguar Basin, located between the states of Rio Grande do Norte and Ceará, is currently the main onshore PW producing region in Brazil. According to Moura *et al.* (2024) the onshore fields in the basin generated approximately 58.86 million m³ of PW in 2021, 59.31 million in 2022 and 55.53 million in 2023, around 50% of the basin's total production. With a daily average of 979,000 barrels, the region has a network of fields with favorable characteristics for agricultural reuse, such as a high water/oil ratio, proximity to rural areas and consolidated logistics infrastructure. A significant part of this volume is reinjected into reservoirs, but the remaining volumes have a high potential for use, especially in semi-arid areas with unmet water demands.

The reuse of PW can benefit the cultivation of crops for biofuel production in marginal areas, expanding the supply of biomass without competing with food agriculture. This strategy also contributes to generating local jobs and reducing greenhouse gas emissions (Schlesinger; Amundson, 2019; Shuaibu *et al.*, 2024). Table 4 shows the main fields in the Potiguar Basin, classifying them according to production volume, operational profile and reuse viability.

Two fields stand out due to the significant volume of PW and the operational conditions that favor agricultural reuse. The Canto do Amaro field, with average production of 307,675 barrels per day, is the largest onshore producer in the region. Located in Mossoró-RN, close to the Santa Cruz do Apodi irrigated perimeter, it combines a high water/oil ratio, installed infrastructure and road access via the BR-304 highway, which makes it an exemplary case for implementing systems to capture, treat and supply water for irrigating crops such as corn, sorghum, beans and tropical fruit. The Estreito field, with 258,076 barrels per day and operated by 3R Petroleum, is located near the rural area of Areia Branca. The concentrated distribution of the wells makes it possible to set up centralized treatment systems, with redistribution by water trucks or small pipelines for local family farming.

Among the intermediate-sized fields, Monte Alegre stands out, with 24,827 barrels per day, close to communities focused on horticulture and irrigated fruit growing, which opens up prospects for decentralized pilot projects. Guamaré, with production of 18,165 barrels per day, stands out due to the presence of industrial infrastructure and its association with refining activities, which could facilitate the integration of PW treatment units. Other fields, such as Lorena (2,604 barrels/day) and Boa Esperança (1,576 barrels/day), although with modest volumes, are well located in relation to small farming communities, which makes reuse possible with reduced logistical costs. Brejinho, Jaçanã and Upanema, with production of less than 2,000 barrels per day, also have a favorable territorial location, in contexts marked by family farming.

On the other hand, fields such as Trinca Ferro, Poço Xavier, Maçarico, Praia do Meio and Colibri have volumes of less than 100 barrels per day. In these situations, the low availability of PW, combined with the lack of infrastructure in the vicinity, compromises the economic viability of reuse solutions, making their agricultural application unfeasible on a large scale.

In general, the Potiguar Basin has significant logistical and territorial advantages for implementing agricultural PW reuse projects. Its structured road network, made up of federal and state highways, provides an efficient connection between the producing fields and the regional agricultural hubs. Its proximity to consolidated irrigated perimeters, such as Mossoró-Assu and Apodi, under the management of institutions such as the National Department for Works Against Droughts (DNOCS) and the São Francisco and Parnaíba Valley Development Company (Codevasf), reinforces the potential for integration. In addition, the presence of rural communities located within a radius of up to 30 kilometers from various fields facilitates decentralized supply by short-distance transport. These factors, combined with the context of water scarcity in the semi-arid region, consolidate the region as a strategic territory for agricultural reuse of the water produced.

Table 4. Potential for agricultural reuse of produced water in Brazilian oil basins.

Field	Operator	Oil (bbl/d)	Crude oil (bbl/d)	Condensate (bbl/d)	Natural Gas (boe/d)	Produced water (bbl/d)	Operations	Agricultural Reuse Potential
Alto do Rodrigues	3R Petroleum	2,333.76	2,333.76	0.00	9.10	6.04	Onshore	Very low
Asa Branca	Potiguar E&P	54.89	54.89	0.00	83.15	220.93	Onshore	Low
Baixa do Algodão	Potiguar E&P	42.50	42.50	0.00	1.24	809.06	Onshore	Low
Lower Juazeiro	Potiguar E&P	0.00	0.00	0.00	3.19	0.00	Onshore	----
Barrinha	3R Petroleum	0.49	0.49	0.00	0.01	5.02	Onshore	Very low
Boa Esperança	Potiguar E&P	678.10	678.10	0.00	510.75	2,595.65	Onshore	Medium
Brejinho	Potiguar E&P	802.54	802.54	0.00	467.72	2,175.33	Onshore	Medium
Cachoeirinha	Potiguar E&P	289.89	289.89	0.00	388.58	560.91	Onshore	Low
Canto do Amaro	**3R Petroleum**	**6,667.45**	**6,667.45**	**0.00**	**143.73**	**307,675.83**	**Onshore**	**Alto**
Cardinal	3R Petroleum	274.40	274.40	0.00	1.69	0.96	Onshore	Very low
Cioba	3R Petroleum	0.00	0.00	0.00	0.00	0.00	Offshore	----
Colibri	3R Petroleum	2.70	2.70	0.00	0.03	1.65	Onshore	Very low
Narrow	**3R Petroleum**	**4,469.27**	**4,469.27**	**0.00**	**11.8**	**258,076.25**	**Onshore**	**High**
Curral Farm	Potiguar E&P	28.36	28.36	0.00	1.04	324.41	Onshore	Low
Junco Farm	Potiguar E&P	9.56	9.56	0.00	1.03	39.70	Onshore	Very low
Fazenda Malaquias	Potiguar E&P	81.41	81.41	0.00	1.00	3,299.56	Onshore	Low
Guamaré	3R Petroleum	809.88	809.88	0.00	3.48	18,164.9	Onshore	Medium
Jaçanã	Potiguar E&P	67.61	67.61	0.00	1.10	1,943.31	Onshore	Middle
Janduí	Potiguar E&P	247.81	247.81	0.00	18.53	35.39	Onshore	Very low
Juazeiro	Potiguar E&P	7.64	7.64	0.00	9.95	39.88	Onshore	Very low
Livramento	Potiguar E&P	570.07	570.07	0.00	352.02	2,653.27	Onshore	Medium
Lorena	Potiguar E&P	1,234.93	1,234.93	0.00	1,317.7	1,535.38	Onshore	Medium
Torch	3R Petroleum	5.20	5.20	0.00	0.35	2.07	Onshore	Very low
Monte Alegre	3R Petroleum	433.87	433.87	0.00	34	24,826.82	Onshore	Middle
Pajeú	Potiguar E&P	92.98	92.98	0.00	1.28	4,851.14	Onshore	Medium
Pardal	Potiguar E&P	14.86	14.86	0.00	17.34	2.64	Onshore	Very low

Patativa	Potiguar E&P	54.79	54.79	0.00	1.26	394.48	Onshore	Low
Paturi	Potiguar E&P	216.18	216.18	0.00	3.03	373.92	Onshore	Low
Green Well	3R Petroleum	19.33	19.33	0.00	0.09	126.87	Onshore	Low
Xavier Well	Potiguar E&P	1.33	1.33	0.00	1.11	91.63	Onshore	Very low
Riacho da Forquilha	Potiguar E&P	1,359.43	1,359.43	0.00	478.93	9,581.57	Onshore	Lower
Mossoró River	Potiguar E&P	28.84	28.84	0.00	2.47	3.44	Onshore	Very low
Sabiá	Potiguar E&P	502.76	502.76	0.00	82.25	332.31	Onshore	Bass
Sabiá Bico-de-Osso	Potiguar E&P	1,598.08	1,598.08	0.00	416.27	598.05	Onshore	Low
Sabiá da Mata	Potiguar E&P	661.83	661.83	0.00	46.39	98.76	Onshore	Very low
Sibite	Potiguar E&P	45.78	45.78	0.00	1.18	271.35	Onshore	Low
Três Marias	Potiguar E&P	25.92	25.92	0.00	0.25	1,187.98	Onshore	Low
Trinca Ferro	Potiguar E&P	40.87	40.87	0.00	9.35	104.37	Onshore	Low
Ubarana	3R Petroleum	0.00	0.00	0.00	0.00	0.00	Offshore	----
Upanema	Potiguar E&P	86.91	68.64	18.27	82.98	1,104.33	Onshore	Low
Varginha	Potiguar E&P	53.12	53.12	0.00	4.06	236.90	Onshore	Low

Legend: Very low: PW < 100 bbl/d or offshore with no logistical viability; Low: 100 ≤ PW < 10,000 bbl/d and/or offshore with limited viability; Medium: 10,000 ≤ PW < 100,000 bbl/d, with partial onshore access or mixed logistics; High: PW ≥ 100,000 bbl/d and predominantly onshore with good access to agricultural areas.

4. MANAGEMENT AND TREATMENT OF PRODUCED WATER

The efficient management of PW requires the careful selection of treatment technologies that are capable of mitigating environmental risks and making its reuse technically feasible. Considering its high physical-chemical complexity, influenced by factors such as the geology of the formation, the length of time the wells have been in production and the additives used, it is essential to adopt technological solutions suited to the specific operating conditions of each producing field.

Figure 3 shows a schematic flowchart that summarizes the essential steps in PW management, from its physical-chemical characterization to the possibilities for reuse after treatment, including the critical requirements for agricultural applications. To make this reuse viable, especially in irrigated agriculture, it is necessary to meet quality criteria defined by international guidelines, such as those of the Food and Agriculture Organization - FAO (1985), which set limits for parameters such as electrical conductivity (CEi), sodium adsorption ratio (SAR), pH and heavy metal concentration. Various technologies have been applied or tested for this purpose, grouped into five broad categories: thermal processes, membrane separation, physical-chemical methods, biological treatments and emerging technologies.

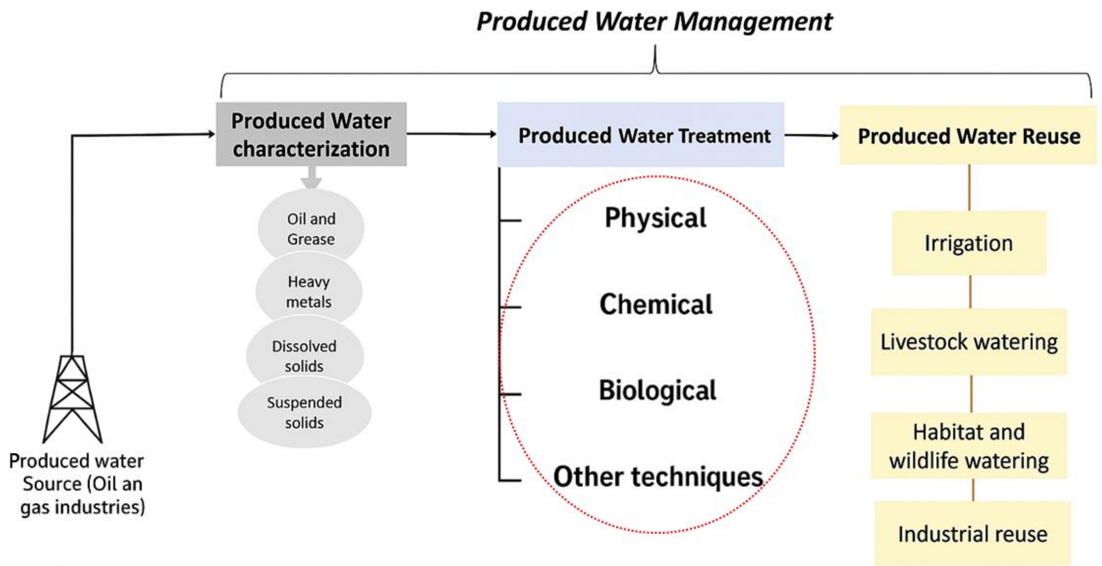

Figure 3. Flowchart of produced water management: characterization, treatment and reuse possibilities. Source: Adapted from Al-Ghouti et al. (2019).

Figure 4 summarizes the main PW treatment technologies, classifying them according to the type of process (physical, chemical, membranes, thermal, biological or advanced) and the estimated relative cost per cubic meter of treated water. This categorization allows for a comparative analysis of the available methods, considering the technical and economic viability of their application in different operational contexts.

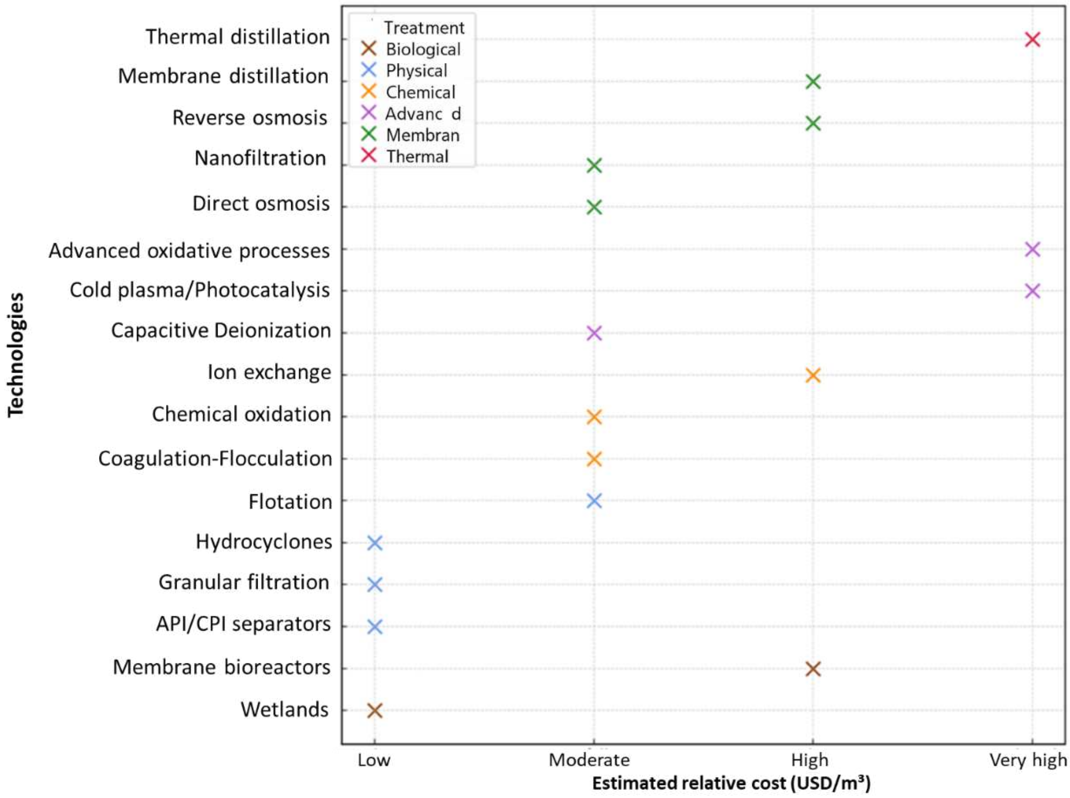

Figure 4. Produced water treatment technologies x costs.

Thermal processes, represented in the figure by conventional thermal distillation, have the highest specific cost, with values above 3.50 USD/m³, classified as "very high" in the metric adopted (Curto; Franzitta; Guercio, 2021; Veil, 2011) . Despite their high efficiency in removing salts and dissolved solids, their intense energy consumption and high operating costs limit their adoption in regions such as the semi-arid northeast, where energy availability and operational infrastructure are limited.

In the membrane group, technologies such as reverse osmosis, nanofiltration, direct osmosis and membrane distillation occupy an intermediate position in terms of cost. Reverse osmosis (RO) and nanofiltration (NF) are estimated to cost between 1.50 - 3.50 USD/m³ and are classified as high cost (Echchelh *et al.*, 2019; Curto *et al.*, 2021). On the other hand, direct osmosis (DO) and membrane distillation (MD), which are more recent, are positioned in the medium cost range, between 0.50-1.50 USD/m³, and are promising for arid regions, given their lower energy demand and greater tolerance to fouling (Du *et al.*, 2024; Khayet; Matsuura, 2011; Nawaz *et al.*, 2016).

Physico-chemical methods, widely represented in the figure, such as flotation, coagulation-flocculation, chemical oxidation and ion exchange, are mostly in the medium cost range. These technologies work to remove turbidity, oils, metals and dissolved organic compounds, and are effective as pre- or post-treatment. Ion exchange, although efficient, is more expensive and appears to be a high-cost technology, given the price of the materials and the need for periodic regeneration (Jiménez *et al.*, 2018).

Physical methods include API/CPI separators, hydrocyclones and granular filtration, all of which are classified as low cost (<0.50 USD/m³). These technologies are simple to operate and are widely used in the initial stages of treatment, removing suspended solids, oils and grease with high efficiency, especially in onshore contexts (Curto; Franzitta; Guercio, 2021; Veil, 2011).

Biological technologies, such as membrane bioreactors (MBRs) and constructed wetlands, have different cost ranges. MBRs are in the high cost range, while wetlands - characterized by simplicity, low energy consumption and integration into the rural environment - are among the lowest relative cost solutions, at less than 0.50 USD/m³, making them particularly attractive for decentralized projects (Scholz, 2023).

Finally, advanced technologies such as Capacitive Deionization (CDI), Cold Plasma/Photocatalysis and Advanced Oxidative Processes (AOPs) are referred to as innovative solutions, but with costs ranging from medium to very high. AOPs (Advanced Oxidation Processes) and Cold Plasma, for example, involve highly energetic reactions and operational complexity, which raises their costs beyond 3.50 USD/m³, restricting their large-scale adoption (Du *et al.*, 2024; Mousset *et al.*, 2021; Naicker *et al.*, 2023). On the other hand, CDI (Capacitive Deionization), with a medium cost, represents a promising alternative for selective salt removal, especially in waters with moderate TDS.

The cost classification metric was based on consolidated references in the literature (Curto; Franzitta; Guercio, 2021; Du *et al.*, 2024; Echchelh *et al.*, 2019; Jiménez *et al.*, 2018; Veil, 2011) and followed the following ranges:

- Very high: > 3.50 USD/m³
- High: 1.50 - 3.50 USD/m³
- Medium: 0.50 - 1.50 USD/m³
- Low: < 0.50 USD/m³

Based on this classification, it can be seen that the technologies with the lowest relative cost are mostly physical and biological, effective in removing solids and biodegradable organic compounds, but with low efficiency for desalination. On the other hand, the most efficient methods for removing salts and persistent contaminants, such as reverse osmosis and thermal distillation, require high investments in energy, maintenance and infrastructure, which can limit their application in remote regions or those with limited technical capacity (Curto; Franzitta; Guercio, 2021; Du *et al.*, 2024; Jiménez *et al.*, 2018).

In this context, hybrid and modular solutions that combine physical-chemical pre-treatment stages with adapted membrane technologies are emerging as a promising alternative for the safe and economically viable reuse of PW. This approach is especially relevant in mature onshore fields, such as those in the Potiguar Basin, where there is proximity to agricultural areas and high generation of PW with a water/oil ratio of over 90% (Figueredo *et al.*, 2014; ANP, 2025).

Furthermore, in situations where PW has low concentrations of oils, heavy metals, BTEX and other contaminants monitored by environmental standards, the use of controlled dilution techniques with freshwater sources can be adopted to reduce salinity and improve the agronomic parameters of the water, such as EC and SAR, to acceptable levels for irrigation (Ayers; Westcot, 1994). This strategy, already applied in semi-arid regions such as northern Africa, southern India and northeastern Brazil, allows optimizing available volumes without the need for high-cost desalination processes, as long as it is accompanied by continuous monitoring of the quality of the final mixture and the irrigated soil (Gabardo *et al.*, 2011; Pichtel, 2016; Silva *et al.*, 2017).

5. REGULATORY FRAMEWORKS FOR AGRICULT URAL REUSE OF PRODUCED WATER

5.1 International panorama

The regulation of agricultural reuse of PW remains fragmented on a global scale, with significant variations between the main producing countries. In the United States, the world's largest generator of PW, legislation is decentralized and defined by state bodies. Currently, only four states have explicit regulations on the reuse of PW in agriculture.

Figure 5 summarizes the main international regulatory frameworks and allows for an objective comparison between different regions in terms of five key dimensions: the existence of a specific standard, formal permission for agricultural reuse, monitoring requirements, the definition of technical limits and the presence of agronomic and health criteria. The US states of California, Texas and New Mexico stand out as having the most robust regulations, with consolidated normative and operational requirements. Australia occupies an intermediate position, adopting guidelines based on risk assessment and classification of the type of crop irrigated. On the other hand, countries like Saudi Arabia, China, Russia and Canada have incipient or non-existent regulations, showing the absence of specific public policies for the reuse of PW in agriculture.

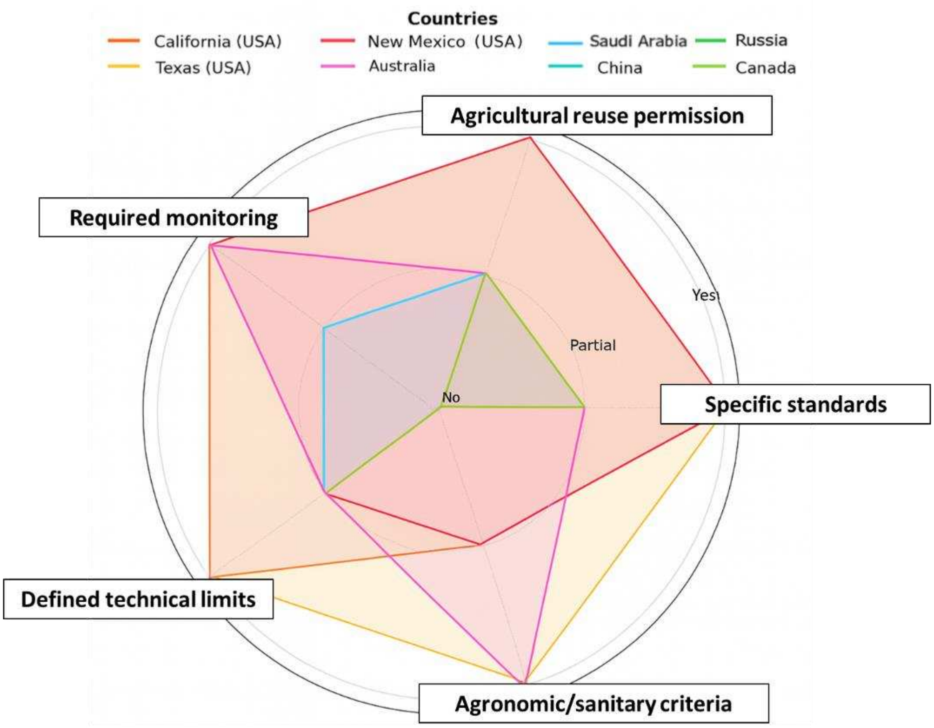

Figure 5. International regulatory frameworks for agricultural reuse of produced water. Sources: GWPC (2021); Echchelh et al. (2020); Al-Ghouti et al. (2019).

In Texas, agricultural reuse of PW is authorized through a specific permit issued by the Texas Commission on Environmental Quality (TCEQ), which sets limits for total dissolved solids (TDS), volatile aromatic hydrocarbons (BTEX), metals and oil and grease. In 2019, the state of New Mexico introduced the Produced Water Act, a regulatory framework that enables the external reuse of produced water (PW) beyond oil and gas operations, with technical support from the Produced Water Research Consortium. This regulatory framework allows PW to be used for beneficial purposes, as long as environmental and health safety criteria are met. On the other hand, California adopts a more restrictive approach, especially with regard to the use of PW in food crops, requiring complete traceability, continuous monitoring and strict compliance with federal health guidelines (Echchelh *et al*., 2021; GWPC, 2021). These regulatory models show different degrees of institutional maturity and normative strategies, and can serve as a reference for countries seeking to structure public policies aimed at reusing PW safely and sustainably.

In Australia, reuse management follows the guidelines of the National Water Quality Management Strategy (NWQMS), which establish criteria based on health risk, type of crop irrigated and intended end use. In countries in the Middle East and North Africa, such as Saudi Arabia, Oman and Morocco, although water scarcity is severe, agricultural reuse of PW is still little explored, mainly due to the low quality of the effluent and the lack of specific technical standards (Al-Ghouti *et al.*, 2019; Echchelh; Hess; Sakrabani, 2020).

In the other major global producers, such as China, Russia and Canada, the scenario remains unstructured. China has broader environmental regulations for industrial effluents, but does not yet have specific standards for the agricultural reuse of PW (Al-Ghouti *et al.*, 2019). In Russia, the practice of re-injecting PW predominates, with no guidelines identified for external reuse. In Canada, regulation takes place at provincial level, with a focus on controlled disposal and resource recovery, without a consolidated federal framework for agricultural uses (Aguirre Hernandez, 2021).

5.2 The Brazilian situation: gaps and opportunities

In Brazil, there is still no specific federal regulatory framework for the agricultural reuse of PW. The resolutions of the National Environment Council CONAMA No.º 357/2005 (BRASIL, 2005) and No.º 393/2007 (BRASIL, 2007) deal with the classification of water bodies and the discharge of effluents, but do not take into account the physical-chemical particularities of PW, such as high salinity, the presence of trace metals and organic compounds typical of oil production (Fakhru'l-Razi *et al.*, 2009; Leite, 2020).

State regulations are also incipient. COEMA Resolution No.° 02/2017 (COEMA, 2017), in force in the state of Ceará, is the closest to a framework for the reuse of non-potable water in agriculture. It establishes important guidelines, such as the mandatory classification of irrigated crops, the systematic monitoring of soil, water and plants, and the preparation of management and sanitary control plans. Although this resolution does not explicitly refer to PW, its structure could serve as a basis for specific regulation.

Recent studies suggest that the reuse of PW in Brazil could be made feasible, as a priority, in mature onshore fields with a high water/oil ratio, located in semi-arid areas close to agricultural hubs. Regions such as the Potiguar Basin (RN-CE) and the Recôncavo Baiano stand out as potential pilot zones for the development of agricultural PW reuse projects, given the coexistence of oil production and water scarcity (Figueredo *et al.*, 2014).

In light of international experiences and the Brazilian reality, it is proposed to create a national regulatory framework that defines minimum criteria for the agricultural reuse of PW, considering agronomic, environmental and public health aspects (Echchelh *et al.*, 2021; GWPC, 2023; Leite, 2020).

Table 5 presents a preliminary proposal for PW quality parameters for irrigation purposes, adapted from FAO and EPA guidelines and Brazilian environmental legislation. The suggested limits aim to guarantee the safety of agricultural use, minimizing the risks of soil contamination, bioaccumulation of heavy metals and phytotoxic effects.

Table 5. Proposed quality criteria for agricultural reuse of PW in Brazil.

Parameter	Proposed Limit	Justification	Reference
TDS	≤ 5,000 mg/L	Adapted from FAO, EPA	Ayers and Westcot, 1985
SAR	≤ 10	Risk of sodicity in clay soils	Ayers and Westcot, 1985
Total BTEX	≤ 0.1 mg/L	Phytotoxic potential and health risk	Oetjen *et al*. (2018)
Oil and grease	≤ 10 mg/L	Adherence to soil and roots	CONAMA No.º 430/2011
Boron	≤ 0.5 mg/L	Sensitivity of fruit trees	Morais *et al*. (2024)
Metals (Zn, Cu, Pb)	According to CONAMA No.º 420/2009	Accumulation and phytotoxicity	CONAMA No.º 420/2009

The construction of these regulations should be guided by an adaptive approach, with gradual implementation in pilot areas and with specific monitoring and management protocols. States like Ceará, Rio Grande do Norte and Bahia, with a history of onshore production and water vulnerability, are strategically positioned to lead this agenda.

Recognizing PW as a potentially reusable water resource, and not just as an environmental liability, is a fundamental step towards consolidating agricultural reuse policies in line with water security, agricultural sustainability and environmental protection.

6. THE USE OF WATER PRODUCED IN AGRICULTURE

The reuse of treated wastewater in agriculture has been consolidated as an essential strategy in regions affected by water scarcity, promoting the efficient use of resources, food security and reducing environmental impacts (Du *et al.*, 2024; Jiménez *et al.*, 2018; Oetjen *et al.*, 2018). In the Brazilian semi-arid region, PW stands out as a viable alternative for non-food agricultural uses, especially in onshore basins such as Potiguar and Recôncavo, where high generation of PW and a chronic lack of conventional water resources overlap.

Experimental studies and systematic reviews (Alley *et al.*, 2011; Echchelh *et al.*, 2019; McAdams *et al.*, 2019) indicate that the use of PW in agriculture depends directly on the efficiency of the treatment adopted, the final composition of the water and the choice of crops with greater tolerance to abiotic stresses. Critical parameters such as EC, SAR, boron content, heavy metals and pH must be strictly monitored and can be adjusted by technologies such as reverse osmosis, controlled dilution or the use of agricultural correctives (Dolan; Cath; Hogue, 2018; Fakhru'l-Razi *et al.*, 2009).

The compatibility between the available volumes of PW and the agronomic requirements of the crops depends on the management strategies adopted. Trials conducted in the Potiguar Basin show that, even with supplementary irrigation equivalent to 20-40% of crop evapotranspiration (ETc), crops such as sorghum and elephant grass maintain high yields (Lima *et al.*, 2021; Santos *et al.*, 2021). The use of fertigation, mulching, application of agricultural gypsum and surface drainage has shown good results in mitigating the effects of salinity on the soil.

The compositional variability of PW over time and between fields reinforces the importance of adaptive operational protocols, including continuous water quality monitoring, ecotoxicological risk analysis, the use of genetically adapted varieties and the application of precision irrigation techniques (Al-Ghouti *et al.*, 2019). The definition of the crops to be used must take into account, in addition to agronomic aspects, economic, logistical and territorial factors.

International literature points out that non-food crops intended for bioenergy, fiber production or animal feed are more suitable for PW reuse, due to their resilience to high levels of salinity and fluctuations in water quality (Echchelh *et al*., 2021; Jha *et al.*, 2022; Santos *et al.*, 2021). Studies conducted in semi-arid environments in California, New Mexico and North Africa confirm the viability of crops such as sorghum, millet, fodder palm, elephant grass and cotton under irrigation regimes with saline water between 3 and 8 dS/m. Table 6 presents a summary of the main crops studied, considering their tolerance to salinity, water use efficiency, productive purpose and regions where field experiments were conducted.

Table 6. Promising crops for reuse with produced water: technical and agronomic characteristics.

Crop	Scientific Name	Salinity tolerance (dS/m)	Water Use Efficiency	Main Purpose	Countries with Applied Studies	References
Sorghum	Sorghum bicolor	Moderate (4-6)	High	Bioenergy / fodder	USA, Morocco, Brazil	Figueredo *et al*. (2014)
Elephant grass	Pennisetum purpureum	Moderate to high (6-8)	Very high	Bioenergy / fodder	Brazil, Nigeria, Mexico	Solano *et al*. (2014)
Cotton	Gossypium hirsutum	Moderate (5-7)	Medium	Textile fiber	India, Brazil, Egypt	Bezerra *et al*. (2012)
Castor bean	Ricinus communis	High (>8)	Medium	Vegetable oil	Brazil, Tunisia	Morais *et al*. (2024)
Sugarcane	Saccharum officinarum	Moderate (3-5)	High	Bioenergy	Brazil, India	Fakhru'l-Razi *et al*. (2009)
Fodder palm	Opuntia spp.	Very high (>10)	High	Animal feed	Brazil, Mexico, Morocco	Echchelh *et al*. (2019)

6.1 Environmental and agronomic impacts of produced water use

Although the reuse of PW in agriculture represents a strategic opportunity for the integrated management of water resources in semi-arid regions, this practice involves significant challenges, especially in relation to preserving soil quality, crop productivity and environmental protection. The complex composition of PW, often rich in soluble salts, sodium, heavy metals, metalloids and naturally occurring radionuclides (NORMs), can jeopardize the sustainability of agricultural systems if adequate monitoring and management measures are not adopted (Jiménez *et al.*, 2018; McAdams *et al.*, 2019; Oetjen *et al.*, 2018).

6.2 Salinity and sodicity

High salinity, expressed by EC values that are often higher than those recommended for irrigation, is one of the main limiting factors for the use of PW in agriculture. The accumulation of salts in the soil can compromise water absorption by plants, cause ionic toxicity, reduce root growth and, consequently, negatively affect productivity (Hualpa-Ramirez *et al.*, 2024; Maas, 1984).

In addition to the effects on plant physiology, the excessive presence of sodium ions in the soil solution can induce sodicity processes, which include dispersion of clay particles, structural collapse, reduced infiltration rate and increased surface compaction. These effects compromise aeration and hinder root development (Echchelh *et al.*, 2019). SAR is an essential indicator for diagnosing this risk. Studies have shown that SAR values of more than 6 can significantly compromise the physical properties of soil irrigated with saline or sodic water (Alley *et al.*, 2011).

Figure 6 illustrates the response of different agricultural crops to soil salinity, according to the classic model proposed by Maas (1984), showing the thresholds of tolerance to the electrical conductivity of the soil saturation extract (ECe).

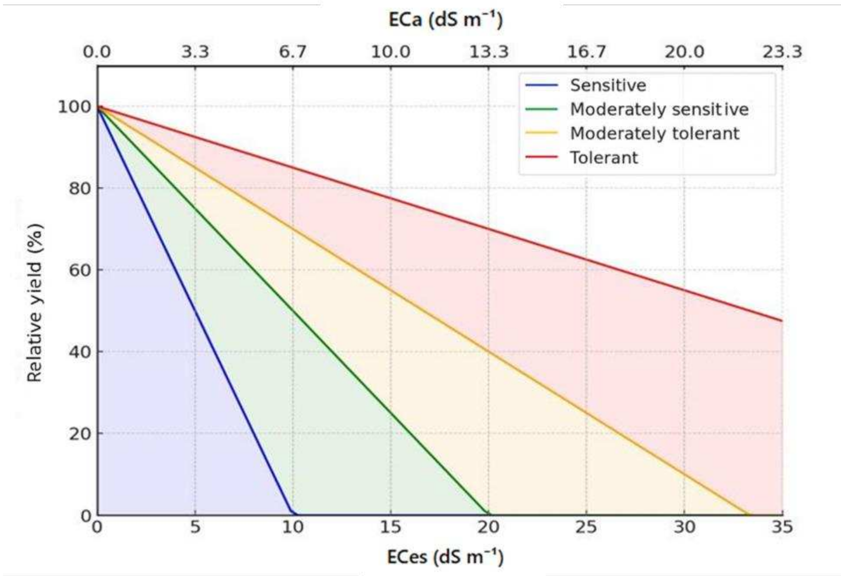

Figure 6. Response curves of agricultural crops to soil salinity.

6.3 Heavy metals and NORMs

PW can contain potentially toxic elements such as barium (Ba), cadmium (Cd), lead (Pb) and arsenic (As), as well as natural radionuclides such as uranium-238 (^{238}U) and radium-226 (^{226}Ra). The presence of these contaminants represents a significant concern, since they have high environmental persistence, bioaccumulation capacity in the soil and potential absorption by plants. When not properly monitored, these elements can cause phytotoxic effects and pose risks to human health and the environment, especially in agricultural food chains (McAdams *et al.*, 2019; Oetjen *et al.*, 2018).

Even in systems with non-food crops, such as those aimed at producing bioenergy or fodder, continuous monitoring of the presence and behavior of these contaminants in the soil is indispensable to ensure the integrity of the ecosystem and avoid indirect impacts, such as leaching into aquifers.

The mobility and bioavailability of heavy metals and radionuclides are influenced by various factors, such as soil pH, textural composition, organic matter content and redox conditions (Dashtey, 2024; Dragović *et al.*, 2012). Clay soils, for example, tend to retain more metals due to their greater ion exchange capacity, while acidic soils increase the solubility and transport of these contaminants. Organic matter can form complexes with metals, increasing or reducing their mobility, depending on the type of interaction.

CONAMA Resolution No.º 420/2009 (BRASIL, 2009) establishes guideline values for the concentration of contaminants in soils, serving as a normative reference for assessing the feasibility of reusing PW. However, factors such as exposure time, the nature of the soil and the physiological characteristics of the crops grown must be considered for a more realistic and contextualized risk assessment.

6.4 Short- and long-term effects and mitigation strategies

In the short term, the negative effects of PW use can be barely perceptible, especially when there is dilution or prior treatments. Field studies indicate that crops such as sorghum, elephant grass and cotton can maintain productivity even under irrigation with treated PW, as long as the parameters are within acceptable ranges (Ebrahimian *et al.*, 2019). However, the long-term impacts are still uncertain, especially in relation to the accumulation of salts and metals in the soil and the potential for groundwater contamination (Echchelh *et al.*, 2019). Table 7 summarizes the main impacts of this effluent on crops and soil attributes, considering different PW compositions and management scenarios.

Table 7. Main impacts of produced water use on agricultural crops and soil.

Impact	Description of impact	Effect on crops
Hydrocarbon toxicity	Presence of compounds such as benzene, toluene and xylenes	Inhibits water absorption; damages cell membranes and causes reduced growth
Heavy metals	Accumulation of lead, cadmium and mercury	Inhibits root growth and reduces photosynthesis
High salinity	High concentration of salts in the PW	Causes water stress, reduces water absorption and has a greater impact on salinity-sensitive crops
Changes in the soil	Reduced porosity, aeration and microbial activity	Causes damage to root development and reduces nutrient cycling
Phytotoxicity	Direct damage to plants due to the presence of chemical compounds	Chlorosis; necrosis and reduced biomass
Accumulation of contaminants	Absorption of heavy metals and hydrocarbons by plants	Causes risks to human and animal health and contaminates grains, fibers and biomass
Reduced productivity	Combination of all of the above	Reduces the production of fibers, grains, oil and biomass

Source: Adapted from Alley *et al*. (2011), Echchelh (2019), McAdams *et al*. (2019) and other data from the literature.

Adopting good management practices is key to reducing environmental and agronomic risks. Some of the most recommended strategies are shown in Figure 7.

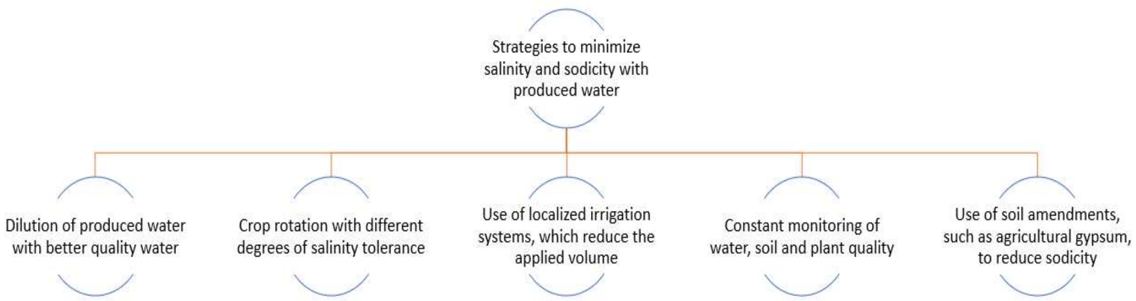

Figure 7. Strategies for mitigating environmental risks with produced water and good management practices.

These practices, when integrated into a management plan adapted to local conditions, can enable the sustainable use of PW in agriculture, promoting economic gains, water conservation and the valorization of marginalized areas.

6.5 Brazilian panorama and convergence with sustainable policies

In Brazil, the reuse of PW in agriculture has aroused growing interest, especially in semi-arid regions, where water scarcity represents a structural challenge. Case studies show that, with appropriate treatment technologies and management strategies, it is possible to use PW to irrigate crops without compromising productivity. Gonçalo Filho *et al.* (2020) identified positive effects on the nutritional status of cotton irrigated with reuse water, while Sousa (2015) highlighted the potential of this practice to guarantee productive autonomy in family farming in the semi-arid region of Paraíba. A systematic review carried out by Jeronimo (2022) reinforces the growing trend in national research on this subject, signaling its potential as a solution to water insecurity.

At the same time, the integration of PW reuse with public policies aimed at bioenergy and sustainability increases its viability. The Brazilian energy matrix is mostly renewable, with 48% of its composition coming from clean sources such as biomass, hydroelectric, solar and wind (EPE, 2022). In the case of the electricity matrix, this share exceeds 80%, driven by the advance of solar energy, whose installed capacity grew from 11.6% to 17% between 2023 and 2024, reaching 39 GW (ABSOLAR, 2024). Even so, sectors such as transportation and part of industry remain heavily dependent on fossil fuels, making biofuels, such as biodiesel and ethanol, strategic components in the energy transition (Demirbas, 2008; Park *et al.*, 2021).

Programs such as Proálcool, PNPB and, more recently, PATEN (launched in 2024), have consolidated Brazil's role as a reference in bioenergy incentive policies (BRASIL, 2025b, 2025a) . Irrigation with PW of dual-purpose crops - energy and fodder - such as sorghum, elephant grass and cotton, can be integrated into these programs, enabling interconnected production systems that simultaneously ensure food production, energy generation and rational use of water.

6.6. Sustainability, Circular Economy and Carbon Credits

The reuse of PW in agriculture is also in line with the principles of the circular economy, as it transforms a waste product from the oil industry into an input for agro-energy production. This reuse reduces the pressure on conventional water sources, optimizes the use of resources and contributes to the sustainability of production systems, especially in regions with water scarcity.

Applying the circular economy to agriculture requires not only technical solutions, but also integrated socio-economic approaches. Purvis; Celebi and Pansera (2023) advocate the adoption of Responsible Research and Innovation (RRI) as a tool to guarantee social justice in the implementation of circularity. Kirchherr *et al.* (2023) and Liu (2024) point out that without incorporating this social dimension, the circular economy runs the risk of being limited to technocratic discourses, disconnected from the reality of the territories.

The PW reuse strategy also contributes directly to achieving the Sustainable Development Goals (SDGs), in particular SDG 6 (drinking water and sanitation), by promoting the reuse and preservation of water resources; SDG 7 (clean and affordable energy), by promoting bioenergy; SDG 12 (responsible consumption and production), by incorporating reuse practices; and SDG 13 (climate action), by increasing carbon sequestration and reducing emissions associated with the use of fossil fuels.

In addition, the use of PW in integrated agricultural systems can generate carbon credits from the sequestration of CO_2 in biomass and soil, the replacement of inputs and the recovery of degraded areas. Crops such as eucalyptus, sugar cane, corn, soybeans and elephant grass have a high potential for carbon capture, especially when associated with conservation practices such as no-till farming, crop rotation and crop-livestock-forest integration (Demirbas, 2008; Tilman; Hill; Lehman, 2006).

Projects structured on the basis of these principles can be included in regulated or voluntary carbon markets, such as Verra or the Brazilian Agricultural Carbon Credit Program (EMBRAPA, 2023), as long as they comply with robust quantification and verification methodologies. Figure 8 below illustrates the interrelationship between the principles of the circular economy, the reuse of PW, the SDGs and carbon credits.

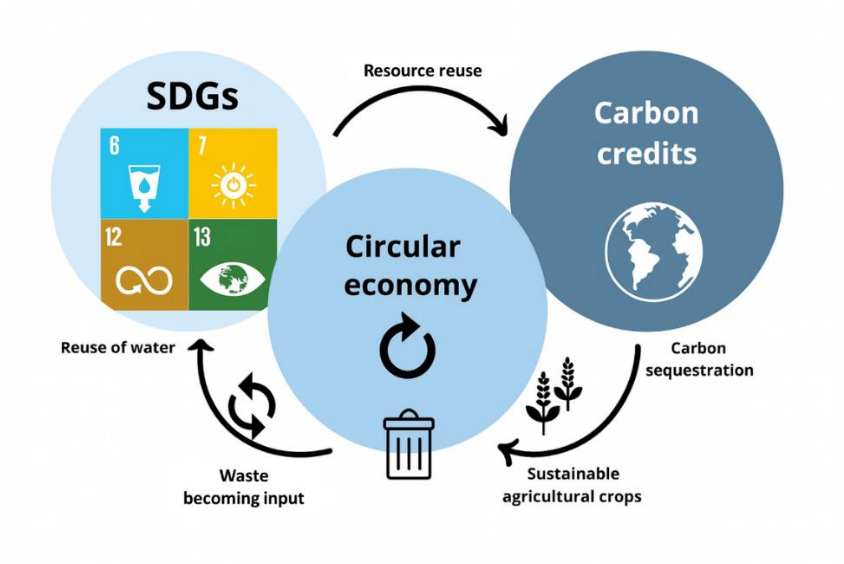

Figure 8. Relationship between the circular economy, reuse of produced water and the SDGs.

In this context, Table 8 presents a summary of the main crops with carbon sequestration potential, their contributions and associated agricultural practices, highlighting their relevance in sustainable bioenergy systems.

Table 8. Energy crops and agricultural practices with carbon sequestration potential.

Crop	Contribution	Associated practices	References
Eucalyptus	High growth; high biomass	Reforestation	Lal (2004)
Sugarcane	High photosynthetic rate; high biomass; use for biofuels	Large-scale cultivation; waste for bioenergy	Tilman, Hill and Lehman (2006)
Maize	High biomass production	No-till; crop rotation; waste for composting	West and Post (2002)
Soybean	Biological nitrogen fixation	No-till; crop rotation; crop-livestock integration	Lal (2004)
Elephant grass	High growth; high biomass; bioenergy; animal feed	Crop-livestock-forest integration; biofuels	Tilman, Hill and Lehman (2006)

Source: Adapted from Lal (2004); West and Post (2002); Tilman, Hill and Lehman (2006).

7. CONCLUSION

The agricultural reuse of produced water is a strategic opportunity for Brazil to advance policies for the rational use of water, climate change mitigation and the consolidation of sustainable production models. Although most of Brazil's PW is generated on offshore platforms, onshore operations, especially in the Potiguar Basin, with daily production close to 1 million barrels, offer the best logistical and agronomic potential for agricultural reuse. The adoption of this resource in irrigated systems depends on tackling technical and regulatory barriers, such as salinity control and the presence of contaminants such as BTEX, trace metals and NORMs. International experiences, such as those in the USA, indicate that the safe reuse of PW is feasible with specific regulations, appropriate technologies and the selection of tolerant crops. In Brazil, the absence of a federal regulatory framework represents an obstacle, but also an opportunity for producing states, such as Rio Grande do Norte, Ceará and Bahia, to lead pilot projects. Valuing PW as an agricultural input in semi-arid regions makes it possible to reduce pressure on aquifers, increase the production of biomass for energy and integrate water resource management into the energy transition agenda and the generation of carbon credits. Brazil has favorable soil, climate and operational conditions for transforming PW from an environmental liability into a productive asset, as long as science, public policies and the productive sector work together.

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CHAPTER III

SOIL QUALITY AND DEVELOPMENT OF BIOENERGY CROPS WITH PRODUCED WATER FROM PETROLEUM

Abstract - The reuse of produced water from petroleum for agricultural purposes is a promising strategy to promote the sustainability of production systems and reduce pressure on water resources in semiarid regions. The objective of this study was to evaluate the effects of irrigation with dilutions of produced water from the petroleum industry in the Potiguar Basin on soil quality and the development of crops with bioenergy potential: sorghum, elephant grass, and cotton. The experiment was carried out in a greenhouse, in a randomized block design. Foundation fertilization and planting with seeds and stalks were performed. The treatments corresponded to the control (WS) and dilutions using produced water from petroleum (PW): 25%, 50%, 75%, and 100% of PW. The cultivation time of the species lasted 90 days. The analyses covered soil chemical characteristics after cultivation (including electrical conductivity, pH, sodium, and metal content) and plant morphological parameters (height, stem diameter and dry biomass). The results indicated that the use of produced water had variable impacts on soil properties and plant growth, depending on the species and dilution applied. In general, higher sodium and salinity levels were observed in treatments with higher PW concentrations, especially in the surface layers of the soil, which required caution regarding its continuous application. Despite this, sorghum and elephant grass crops demonstrated relative tolerance to the treatments, standing out as viable alternatives for the use of this water in agricultural systems focused on biomass and bioenergy production. The findings reinforce the importance of appropriate management practices and the selection of resilient species to enable the agricultural use of produced water as a strategic resource in sustainable agriculture and in the Brazilian energy transition.

Keywords: Salinity; Water reuse; Alternative irrigation.

1. INTRODUCTION

The continued global dependence on the oil industry keeps the environmental impacts of its operations as a critical challenge for sustainability (Al Zarkani; El Fadel, 2024). Produced water (PW) generally contains high levels of salts, dissolved and emulsified hydrocarbons, trace metals, and a variety of organic contaminants, which imposes limitations on its disposal or direct use in agriculture without appropriate treatment (Hisham *et al*., 2019; Yang *et al*., 2022). The increase in industrial activities has intensified the generation of PW, making its treatment and reuse a growing concern from an environmental point of view. The agricultural application of wastewater, such as PW, raises concerns about the accumulation of toxic minerals in the soil and possible effects on plant development, requiring rigorous assessment of its impacts (Sousa *et al*., 2017).

Several studies indicate that prolonged irrigation with wastewater can gradually alter the physical and chemical properties of the soil, in addition to favoring the accumulation of contaminants in plants (Guimarães *et al*., 2010; Mota *et al*., 2012; Varallo *et al*., 2010). However, in arid and semi-arid regions, the reuse of treated PW emerges as a viable alternative to water scarcity, provided that appropriate management practices are adopted (Echchelh *et al*., 2019b). When properly selected and treated, this water can supply part of the water and nutritional needs of crops, offering a safe alternative for effluent disposal in agriculture.

The selection of salt-tolerant species is essential, as this is one of the main factors limiting the use of PW in irrigation. Forage crops such as sorghum and elephant grass have favorable agronomic characteristics, such as rapid growth, high biomass production (Monção *et al*., 2020), and resistance to abiotic stresses, making them suitable for energy purposes and adaptable to the use of saline water. The use of diluted PW in water supplies for irrigating these crops represents a sustainable strategy that combines the reuse of industrial waste with the generation of renewable energy, provided that its influence on plant development and biomass quality is evaluated. Sorghum and elephant grass have been widely studied as alternatives to petroleum coke, especially in industries such as cement, which seek renewable sources to replace fossil fuels (Amaral *et al*., 2021).

Among oilseeds, cotton (*Gossypium hirsutum*) stands out as a crop with moderate salinity tolerance and good adaptation to semi-arid conditions. Cotton, which is of socioeconomic importance in Brazil, is resistant to water stress. In addition, it has potential for biofuel production and can be integrated into sustainable agricultural systems based on the circular economy, contributing to the use of PW.

The assessment of the effects of effluent irrigation on soil is usually done by comparing irrigated and non-irrigated areas, based on chemical parameters and accumulated contaminants (Xu *et al*., 2010). Given the environmental risks associated with the oil industry, it is essential to develop sustainable strategies for managing this waste (Leontari *et al*., 2021), in line with the principles of the circular economy.

This research is directly relevant to onshore oil production companies, notably those located in the Potiguar Basin, where the volumes of produced water are particularly high (Morais *et al*., 2024). By generating experimental data on the response of soil and crops irrigated with PW dilutions, this work supports the development of sustainable reuse solutions for effluent, promoting integration between oil activities and regenerative agriculture in a semi-arid context.

Thus, the objective was to evaluate the use of PW, at different dilutions, in the irrigation of energy crops, analyzing the initial development of sorghum, elephant grass, and cotton, and the effects on soil chemical conditions.

2. MATERIAL 0AND METHODS

2.1 Soil collection and experiment location

The experiment was conducted with soil classified by the Brazilian Soil Classification System as Quartzarenic Neosol (Santos *et al*., 2018) and by the World Reference Base international system as Arenosols (WRB/FAO, 2015). In conducting the experiment, soil was collected from the surface layer (0-20 cm) in the region of Icapuí, state of Ceará, Brazil, at the geographical coordinates -4.71206º S and -37.49864º W. The experiment was conducted in a greenhouse on the east campus of the Federal Rural University of the Semi-Arid Region, in the city of Mossoró, state of Rio Grande do Norte, Brazil, at the geographical coordinates -5.203467º S and -37.324122º W. This greenhouse has a transparent low-density polyethylene cover, 0.10 mm thick, treated against ultraviolet rays and in an arch shape, 6.5 m wide, 12 m long, and 3 m high. The side and front walls are made of anti-aphid screens (50%) and a 0.24 m masonry baseboard.

2.2 Characterization of the waters studied

As this water contains hydrocarbons, an initial analysis was carried out for BTEX components (benzene, toluene, xylene, and ethylbenzene). The samples were analyzed by solid-phase microextraction in headspace mode (HS-SPME) using gas chromatography (GC) coupled with a flame ionization detector (FID). Table 1 shows the results for the samples analyzed.

Table 1. Analysis of BTEX components in produced water and water supply samples.

Sample	Analyte (µg L^{-1})				
	Benzene	Toluene	Ethylbenzene	m-p-xylenes	o-xylene
WS	< LD	< LD	< LD	< LD	< LD
25%	< LD	< LD	< LD	< LD	< LD
50%	< LD	< LD	< LD	< LD	< LD
50%	< LD	< LD	< LD	< LD	< LD
75%	< LD	< LD	< LD	< LD	< LD
100%	< LD	< LD	< LD	< LD	< LD

Legend: < LD: below detection limit.

Tables 2 and 3 present the chemical analysis of the waters studied in the experiment and metal analysis, carried out at UFERSA and UFC, respectively. The produced water from oil came from a producing basin onshore in Rio Grande do Norte. It was treated at the company's facilities before being transported to the university to conduct this experiment.

Table 2. Physical-chemical and chemical characterization of the waters studied.

Treatment	pH	EC	K^+	Na^+	Ca^{2+}	Mg^2	Cl^-	CO^3	HCO_3^-	SAR	Hardness	Cation	Anion
	H_2O	dS m^{-1}	--------------------mmolc / L-----------------------								mg/ L	mmolc/ L	
WS	8.8	0.44	0.26	3.65	0.75	0.75	3	0.8	2.7	4.2	75	5.4	6.5
PW 25%	8.2	1.67	0.56	12.37	2.6	1.7	15.2	0.8	3.3	8.4	215	17.2	19.3
PW 50%	8.2	2.74	0.79	18.17	3.9	2.8	28.4	0.6	2.7	9.9	335	25.7	31.7
PW 75%	8.2	3.93	1.1	26.47	5.9	3.7	39.6	0.6	5.2	12.1	480	37.2	45.4
PW 100%	8.3	4.76	1.28	34.76	7.5	4.1	49.4	0.6	2.2	14.4	580	47.6	52.2

Legend: WS: water supply; PW: produced water; pH: hydrogen ion concentration; EC: electrical conductivity; K^+: potassium; Na^+: sodium; Ca^{2+}: calcium; Mg^{2+}: magnesium; Cl^-: chloride; CO^3: carbonate; HCO^{3-}: bicarbonate; SAR: sodium adsorption ratio.

The chemical characterization of the water samples was performed according to the methods described in APHA (2017). The pH and electrical conductivity (EC) parameters were determined by potentiometry and conductimetry, respectively, using properly calibrated equipment. The levels of potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) were obtained by atomic absorption spectrophotometry (AAS) or, when applicable, by flame photometry and complexometric titration with EDTA. The chloride (Cl^-) concentration was determined by titration with silver nitrate (Mohr method), while the bicarbonate (HCO_3^-) and carbon dioxide (CO_2) contents were obtained by acid-base titration with appropriate indicators. The total hardness of the water was estimated by the sum of Ca^{2+} and Mg^{2+} ions, expressed in mg/L of $CaCO_3$. The sodium adsorption ratio (SAR) was calculated based on the concentrations of Na^+, Ca^{2+}, and Mg^{2+}, using the formula $SAR = Na^+ / \sqrt{[(Ca^{2+} + Mg^{2+})/2]}$, according to Richards (1954). The total values of cations and anions were obtained by the individual sum of the respective ions.

Table 3. Characterization of metals in samples of produced water, dilutions and water supply.

Parameter	Unit	100%	75%	50%	25%	WS	Limit
Al	$mg \cdot L^{-1}$	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	10^(1)^
Sb	$mg \cdot L^{-1}$	< 0.010	<0.010	< 0.010	< 0.010	< 0.010	-
As	$mg \cdot L^{-1}$	0.007451	0.00694	0.004	0.004918	0.003282	0.5^(1)^
Ba	$mg \cdot L^{-1}$	2.147	1.701	1.158	0.6342	0.04071	5^(1)^
B	$mg \cdot L^{-1}$	0.5313	0.4407	0.334	0.2346	0.1235	5^(1)^
Cd	$mg \cdot L^{-1}$	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.0005	0.2^(1)^
Pb	$mg \cdot L^{-1}$	0.00302	0.001537	0.001	0.001522	< 0.001	0.5^(1)^
Co	$mg \cdot L^{-1}$	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.05^(2)^
Cu	$mg \cdot L^{-1}$	0.002745	0.002389	0.002	0.00185	0.001412	1.0^(1)^
Cr	$mg \cdot L^{-1}$	< 0.001	0.001301	0.002	0.003596	0.005124	0.1^(1)^
Fe	$mg \cdot L^{-1}$	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	15^(1)^
Mn	$mg \cdot L^{-1}$	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	1.0^(1)^
Hg	$mg \cdot L^{-1}$	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.01^(1)^
Mo	$mg \cdot L^{-1}$	0.000892	0.000776	0.0008	0.000705	0.000708	0.01^(2)^
Ni	$mg \cdot L^{-1}$	0.004077	0.03544	0.02109	0.01113	0.001087	2.0^(1)^
Ag	$mg \cdot L^{-1}$	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.1^(1)^
Se	$mg \cdot L^{-1}$	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.05^(1)^
V	$mg \cdot L^{-1}$	< 0.001	0.003226	0.0068	0.01035	< 0.001	0.1^(2)^
Zn	$mg \cdot L^{-1}$	0.001101	0.001525	0.001793	0.001531	0.001274	5^(1)^
Cl^-	$mg \cdot L^{-1}$	2535.49	2045.76	1261.73	535.75	58.21	-
SO_4^{2-}	$mg \cdot L^{-1}$	17.39	36.04	25.67	35.16	17.45	-
Br^-	$mg \cdot L^{-1}$	17.00	12.98	9.99	9.47	2.53	-
NO_3^-	$mg \cdot L^{-1}$	407.67	21.55	37.72	20.41	4.30	10^(1)^

Legend: 100%: Produced Water from petroleum (PW); WS: Water Supply; 75%: Mixture of 75% PW with 25% WS; 50%: Mixture of 50% PW with 50% WS; 25%: Mixture of 25% PW with 75% WS; Al: Aluminum; Sb: Antimony; As: Arsenic; Ba: Barium; B: Boron; Cd: Cadmium; Pb: Lead; Co: Cobalt; Cu: Copper; Cr: Chromium; Fe: Iron; Mn: Manganese; Hg: Mercury; Mo: Molybdenum; Ni: Nickel; Ag: Silver; Se: Selenium; V: Vanadium; Zn: Zinc; Cl^-: Chloride; SO_4^{2-}: Sulfate; Br^-:Bromide; and NO_3^-: Nitrate. (1) Specific parameters for effluent discharge from Annex I of COEMA Resolution No. º 02/2017 (CEARÁ, 2017). (2) Parameters referring to the presence of metals in irrigation water (National Academy of Sciences, 1972; Pratt 1972).

The metals Al, Ba, B, Cd, Pb, Co, Cu, Cr, Fe, Mn, Mo, Ni, Ag, V, and Zn were determined by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry). The metals Sb, As, Hg, and Se were quantified by ICP-MS (Mass Spectrometry). For validation and complementary analysis of some specific elements, such as Cu, Zn, Cd, Pb, Fe, Mn, Ni, and Cr, AAS (Atomic Absorption Spectrophotometry) was also used, depending on equipment availability and analytical sensitivity.

Based on the chemical characteristics of the irrigation water, the CROSS index (Cation Ration of Soil Structural Stability) was estimated, according to the methodology proposed by Marchuk and Rengasamy (2011) (Equation 1), where C represents the concentrations in $mmol_c/L$ of the cations. The calculation considers the dispersive capacities of Na and K (coefficient of 0.56) and flocculants of Ca and Mg (coefficient of 0.60).

$$CROSS = \frac{C_{Na}+0{,}56C_K}{\left[\frac{C_{Ca}+0{,}60C_{Mg}}{2}\right]^{0{,}5}} \quad (1)$$

2.3 Water microbiology

A microbiological serial dilution was performed to analyze the microbial community in the PW and water supply (WS) samples. Serial dilution is a technique used to reduce the concentration of microorganisms present in a sample, facilitating the counting of colony-forming units (CFU) and the characterization of the microbial community. In the case of PW, this methodology is essential for assessing the diversity and abundance of bacteria and fungi that may be present in the aqueous environment. To perform the serial dilutions, test tubes containing 9 mL of autoclaved water were used. One mL of the PW sample was transferred to the first tube containing the diluent, obtaining a dilution of 10^{-1}. After homogenization, 1 mL of this solution was removed and transferred to a second tube with 9 mL of diluent, resulting in a dilution of 10^{-2}. This process was repeated to obtain a dilution of 10^{-3}, and the same was done for WS.

Next, 100 microliters of each serial dilution were transferred to Petri dishes containing specific culture media for the growth of microorganisms, such as Nutrient Agar (NA) for bacteria and Potato Dextrose Agar (PDA) for fungi. The inoculum is spread with the aid of a Drigalski loop, ensuring homogeneous distribution. Subsequently, the plates were incubated at 28 °C for 24 to 72 hours. After the incubation period, the colonies formed were counted, expressing the results in Colony Forming Units per milliliter of sample (CFU mL^{-1}). This methodology allows the estimation of microbial abundance in PW, assisting in environmental studies, in the detection of microorganisms that degrade organic compounds, and in the monitoring of potential microbiological impacts associated with the use of PW.

2.4 Soil characterization

Tables 4 and 5 present the chemical analysis of the soil and metal analysis, respectively, before the application of the treatments. Soil samples for metal analysis were collected according to the recommendations of COEMA Resolution No. º 02/2017.

Table 4. Characterization of the physical-chemical and chemical properties of the initial soil used in the experiment.

pH	EC	OM	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	SB	t	CEC	BS	AS	ESP
H_2O	dS m^{-1}	g/kg	-------mg/dm^3-------		-------------$cmol_c$ /dm^3 ------------							-----%-----		
7.4	0.14	6.69	41.5	105.8	11.4	2.7	0.8	0	3.82	3.82	3.82	100	0	1

Legend: pH: hydrogen ion potential; EC: electrical conductivity; OM: organic matter; P: phosphorus; K^+: potassium; Na^+: sodium; Ca^{2+}: calcium; Mg^{2+}: magnesium; Al^{3+}: aluminum; exchangeable acidity; SB: sum of bases; CEC: cation exchange capacity; BS: base saturation; AS: aluminum saturation; ESP: exchangeable sodium percentage.

Table 5. Metal and anion contents of the initial soil used in the experiment.

Sample	Al	Sb	As	Ba	B	CD	Pb	Co	Cu	Cr
	mg/kg^{-1}									
Soil	3845	0.01	0.01	7.35	4.76	0.45	4.65	2.19	2.17	5.18
Limit (1)	-	2	15	150	1.7	1.3	72	25	60	75

Sample	Fe	Mn	Hg	Mo	Ni	Ag	Se	V	Zn
	mg/kg^{-1}								
Soil	2668	138.6	0.0001	0.24	2.10	0.01	0.01	5.62	11.43
Limit (1)	-	-	0.5	30	30	2	5	1.7	300

Legend: Al: Aluminum; Sb: Antimony; As: Arsenic; Ba: Barium; B: Boron; Cd: Cadmium; Pb: Lead; Co: Cobalt; Cu: Copper; Cr: Chromium; Fe: Iron; Mn: Manganese; Hg: Mercury; Mo: Molybdenum; Ni: Nickel; Ag: Silver; Se: Selenium; V: Vanadium; and Zn: Zinc. (1) Specific parameters for soil saturation limits from COEMA Resolution No. º 02/2017 (CEARÁ, 2017).

2.5 Experimental conductio s with species of energy interest

Forage crops of the species *Sorghum bicolor* (L.) Moench (sorghum) variety IPA SF15 and *Pennisetum purpureum* (elephant grass) (variety BRS Capiaçu) and oilseed *Gossypium hirsutum* L. (cotton) were cultivated, comprising three distinct experiments. The crops were irrigated using WS, supplied by the Rio Grande do Norte Water and Sewage Company (CAERN), and PW treated by the company that supplied it.

In each experiment, the experimental design adopted was randomized blocks (DBC), consisting of five treatments, each with five replicates. The treatments were 100%

WS (only tap water); 25% (25% PW + 75% WS); 50% (50% PW + 50% WS); 75% (75% PW + 25% WS); and 100% (only PW).

Polyvinyl chloride (PVC) columns 100 mm in diameter and 60 cm in height were filled with soil and foundation fertilization with 2 grams (g) MAP (monoammonium phosphate) per plant. The columns were irrigated with WS prior to sowing to aid in fertilizer dilution. Elephant grass was sown from culms, and sorghum and cotton from seeds. Subsequently, the plants received top dressing with potassium chloride (0.5 g) and urea (0.5 g). Irrigation was performed daily or as needed by the crops. The experiments were conducted for 90 days.

2.6 Soil quality assessment

After the experimental development, chemical analyses of the soil were performed to evaluate the effects of irrigation with PW dilutions. Samples were collected at depths of 0-30 cm and 30-60 cm, and the conventional chemical attributes of the soil were determined. The heavy metal contents were also quantified at the same depths. In addition to the predictive CROSS calculation based on water and soil cations, the diagnostic CROSS was also performed after the experiment, considering soil cations (Equation 1).

2.7 Morphological analyses of plants

Plant height and dry mass were used as parameters for evaluating plant growth, allowing the analysis of crop response to experimental conditions. Dry mass was used as an indicator of accumulated biomass. Plant height (cm) was determined by measuring the distance from the soil surface to the upper end of the main stem using a tape measure. Stem diameter (cm) was measured 3 cm above the soil using a digital caliper. After collection, the plants were divided into leaves, stems, and roots and dried in an oven at 65 °C until they reached a constant weight.

2.8 Statistical analysis of data

Statistical analyses were performed using RStudio software. The data from each experiment were submitted to analysis of variance (ANOVA) to verify the significance of the effect of the applied doses. When significance was observed by the F test ($p < 0.05$), the means of the treatments were compared by Tukey's test at a 5% probability level.

3. RESULTS AND DISCUSSION

3.1 Microbiology of produced water and water supply

Figure 1 shows the microbiological analysis of Colony Forming Units (CFU) in samples of produced water in NA culture medium with total bacterial colonies (A), spore-forming bacteria (B), and PDA medium for fungi (C).

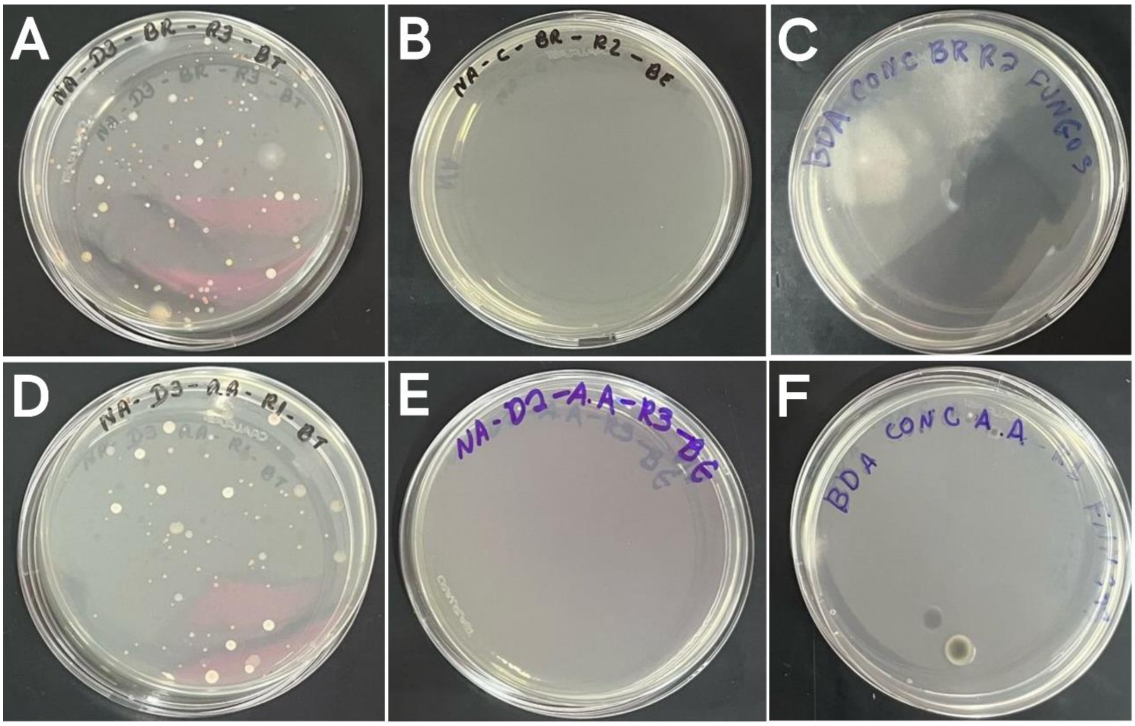

Figure 13. Microbiological analysis of Colony Forming Units in samples of produced water and water supply in culture media.

Water supply samples in NA culture medium with total bacterial colonies (D), spore-forming bacteria (E) in PDA medium for fungi (F) show that, in microbiological terms, WS does not present visual differences in relation to PW in terms of the number of colonies. Therefore, according to the colony-forming unit test, PW was not inferior to WS in terms of the morphotype and number of microorganism colonies.

3.2 Effects of irrigation with produced water on the soil

3.2.1 Evaluation of cultivation system conditions based on the CROSS index

The structural risk analysis of the soil associated with irrigation with produced water dilutions was performed based on the Cationic Ratio of Structural Stability (CROSS) index, a relevant parameter for estimating the dispersion potential of soil particles and their physical stability. CROSS differs from other indices in that it considers not only the dispersive effect of sodium, but also that of potassium, and assigns different weights to the flocculating effects of calcium and magnesium (Drechsel *et al.*, 2023).

CROSS values ranged from 4.90 in the WS treatment to 15.90 in the 100% PW treatment (Figure 2), with a progressive increase as the proportion of PW increased. Despite the greater dispersive potential of water with a higher proportion of PW, the effective structural risk is mitigated by the physical characteristics of the soil used in the experiment, a Quartzarenic Neosol/Arenosol, with a sandy texture, 90% sand, and 8% clay.

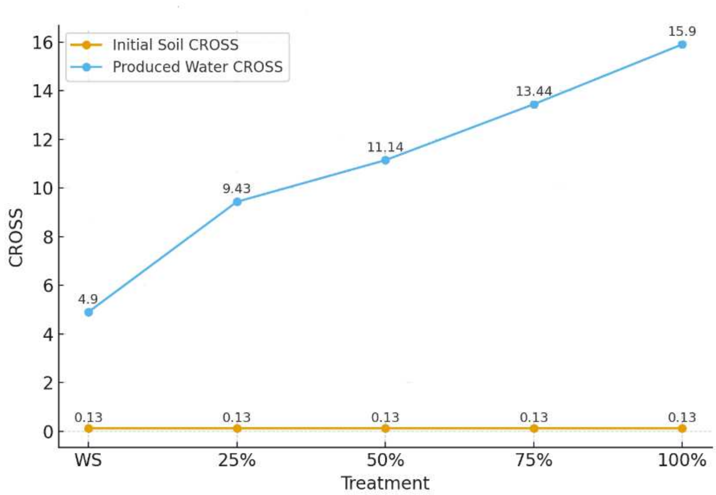

Figure 14. CROSS (Cationic Ratio of Structural Stability) index values for irrigation water and soil before the start of cultivation.

Soils with this low clay content are less dependent on colloidal interactions to maintain their physical structure, which reduces their susceptibility to dispersion and surface sealing. In these cases, the main risk associated with saline water is not the degradation of the physical structure of the soil, but sodification, increased electrical conductivity, ionic toxicity, and nutritional imbalance, which can compromise crop development.

3.2.2 Sorghum (*Sorghum bicolor* (L.) Moench)

Soil fertility attributes are shown in Table 6, where the analyses are distributed in two soil layers, 0-30 cm and 30-60 cm, used in the sorghum experiments. Some values exceed the limits established by current legislation, COEMA No. º 02/2017.

Table 6. Characterization of the physical-chemical and chemical properties of the soil for sorghum cultivation after application of treatments with different waters at depths of 0-30 cm and 30-60 cm.

Treatment	pH	EC	OM	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	H + Al	SB	CEC	ESP
	H_2O	dS m^{-1}	g/kg	----------- mg/dm^{-3}	--------		----------- cmolc/dm^{-3}	------------				%
WS 0-30	7.14	0.59	18.77	104.27	30.97	114.10	1.96	0.80	0.00	3.34	3.34	14.9
WS 30-30	7.30	0.54	-	73.44	36.93	98.03	1.70	1.01	0.00	3.23	3.23	13.2
25% 0-30	7.18	1.08	15.29	104.9	27.35	189.39	1.81	1.29	0.00	3.99	3.99	20.6
25% 30-60	7.23	2.60	-	80.36	27.99	287.44	1.88	0.71	0.00	3.91	3.91	32.0
50% 0-30	6.90	2.32	18.41	109.94	38.91	191.43	1.96	1.14	1.72	4.03	5.75	14.5
50% 30-60	6.23	4.00	-	85.39	39.91	466.48	1.76	1.13	1.63	5.02	6.65	30.5
75% 0-30	6.89	2.11	18.76	118.12	56.78	217.15	2.08	1.13	2.13	4.29	6.42	14.7
75% 30-60	6.13	4.06	-	85.39	37.92	194.97	1.78	0.88	2.44	3.60	6.04	14.0
100% 0-30	6.94	3.84	17.72	152.1	83.59	267.36	2.63	0.91	2.03	4.91	6.94	16.8
100% 30-60	6.20	2.81	-	102.39	50.83	275.43	1.63	1.21	2.34	4.17	6.51	18.4
Limit (1)		< 4(1)										< 7.0
Reference (2)	7.4	0.14	6.69	41.5	105.8	11.4	2.7	0.8		3.82	3.82	1

Legend: WS: water supply; pH: hydrogen ion potential; EC: electrical conductivity; OM: organic matter; P: phosphorus; K^+: potassium; Na^+: sodium; Ca^{2+}: calcium; Mg^{2+}: magnesium; H +Al: potential acidity; SB: sum of bases; CEC: cation exchange capacity; ESP: exchangeable sodium percentage. (1) Specific parameters for soil saturation limits from Annex II of COEMA Resolution No. º 02/2017 (CEARÁ, 2017); (2) Reference values for metals obtained in the topsoil layer (0-20 cm) before treatment application.

The pH values in the reference soil (soil before treatment application) indicated low alkalinity (7.4), according to the standards for the state of Ceará (Souza *et al.*, 2015). After treatments with PW (25%, 50%, 75%, and 100%) and WS, it was observed that none of the treatments had an increase in pH, remaining in ranges classified as low acidity (6.0 to 6.9) and, in some cases, low alkalinity (7.1 to 7.4). In the study by Rodrigues *et al.* (2019a), who grew corn with saline water, no changes in soil pH were identified either.

After applying the PW treatments, the potassium (K^+) levels in the soil cultivated with sorghum decreased in relation to the initial reference value (105.8 mg/dm^3), even in treatments with high PW concentrations, such as 100% (83.59 mg/dm^3 at 0–30 cm). Sorghum is a crop that is highly demanding in K^+, especially under saline stress, using this nutrient in osmotic regulation and in maintaining cell turgidity (Santos, 2013). Even in the WS treatment, there was a reduction in K^+ to 30.97–36.93 mg/dm³, suggesting that absorption by the crop contributed to the decrease in the nutrient.

Phosphorus (P) increased in all treatments due to fertilization with monoammonium phosphate (MAP), with higher values predominantly found in the 0-30 cm layer. There was a significant increase in sodium (Na^+) levels in the soil in all treatments as the use of produced water in irrigation intensified. The values rose from 114.10 mg/dm³ (WS, 0-30 cm) to 466.48 mg/dm³ (50% PW, 30-60 cm). This increase is attributed to the high salt load of the produced water and low absorption by plants. Irrigation systems using Na^+ rich effluents can pose risks of soil structure degradation and decreased permeability, requiring continuous monitoring of water quality (Jalali *et al.*, 2008; Minhas *et al.*, 2021).

The intense ionic dynamics in the soil, evidenced by the significant increase in sodium levels and the variation of other elements, reinforces the integrated need for soil condition after irrigation with different waters. To this end, the CROSS indices of the post-crop soil and the classification of salinity and sodicity according to Richards (1954), which is based on EC, ESP, and pH, were analyzed (Figure 3). Soils are considered normal when EC is less than 4 dS m^{-1}, ESP is less than 15%, and pH is less than 8.5; saline when EC is equal to or greater than 4 dS m^{-1}, ESP is less than 15%, and pH is less than 8.5; sodic when the EC is less than 4 dS m^{-1}, the ESP is greater than or equal to 15%, and the pH is greater than or equal to 8.5; and saline-sodic when the EC is equal to or greater than 4 dS m^{-1}, the ESP is greater than or equal to 15%, and the pH is less than 8.5.

As discussed earlier, the soil had a low initial CROSS (0.13), indicating structural stability, while irrigation water had an increasing CROSS from 4.90 to 15.90. The soil CROSS index values increased after sorghum cultivation (Figure 3A), reaching 3.22 in the treatment with 100% PW in the 0-30 cm layer and 5.98 in the treatment with 50% PW in the 30-60 cm layer. Although they did not reach the CROSS values of irrigation water, the increase in values shows that the cationic composition of the water influenced the balance in the soil exchange complex.

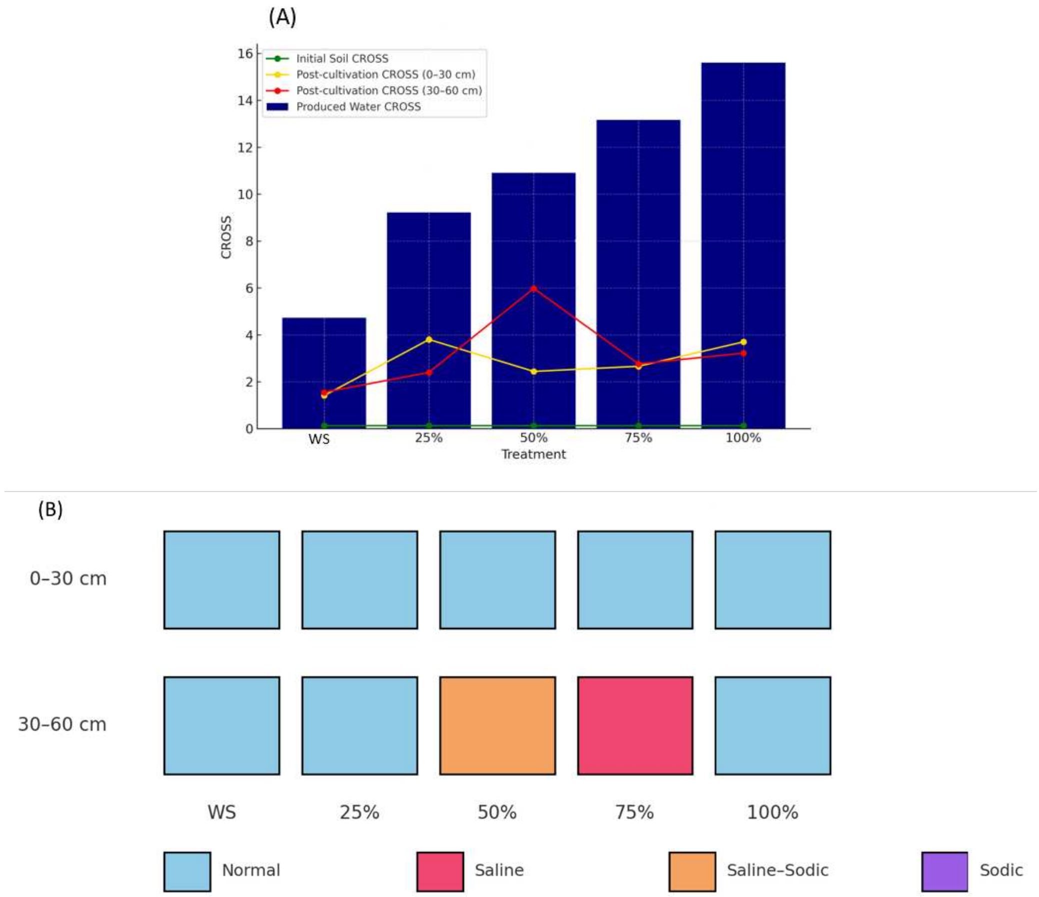

Figure 15. Evaluation of the impact of irrigation with produced water dilutions on the soil after 90 days of sorghum cultivation.

Legend: (A) CROSS values of irrigation water and soil in the 0-30 cm and 30-60 cm layers. (B) Soil classification for salinity and sodification based on Richards criteria (1954) for the 0-30 cm and 30-60 cm layers.

In the surface layer (0-30 cm), soil classification showed no salinity or sodicity problems in any of the treatments, all of which were classified as normal. In the subsurface layer (30-60 cm), the 50% and 75% treatments were classified as saline-sodic and sodic, respectively (Figure 3 B). Saline soils can return to normal through the establishment of good drainage, while saline-sodic soils result from combined processes of salinization and sodification and require more complex management.

Saline-sodic soils are more challenging to recover than saline soils because, in addition to the accumulation of soluble salts, they have high exchangeable sodium saturation (ESS), which disperses soil colloids, impairs structure, reduces infiltration, and hinders plant growth (Song *et al.*, 2020). Practices such as gypsum application, use of organic matter, plant cover, EC and ESP monitoring, and pH correction are considered alternative management strategies for saline-sodic soils (Ferreira *et al.*, 2019).

The saline-sodic classification of 50% PW is corroborated by the CROSS index, which presented the highest value among the treatments analyzed. This convergence between CROSS and the EC/ESP/pH classification reinforces the understanding that, in this deeper layer, the soil is impacted by simultaneous processes of salinity and sodicity.

The environmental quality of the system was also assessed based on the heavy metal content present in the soil after cultivation. The elements antimony (Sb), silver (Ag), selenium (Se), arsenic (As), and mercury (Hg) presented concentrations above the reference values in all treatments (Table 7), but below the legal limits defined by state legislation, COEMA Resolution No. º 02/2017. The highest levels of barium (Ba) were observed in the 0-30 cm layer in the 50% and 100% treatments, although all values remained below the limit of 150 mg/kg. Regarding boron (B), the levels exceeded the legal limit of 1.7 mg/kg in all treatments, including WS, suggesting natural accumulation or accumulation resulting from irrigation.

Table 7. Metal levels in the soil in the 0-30 cm and 30-60 cm layers for sorghum cultivation.

Treatment	Al	Sb	As	Ba	B	Cd	Pb	Co	Cu	Cr
	mg·kg^{-1}									
WS 0-30	2852	0.02	0.33	8.31	3.67	0.17	4.84	2.25	2.38	5.28
WS 30-60	3268	0.02	0.01	4.81	3.14	0.51	4.91	2.08	3.76	3.99
25% 0-30	3736	0.02	0.27	8.71	6.96	0.21	4.60	2.52	3.48	5.72
25% 30-60	3510	0.02	0.17	5.46	4.86	0.34	3.65	2.30	2.81	5.48
50% 0-30	3788	0.03	0.21	9.71	4.69	0.19	3.78	2.28	3.21	7.18
50% 30-60	2953	0.02	0.36	5.44	3.86	0.18	3.02	2.15	2.64	5.16
75% 0-30	3535	0.02	0.17	0.80	0.48	0.18	4.82	2.42	3.03	2.97
75% 30-60	4088	0.02	0.01	5.75	4.42	0.45	5.59	2.39	4.37	5.50
100% 0-30	3491	0.02	0.21	11.27	4.80	0.22	5.23	2.35	3.71	6.63
100% 30-60	2526	0.02	0.01	4.39	6.12	0.55	5.12	1.77	4.15	5.31
Limit (1)	-	2	15	150	1.7	1.3	72	25	60	75
Reference (2)	3845	0.01	0.01	7.35	4.76	0.45	4.65	2.19	2.17	5.18

Treatment	Fe	Mn	Hg	Mo	Ni	Ag	Se	V	Zn
	mg·kg^{-1}								
WS 0-30	2492	207.2	0.00025	0.29	3.01	0.02	0.02	6.0	12.8
WS 30-60	2157	179.7	0.00024	0.19	3.05	0.02	0.02	2.91	10.21
25% 0-30	2770	225.8	0.00024	0.24	4.17	0.02	0.02	6.4	12.7
25% 30-60	2690	193.4	0.00023	0.45	3.57	0.02	0.02	5.9	13.1
50% 0-30	2735	211.4	0.00025	0.27	3.72	0.03	0.03	6.5	14.5
50% 30-60	2530	198.1	0.00025	0.26	2.23	0.02	0.02	5.8	10.5
75% 0-30	2427	191.2	0.00024	0.37	3.00	0.02	0.02	6.6	14.4
75% 30-60	2719	195.8	0.00025	0.21	3.26	0.02	0.02	5.47	10.41
100% 0-30	2670	206.6	0.00024	0.25	4.40	0.02	0.02	6.2	14.0
100% 30-60	2216	151.4	0.00024	0.14	2.52	0.02	0.02	4.25	8.14
Limit (1)	-	-	0.5	30	30	2	5	1.7	300
Reference (2)	2668	138.6	0.0001	0.24	2.10	0.01	0.01	5.62	11.43

Legend: WS: Water supply; 100: Produced water (PW); 25: 25% PW + 75% WS; 50: 50% PW + 50% WS; 75: 75% PW + 25% WS; Al: Aluminum; Sb: Antimony; As: Arsenic; Ba: Barium; B: Boron; Cd: Cadmium; Pb: Lead; Co: Cobalt; Cu: Copper; Cr: Chromium; Fe: Iron; Mn: Manganese; Hg: Mercury; Mo: Molybdenum; Ni: Nickel; Ag: Silver; Se: Selenium; V: Vanadium; Zn: Zinc. (1) Specific parameters for soil saturation limits from Annex II of COEMA Resolution No. º 02/2017 (CEARÁ, 2017); (2) Reference values for metals obtained in the topsoil layer (0-20 cm) before treatment application.

The increases in boron (B) levels were more significant in the surface layers, especially in treatments up to 50% PW, but above the limits in all treatments applied. This trend was also reported by Kondash *et al.* (2020), who pointed out the accumulation of salts and boron on the soil surface as an expected effect of continuous wastewater application, especially in soils with medium texture and low drainage capacity.

The metals cadmium (Cd), lead (Pb), cobalt (Co), copper (Cu), chromium (Cr), molybdenum (Mo), nickel (Ni), and zinc (Zn) presented concentrations below the limits established in COEMA Resolution No. º 02/2017 for all treatments, indicating a low risk of contamination by these elements. Vanadium (V) presented levels above the standard of 1.7 mg/kg of the Resolution limit. For arsenic (As), the analysis revealed leaching from the 0-30 cm surface layer to the 30-60 cm layer in the 50% treatment. Considering the variability of metals and their relationship with the treatments, the results indicate that irrigation with treated PW, under conditions similar to those of the experiment, did not promote soil contamination.

3.2.3 Elephant grass (*Pennisetum purpureum*)

Soil fertility and metal attributes were analyzed in the 0-30 cm and 30-60 cm layers of the samples used in the elephant grass experiments, as shown in Table 8. The pH value in the reference soil indicates low alkalinity (7.4), while the representativeness of the treatments with PW also reached ranges from low acidity (6.0 to 6.9) to medium alkalinity (7.5 to 7.9), according to the classification criteria for the state of Ceará (Souza *et al.,* 2015).

In elephant grass cultivation, K^+ levels were also reduced, ranging from 24.02 to 45.86 mg/dm³, compared to the initial reference value (105.8 mg/dm³). Elephant grass, being a forage species with high productivity and biomass accumulation, has a high demand for potassium to support physiological processes such as cell growth, photoassimilate transport, and osmotic control. H + Al representations were above zero in treatments starting at 50%. SB and CEC increased in all treatments with PW.

Table 8. Characterization of the physical-chemical and chemical properties of the soil for elephant grass cultivation after application of treatments with different waters at depths of 0-30 cm and 30-60 cm.

Treatment	pH	EC	OM	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	H + Al	SB	CEC	ESP
	H_2O	dS m^{-1}	g/kg	------mg/dm^3------			------------------cmolc/dm^3-------------					%
WS 0-30	7.29	0.92	16.33	81.62	45.86	118.12	1.8	1.26	0.00	3.69	3.69	13.92
WS 30-60	7.12	1.02	-	111.83	39.91	129.16	1.74	1.33	0.00	3.73	3.73	15.06
25% 0-30	7.54	1.94	10.77	75.32	32.96	182.39	2.39	1.03	0.00	4.29	4.29	18.48
25% 30-60	7.03	4.44	-	90.43	36.93	396.09	2.08	1.05	0.00	4.94	4.94	34.86
50% 0-30	6.24	5.63	11.46	82.25	27.99	588.70	2.05	0.78	2.44	5.46	7.90	32.40
50% 30-60	7.14	3.03	-	133.22	39.91	327.61	2.74	0.59	0.00	4.85	4.85	29.37
75% 0-30	6.56	4.93	11.12	130.71	29.98	387.86	1.84	0.98	3.30	4.58	7.88	21.40
75% 30-60	6.67	8.07	-	87.91	24.02	618.83	2.11	0.85	1.90	5.72	7.61	35.36
100% 0-30	6.7	4.17	11.46	149.58	39.91	417.99	2.55	0.94	2.16	5.41	7.57	24.01
100% 30-60	6.04	6.17	-	82.25	37.92	709.21	2.39	0.58	0.00	6.14	6.14	50.22
Limit (1)		< 4(1)										< 7.0
Reference (2)	7.4	0.14	6.69	41.5	105.8	11.4	2.7	0.8		3.82	3.82	1

Legend: WS: water supply; pH: hydrogen ion potential; EC: electrical conductivity; OM: organic matter; P: phosphorus; K^+: potassium; Na^+: sodium; Ca^{2+}: calcium; Mg^{2+}: magnesium; H +Al: potential acidity; SB: sum of bases; CEC: cation exchange capacity; ESP: exchangeable sodium percentage. (1) Specific parameters for soil saturation limits from Annex II of COEMA Resolution No. º 02/2017 (CEARÁ, 2017); (2) Reference values for metals obtained in the topsoil layer (0-20 cm) before treatment application.

The presence of essential nutrients in adequate concentrations and the good performance of elephant grass under these conditions reinforce its potential as a viable energy crop in areas with water restrictions, contributing to the rational use of effluents and the diversification of plant biomass sources.

The EC was higher in the treated PW treatments, reflecting the higher salt input. Values above the limit of 4.0 dS m^{-1} were observed in the 0-30 cm and 30-60 cm layers of the 75% and 100% treatments, as well as 50% (0-30 cm) and 25% (30-60 cm). Lucena and Amaral (2015) point out that elephant grass requires values below 1.4 dS m^{-1} on the soil surface, but can accept values of around 5.0 dS m^{-1}.

There was salt accumulation at greater depths with the full use of PW in the 25%, 75%, and 100% treatments. This behavior may be related to the leaching of soluble salts or the greater mobility of certain ions in the soil profile, which is a factor to be monitored through continuous applications.

High salinity can negatively affect plant growth, especially less tolerant species (Song *et al.*, 2020). However, elephant grass has shown good performance in environments with moderate salinity, as reported by Santos *et al.* (2019), which justifies its choice as a bioenergy crop adapted to marginal conditions. The combination of irrigation with diluted PW and the use of adapted species, such as elephant grass, reinforces the potential for effluent reuse in areas of low agricultural suitability.

The CROSS index analysis and classification regarding salinity and sodicity were also performed for the soil cultivated with elephant grass. The CROSS of the WS treatment remained similar to that observed for sorghum, being 1.62 in the 0-30 cm layer and 1.74 in the 30-60 cm layer. In the 25%, 75%, and 100% treatments, the subsurface layer showed a significant increase in CROSS values compared to the surface layer (Figure 4A), from 2.17 to 4.82, from 4.97 to 7.53, and from 4.75 to 8.48, respectively, indicating the leaching of salts, particularly sodium.

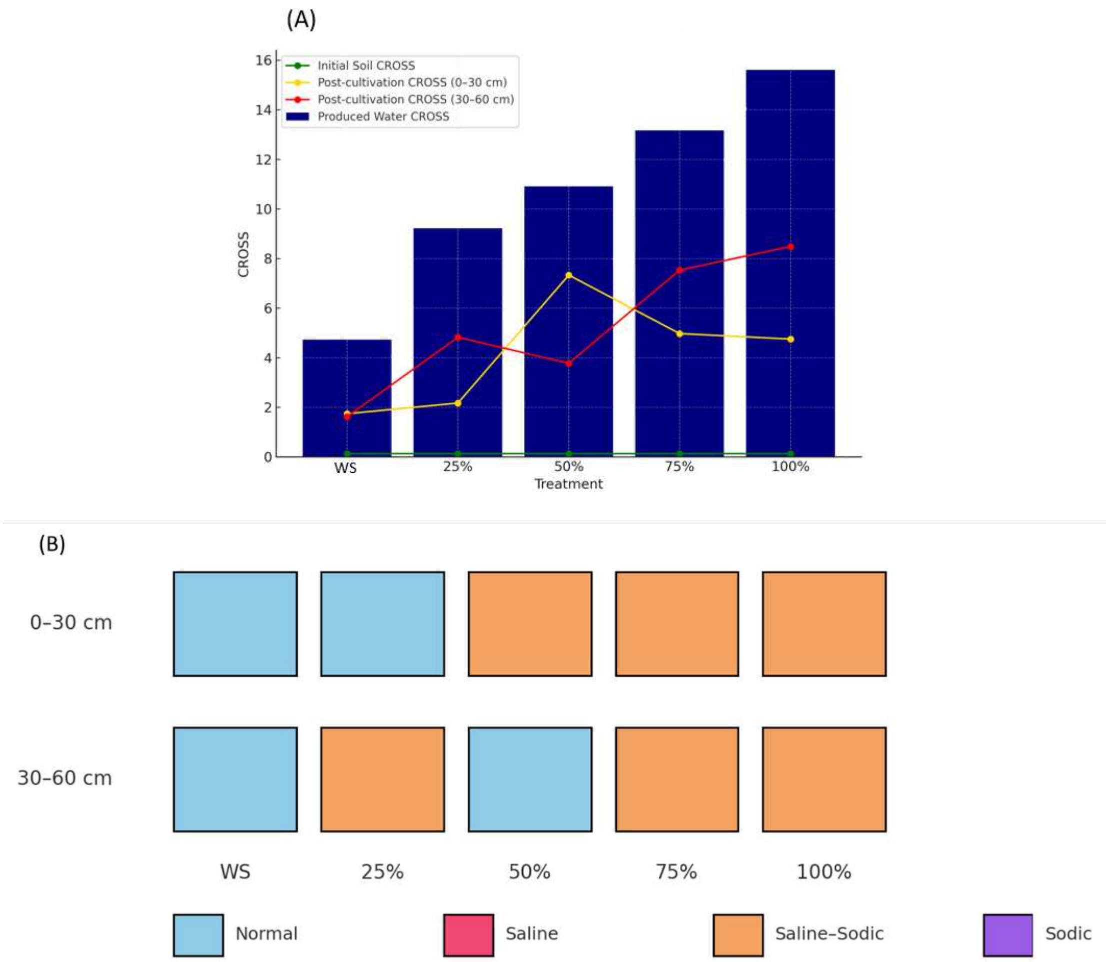

Figure 16. Evaluation of the impact of irrigation with produced water dilutions on the soil after 90 days of elephant grass cultivation.

Legend: (A) CROSS values of irrigation water and soil in the 0-30 cm and 30-60 cm layers. (B) Soil classification for salinity and sodification based on Richards criteria (1954) for the 0-30 cm and 30-60 cm layers.

The 50% treatment showed distinct behavior, with a higher CROSS value in the surface layer. The same pattern was observed in the classification regarding salt accumulation, in which the soil was classified as saline-sodic in the 0-30 cm layer and normal in the 30-60 cm layer (Figure 4B), indicating sodium retention and high salinity on the surface. Irrigation with 75% and 100% PW affected the entire soil profile, making it saline-sodic, with high amounts of salts and exchangeable sodium.

Even with the soil under chemical stress, physical aspects such as infiltration and aeration may not be immediately compromised, considering the low proportion of clay. The implementation of continuous management practices for the removal and control of excess salts and sodium is necessary to maintain soil quality in the long term. These practices include incorporating substances into the soil that favor calcium solubilization, enabling the replacement of exchangeable sodium with calcium in the cation exchange complex (Bello *et al.*, 2021).

Table 9 shows the metal contents in the 0-30 cm and 30-60 cm layers of soil used in the elephant grass experiments. Metals such as Cd, Pb, Co, Cu, Cr, Mo, Ni, and Zn were found in concentrations within legal limits. However, Cr stands out, whose content in the 0-30 cm layer in 100% was much higher than the reference value, although below the legal limit. Pb contents above the reference value were observed in 25% in 0-30 cm and 75% in 30-60 cm, but remaining below the limit of 72 mg/kg^{-1}. The higher concentration of Mn in the deeper layers, especially at 100%, indicates probable leaching, a behavior that has also been reported by Dube *et al.* (2022) in soils irrigated with wastewater rich in soluble salts.

Table 9. Metal levels in the soil in the 0-30 cm and 30-60 cm layers for elephant grass cultivation.

Treatment	Al	Sb	As	Ba	B	Cd	Pb	Co	Cu	Cr
	mg/kg-1									
WS 0-30	2469	0.02	0.07	1.25	0.61	0.38	5.81	0.31	3.68	0.70
WS 30-60	2949	0.02	0.01	5.83	3.91	0.89	5.53	2.06	3.53	4.61
25% 0-30	2539	0.02	0.01	5.26	3.79	2.31	15.46	1.81	12.27	3.96
25% 30-60	*	*	*	*	*	*	*	*	*	*
50% 0-30	*	*	*	*	*	*	*	*	*	*
50% 30-60	*	*	*	*	*	*	*	*	*	*
75% 0-30	2711	0.02	0.01	6.31	2.76	0.99	6.13	1.70	4.84	4.11
75% 30-60	3352	0.02	0.01	5.34	5.55	0.61	10.96	1.98	9.17	4.03
100% 0-30	3321	0.02	0.62	10.43	9.42	0.26	3.88	3.04	3.09	36.93
100% 30-60	3301	0.02	0.27	6.18	4.82	0.22	3.82	2.48	2.91	5.78
Limit (1)	-	2	15	150	1.7	1.3	72	25	60	75
Reference (2)	3845	0.01	0.01	7.35	4.76	0.45	4.65	2.19	2.17	5.18

Treatment	Fe	Mn	Hg	Mo	Ni	Ag	Se	V	Zn
	mg/kg-1								
WS 0-30	354	28.3	0.00025	0.02	0.44	0.02	0.02	0.39	2.65
WS 30-60	2194	171.0	0.00024	0.13	2.88	0.02	0.02	2.91	10.03
25% 0-30	2173	156.2	0.00024	0.13	2.37	0.02	0.02	4.12	7.86
25% 30-60	*	*	*	*	*	*	*	*	*
50% 0-30	*	*	*	*	*	*	*	*	*
50% 30-60	*	*	*	*	*	*	*	*	*
75% 0-30	1761	148.6	0.00025	0.11	2.39	0.02	0.02	2.39	7.93
75% 30-60	2013	177.9	0.00025	0.17	2.94	0.02	0.02	2.56	10.11
100% 0-30	3696	226.0	0.00025	0.41	4.64	0.02	0.02	9.3	11.5
100% 30-60	2792	241.2	0.00025	0.32	3.48	0.02	0.02	6.7	12.8
Limit (1)	-	-	0.5	30	30	2	5	1.7	300
Reference (2)	2668	138.6	0.0001	0.24	2.10	0.01	0.01	5.62	11.43

Legend: WS: Water supply; 100: Produced water (PW); 25: 25% PW + 75% WS; 50: 50% PW + 50% WS; 75: 75% PW + 25% WS; Al: Aluminum; Sb: Antimony; As: Arsenic; Ba: Barium; B: Boron; Cd: Cadmium; Pb: Lead; Co: Cobalt; Cu: Copper; Cr: Chromium; Fe: Iron; Mn: Manganese; Hg: Mercury; Mo: Molybdenum; Ni: Nickel; Ag: Silver; Se: Selenium; V: Vanadium; Zn: Zinc. (1) Specific parameters for soil saturation limits from Annex II of COEMA Resolution No. º 02/2017 (CEARÁ, 2017); (2) Reference values for metals obtained in the topsoil layer (0-20 cm) before treatment application.

The metals Sb, Ag, and Se presented values slightly higher than the references in WS, 75%, and 100%, but within legal limits. Ba did not exceed the limit of 150 mg/kg⁻¹ in any treatment, although the values at 75% and 100% (0-30 cm) were higher than the references. The element B exceeded the COEMA Resolution standard of 1.7 mg/kg⁻¹ in these treatments, especially in the surface layer. Elephant grass, however, has been described as a species with medium tolerance to this element, which may explain the absence of visual symptoms of toxicity during the experiment. The opposite result was reported by Bañuelos *et al.* (2005) studying different plant species, where elephant grass was the only one that showed visual symptoms such as necrosis at the leaf margins in response to B toxicity already present in the soil.

Finally, V exceeded the standard of 1.7 mg/kg^{-1} of COEMA Resolution No. º 02/2017, but presented lower values up to a concentration of 75% PW, in relation to the soil before treatment. Its highest expression occurred in the 100% treatment. Mn leaching from 0-30 cm to 30-60 cm was also observed in the treatments, with greater accumulation at 100%, indicating vertical mobility of this element in the soil profile. In general, the results indicate that, under the experimental conditions adopted, the use of PW did not promote critical accumulation of heavy metals in the soil when compared to the value of these metals in the initial soil. The presence of some elements at high levels reinforces the importance of proper management and periodic control of soil quality.

3.2.4 Cotton (*Gossypium hirsutum* L.)

The analysis of soil chemical elements in the cotton experiment is shown in Table 10. The pH values of the soils cultivated and irrigated with PW were classified as medium acidity (5.1 to 5.9), low acidity (6.0 to 6.9), low alkalinity (7.1 to 7.4), and, in some cases, medium alkalinity (7.5 to 7.9).

Table 10. Characterization of the physical-chemical and chemical properties of the soil for cotton cultivation after application of treatments with different waters at depths of 0-30 cm and 30-60 cm.

Treatment	pH	EC	OM	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	H + Al	SB	CEC	ESP
	H_2O	dS m^{-1}	g/kg	--------mg/dm^3 ----------			--------------cmolc/dm^3----------------					%
WS 0-30	7.75	1.02	15.98	69.13	82.60	133.18	2.09	0.62	0.00	3.50	3.50	16.54
WS 30-60	7.49	1.51	-	70.29	82.60	174.35	1.71	1.20	0.00	3.88	3.88	19.54
25% 0-30	7.47	0.64	9.73	99.87	78.63	139.21	3.00	0.06	0.00	3.87	3.87	15.64
25% 30-60	7.16	4.33	-	77.21	118.34	426.26	1.45	1.13	0.00	4.73	4.73	39.18
50% 0-30	6.81	3.63	13.72	67.14	91.53	396.09	1.88	0.73	1.75	4.56	6.31	27.29
50% 30-60	6.66	3.73	-	96.09	106.43	285.47	2.25	1.21	1.96	4.98	6.94	17.88
75% 0-30	7.28	3.14	9.03	152.73	102.46	287.44	3.44	0.80	0.00	5.46	5.46	22.89
75% 30-60	5.96	8.99	-	152.73	137.20	848.60	1.44	1.45	2.41	6.93	9.34	39.50
100% 0-30	7.51	3.08	12.85	159.65	117.35	317.57	3.61	0.19	0.00	5.48	5.48	25.20
100% 30-60	6.04	7.04	-	86.65	98.48	468.20	1.46	1.38	2.87	5.13	8.00	25.45
Limit (1)		< 4(1)										< 7.0
Reference (2)	7.4	0.14	6.69	41.5	105.8	11.4	2.7	0.8		3.82	3.82	1

Legend: WS: water supply; pH: hydrogen ion potential; EC: electrical conductivity; OM: organic matter; P: phosphorus; K^+: potassium; Na^+: sodium; Ca^{2+}: calcium; Mg^{2+}: magnesium; H +Al: potential acidity; SB: sum of bases; CEC: cation exchange capacity; ESP: exchangeable sodium percentage. (1) Specific parameters for soil saturation limits from Annex II of COEMA Resolution No. º 02/2017 (CEARÁ, 2017); (2) Reference values for metals obtained in the topsoil layer (0-20 cm) before treatment application.

K^+ levels ranged from 78.63 to 137.20 mg/dm³ after treatment, with most values also below the initial standard of 105.8 mg/dm³. In some dilutions, such as in the 75% PW treatment (137.20 mg/dm³ at 30-60 cm), a localized increase was observed, possibly related to the vertical redistribution of the nutrient. However, the general trend indicates a reduction in K^+, especially at depth, associated with both sodium-induced leaching and absorption by the crop, which has significant nutritional demands during fiber yield and quality (Oosterhuis; Loka; Raper, 2013). In the 25%, 50%, and 100% treatments, K^+ levels were also higher than the reference value.

The levels of phosphorus (P), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) increased in most treatments, as a result of supplemental fertilization and the composition of the water used. Sousa *et al*. (2016) highlight that PW, when properly treated, can act as an additional source of nutrients. SB and CEC increased in all treatments compared to the reference soil.

The sharp increase in sodium (Na^+) levels, especially in the deeper layers, is directly related to the high concentration of this ion in the PW used for irrigation. As a by-product of oil extraction, this water has high salt levels, with Na^+ being one of the main constituents. Unlike other cations such as potassium and calcium, sodium has low absorption by plants, which favors its accumulation in the soil solution. In addition, in soils with limited drainage or under continuous irrigation, there is a tendency for nutrient leaching and Na^+ retention, increasing the percentage of exchangeable sodium (ESP).

The ESP also increased in all treatments, reflecting the supply of Na^+ via irrigation, which also increased, contributing to the increase in the percentage of exchangeable sodium. The ESP showed varied classification, mainly in treatments with PW. The increase in ESP is a recurring concern in systems irrigated with wastewater with a high sodium adsorption ratio (SAR), as it can affect soil structure, reducing its permeability and causing increased salinity and sodicity, as described by Wang *et al*. (2024) and Wu *et al*. (2022). Continuous monitoring of this parameter is essential to prevent physical degradation of the soil, especially in perennial or long-cycle crops.

The EC was higher at a depth of 30-60 cm, reflecting salt leaching, especially in treatments with PW. The values at 25%, 75%, and 100% in the 30-60 cm layer exceeded the limit of 4.0 dS m^{-1} established by Souza *et al*. (2015). The increase in electrical conductivity of soil irrigated with PW, especially in treatments with higher concentrations, is consistent with the behavior reported in studies evaluating the use of treated saline effluents in agriculture. Guo *et al*. (2023) observed that the use of water with high salt content promotes gradual salinity accumulation, which can compromise soil structure and nutrient absorption in the long term. The progressive increase in salinity reinforces the importance of continuous monitoring and the adoption of strategies that minimize the effects of sodium and other salts on soil structure and fertility, especially in sensitive crops such as cotton.

The CROSS index also showed higher values in the 30-60 cm layer, with the exception of the 50% PW treatment, similar to the behavior observed in elephant grass cultivation. There was a significant increase in the treatment with 75% PW (Figure 5A). However, no linear or increasing pattern was observed between treatments, indicating th ly the dynamics of cations may have been influenced by additional factors, such as selective absorption by the plant and the differentiated mobility of ions.

The classification regarding salinity and sodicity (Figure 5B) showed that the soils remained classified as normal in the 0-30 cm layer in all treatments, while the 30-60 cm layer showed greater impairment. The 25%, 75%, and 100% PW treatments were classified as saline-sodic on the surface, evidencing the accumulation of exchangeable sodium at this depth.

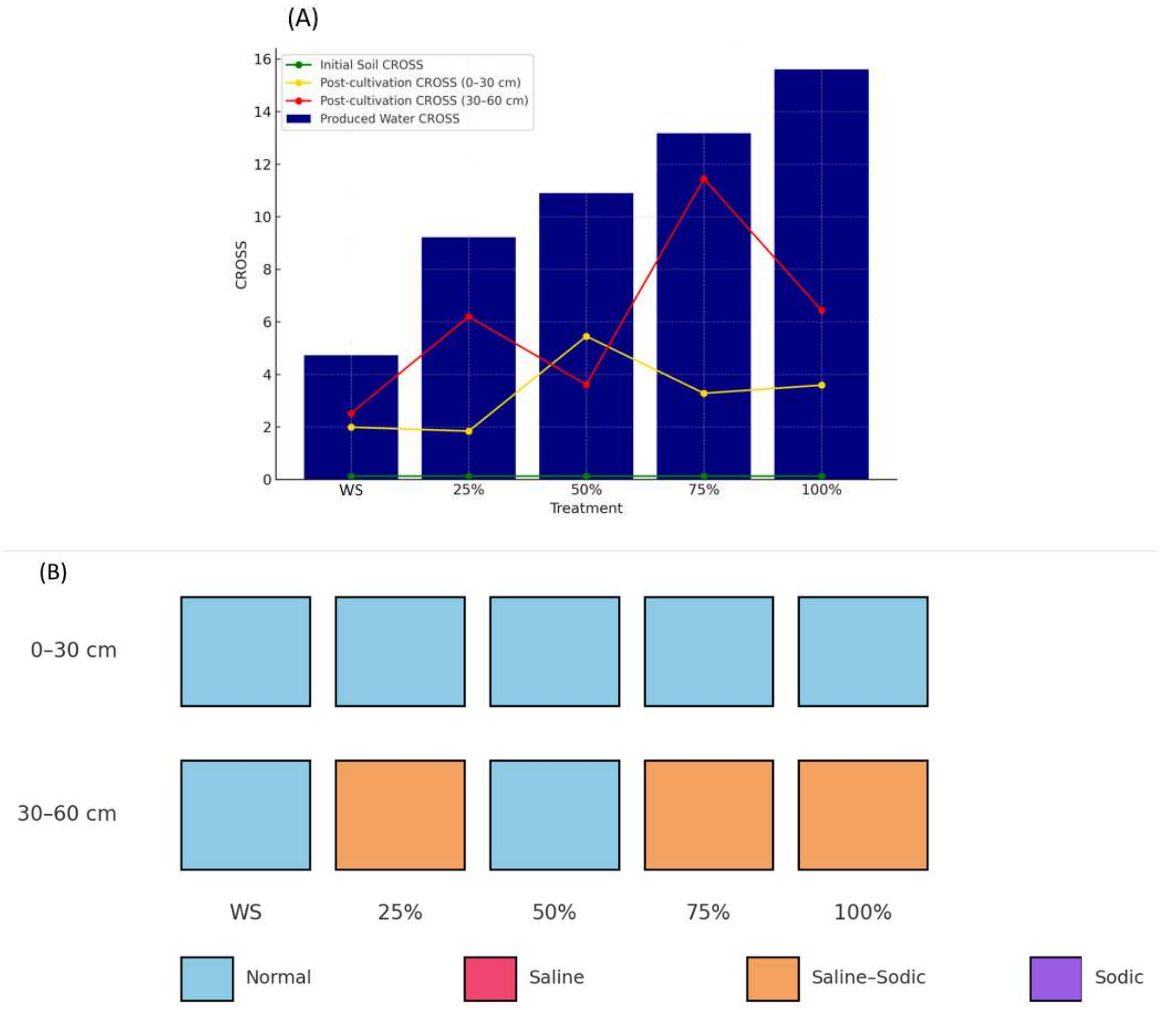

Figure 17. Assessment of the impact of irrigation with produced water dilutions on the soil after 90 days of cotton cultivation.

Legend: (A) CROSS values of irrigation water and soil in the 0-30 cm and 30-60 cm layers. (B) Soil classification for salinity and sodification based on Richards criteria (1954) for the 0-30 cm and 30-60 cm layers.

Analysis of metals in soil cultivated with cotton revealed that, despite some increases in the levels of specific elements, the values remained within the limits established by COEMA Resolution No. º 02/2017 for agricultural use. In treatments WS, 25%, and 50%, leaching of some elements from the surface layer to the 30-60 cm layer was observed.

Table 11 shows the metal levels, in which Sb, Ag, and Se had concentrations slightly higher than the reference values in all treatments but remained below the legal limits, indicating low immediate risk to soil quality or plant health. The elements As and

Hg, at 100%, also exceeded the reference values but remained below the established limits of 15 mg/kg and 0.5 mg/kg, respectively.

Ba showed its highest levels in the 0-30 cm layer in 75% and 100% with values above the reference values, but still below the limit of 150 mg/kg stipulated by COEMA. Element B, in turn, exceeded the COEMA Resolution standard of 1.7 mg/kg in all treatments, although, contradictorily, most levels remained below the reference values, indicating possible interference from the soil or the dynamics of the element. As cotton is considered a moderately boron-tolerant crop, the short-term effects observed tend to be limited.

Table 11. Metal levels in the soil in the 0-30 cm and 30-60 cm layers for cotton cultivation.

Treatment	Al	Sb	As	Ba	B	Cd	Pb	Co	Cu	Cr
	mg/kg^{-1}									
WS 0-30	2909	0.02	0.23	5.04	3.85	0.21	3.27	1.99	2.68	4.95
WS 30-60	3831	0.02	0.25	7.76	4.73	0.26	4.85	3.11	3.90	7.10
25% 0-30	2351	0.03	0.28	4.39	3.40	0.13	2.36	1.55	1.95	3.63
25% 30-60	2860	0.02	0.03	5.12	4.03	0.16	3.24	2.12	2.42	5.63
50% 0-30	3159	0.02	0.34	5.63	4.45	0.31	3.76	2.23	5.35	5.35
50% 30-60	3191	0.02	0.20	6.39	3.98	0.25	5.33	2.54	3.29	6.08
75% 0-30	3489	0.02	0.39	9.87	5.24	0.22	3.66	2.34	3.10	5.72
75% 30-60	3250	0.02	0.34	5.27	4.59	0.43	4.99	2.22	4.82	10.78
100% 0-30	3547	0.03	0.26	14.04	4.89	0.22	3.68	2.41	3.01	5.44
100% 30-60	3511	0.02	0.16	5.62	4.33	0.33	1.55	2.06	0.91	0.92
Limit (1)	-	2	15	150	1.7	1.3	72	25	60	75
Reference (2)	3845	0.01	0.01	7.35	4.76	0.45	4.65	2.19	2.17	5.18

Treatment	Fe	Mn	Hg	Mo	Ni	Ag	Se	V	Zn
	mg/kg^{-1}								
WS 0-30	2490	184.2	0.00025	0.27	2.88	0.02	0.02	5.7	10.4
WS 30-60	3294	278.3	0.00025	0.25	4.80	0.02	0.02	7.9	15.1
25% 0-30	1999	147.4	0.00025	0.22	2.29	0.03	0.03	4.3	7.4
25% 30-60	2471	230.5	0.00024	0.29	3.95	0.02	0.02	5.4	10.8
50% 0-30	2615	204.3	0.00025	0.32	3.29	0.02	0.02	6.2	11.4
50% 30-60	2760	241.4	0.00024	0.20	3.88	0.02	0.02	6.1	12.9
75% 0-30	2762	201.4	0.00025	0.38	3.88	0.02	0.02	6.4	16.3
75% 30-60	2719	208.8	0.00025	0.25	3.43	0.02	0.02	6.6	10.5
100% 0-30	2721	208.8	0.00025	0.33	4.01	0.03	0.03	6.5	12.8
100% 30-60	2612	191.6	0.00025	0.36	3.13	0.02	0.02	4.1	8.8
Limit (1)	-	-	0.5	30	30	2	5	1.7	300
Reference (2)	2668	138.6	0.0001	0.24	2.10	0.01	0.01	5.62	11.43

Legend: WS: Water supply; 100: Produced water (PW); 25: 25% PW + 75% WS; 50: 50% PW + 50% WS; 75: 75% PW + 25% WS; Al: Aluminum; Sb: Antimony; As: Arsenic; Ba: Barium; B: Boron; Cd: Cadmium; Pb: Lead; Co: Cobalt; Cu: Copper; Cr: Chromium; Fe: Iron; Mn: Manganese; Hg: Mercury; Mo: Molybdenum; Ni: Nickel; Ag: Silver; Se: Selenium; V: Vanadium; Zn: Zinc. (1) Specific parameters for soil saturation limits from Annex II of COEMA Resolution No. º 02/2017 (CEARÁ, 2017); (2) Reference values for metals obtained in the topsoil layer (0-20 cm) before treatment application.

The metals Cd, Pb, Co, Cu, Cr, Mo, Ni, and Zn presented concentrations below the limits of COEMA Resolution in all treatments. However, Cr in 75% (30-60 cm) exceeded the reference values. In addition, V was above the standard of 1.7 mg/kg in all treatments. Finally, in 100%, leaching of Cd, and Mo was identified from the 0-30 cm layer to the 30-60 cm layer, indicating vertical mobility of these elements in the soil profile.

The data indicate that the use of treated PW, even in treatments with higher concentrations, did not cause soil contamination by metals. Nevertheless, the presence of elements such as B, V, and Cr close to or slightly above the attention values highlights the importance of periodic monitoring and detailed analysis of water quality before its continuous application.

3.3 Effects of irrigation with produced water on the plant

3.3.1 Sorghum (*Sorghum bicolor* L.)

The morphological parameters evaluated in sorghum (height, stem diameter, and dry mass production) showed different responses depending on the concentration of produced water used for irrigation. In general, treatments with up to 50% produced water promoted good agronomic performance, with emphasis on biomass accumulation, which exceeded the control in some dilutions. Among the attributes analyzed, height was the most sensitive to salt stress, showing a significant reduction at higher concentrations (75% and 100%), which highlights the crop's tolerance limits to salinity and the chemical composition of the water applied. Plant height (Figure 6) was statistically higher in the WS, 25%, and 50% treatments, with averages above 170 cm.

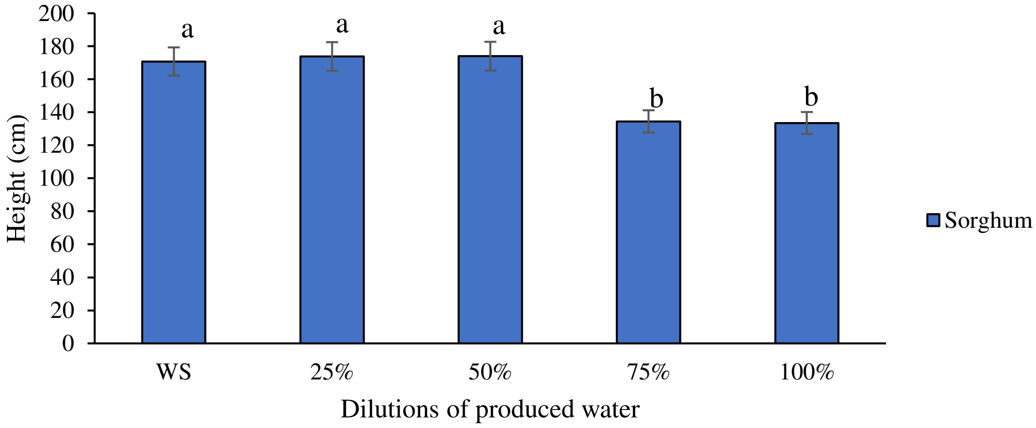

Figure 18. Height of sorghum plants grown under proportions of produced water (WS, 25%, 50%, 75%, and 100% produced water).

From 75% onwards, a sharp drop in height was observed, reaching 134 and 133 cm in the 75% and 100% treatments, respectively, which represents a reduction of approximately 22% compared to the most productive treatments. Although sorghum is classified as moderately tolerant to salinity, this tolerance is restricted to mild to moderate salinity conditions (Morsy *et al*., 2021; Zahedi; Piernik; Dehnavi, 2024) . In environments with high salt accumulation, as evidenced by the EC and Na^+ values in the most concentrated treatments, significant losses in growth may occur, resulting from limited cell expansion, turgor maintenance, stomatal functioning, and nutrient assimilation.

Sensitivity to high salt concentrations is consistent with the findings of Oliveira *et al*. (2021), who observed a significant reduction in sorghum height when irrigated with water with electrical conductivity greater than 3 dS m^{-1}. The crop's tolerance to moderate salinity allows it to be grown with diluted reused water, but high limits compromise vegetative development. In contrast, Soni *et al*. (2021) identified a higher threshold, with tolerance up to 6.86 dS m^{-1}, which highlights variations between cultivars and soil and climate conditions in different studies.

The stem diameter (Figure 7) showed no statistical difference between the WS, 50%, 75%, and 100% treatments, suggesting low sensitivity of this variable to salinity in the evaluated period. The 25% PW treatment had the highest mean and differed significantly from the others, which may indicate a moderate positive effect of salinity on stem development under controlled conditions. The maintenance of diameter in the other treatments may be related to tolerance mechanisms that preserve the plant structure even under saline stress.

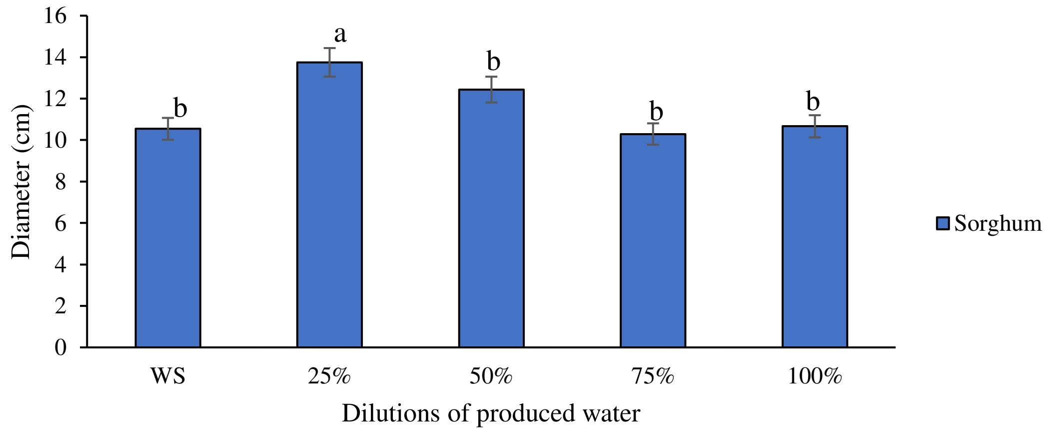

Figure 19. Diameter of sorghum plants grown under produced water dilutions (WS, 25%, 50%, 75%, and 100% produced water).

The dry mass production of sorghum (Figure 8) varied according to the concentration of PW used in irrigation. In the treatments with 75% and 100% PW, no significant reductions in biomass were observed in relation to the control (WS) in the stem, root, and total compartments. Even under conditions of higher salinity and sodium content, sorghum was able to maintain its development, showing physiological resilience. The stability observed reinforces the crop's suitability for use in areas with a high risk of irrigation-induced salinization.

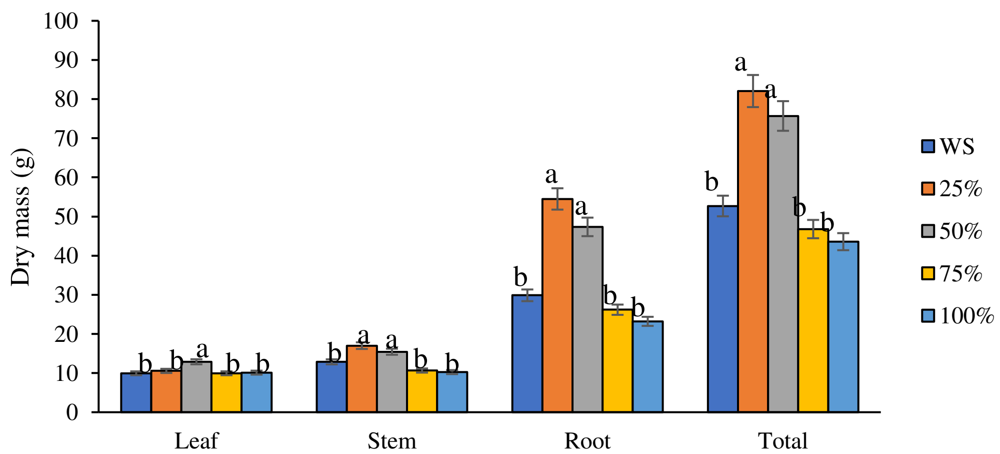

Figure 20. Dry mass of leaves, stems, roots, and total sorghum plants grown under produced water dilutions (WS, 25%, 50%, 75%, and 100% produced water).

The 25% and 50% treatments showed the highest biomass values in the stem, root, and total compartments, significantly exceeding the control (WS). These results suggest a positive physiological response to moderate salt stress, possibly associated with mechanisms such as osmotic adjustment and greater efficiency in nutrient absorption, which favor biomass accumulation. This demonstrates the crop's ability to tolerate moderate saline conditions and reinforces its agronomic potential in environments irrigated with lower quality water, provided it is well managed. Guimarães *et al*. (2022) report physiological adjustments and activation of antioxidant defenses in sorghum irrigated with saline water, which reflected in a positive response in the productivity of some varieties.

It is important that the use of PW be controlled and that management strategies that consider its composition and crop tolerance limits be implemented. These findings suggest that moderate levels of salts may not only be tolerated but also stimulate beneficial adaptive responses. Cultivars adapted to the semi-arid region have the capacity to maintain dry matter production under moderate salinity (Costa; Medeiros, 2017), with sorghum being one of the species recognized for its physiological tolerance to salinity.

Previous studies reinforce the potential of sorghum for use in bioenergy systems under saline water irrigation. Costa and Medeiros (2017) highlight that the Ponta Negra cultivar showed higher dry matter and energy production, while BRS 506 showed higher sugar and ethanol productivity, evidencing variations in tolerance between genotypes. This tolerance can be attributed to specific physiological and biochemical characteristics that confer greater resilience to saline stress. Another study, testing the impact of saline water on sorghum and wheat cultivation, concluded that the adoption of deficient irrigation and the use of mulch is effective in the cultivation of sorghum for bioenergy, making it a candidate for rotation systems in semi-arid regions (Rai *et al*., 2022).

Figure 9 shows the visual appearance of sorghum plants at the end of cultivation. It can be observed that in sorghum plants, treatments with higher concentrations of PW (75% and 100%) resulted in smaller plants, consistent with the height data, indicating symptoms of water and salt stress. In contrast, the best visual development was observed in the treatments with 25% and 50%, which had longer stalks and more vigorous leaves. Although the visual analysis is illustrative, it reinforces the patterns observed in the quantitative parameters.

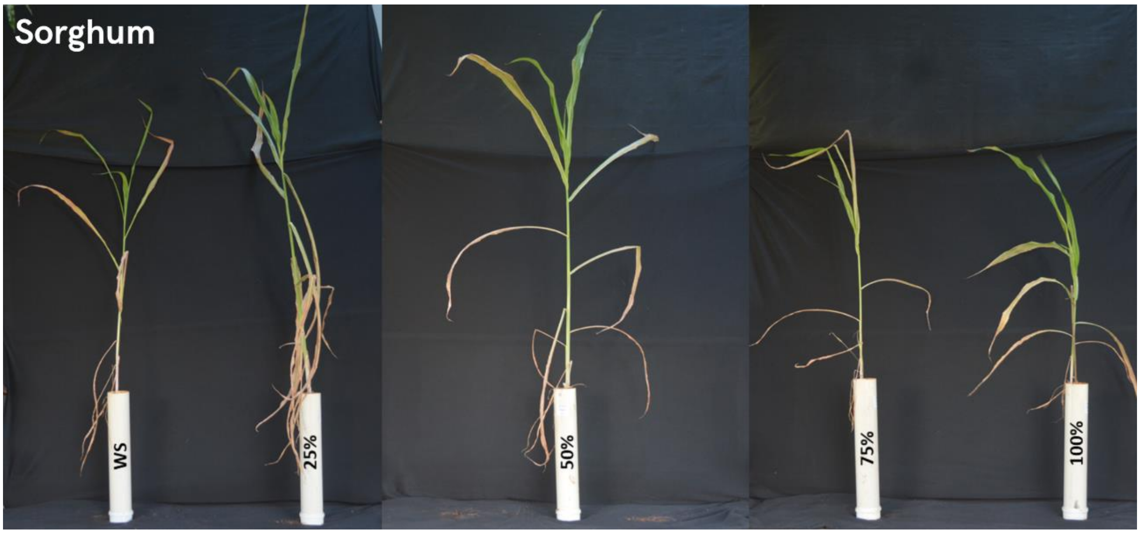

Figure 21. Sorghum plants at 90 days of cultivation under irrigation with dilutions of produced water (WS, 25%, 50%, 75%, and 100% produced water).

The data obtained indicate that sorghum shows satisfactory agronomic performance under irrigation with treated PW, maintaining biomass production even at the highest concentrations evaluated. The 25% and 50% PW treatments promoted significant increases in dry mass, surpassing the control, which suggests a response to moderate salt stress. In the 75% and 100% treatments, there was no statistical difference from the control, demonstrating the crop's tolerance under higher salinity conditions. Thus, sorghum has potential as a viable energy crop for use in environments irrigated with lower quality water.

3.3.2 Elephant grass (*Pennisetum purpureum*)

The morphological evaluation of elephant grass, considering the parameters of height, culm diameter, and total dry mass, revealed that the crop performs well agronomically under irrigation with PW. With maintenance or increase in the morphological parameters analyzed. Plant height (Figure 10) was significantly lower in the treatment with WS, with an average of 105.60 cm. In the other treatments, with 25% to 100% PW, there was no statistical difference, with average values between 156 cm and 174 cm. This behavior indicates the ability of elephant grass to maintain vertical growth even under higher salinity conditions.

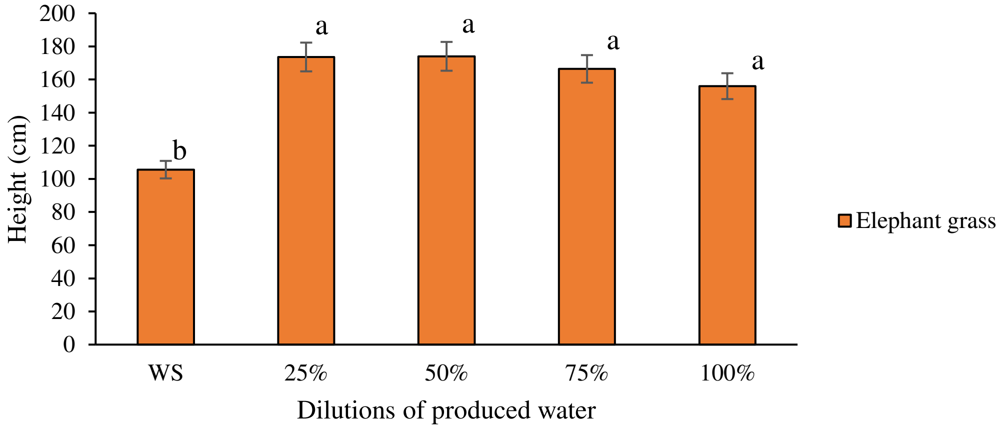

Figure 22. Height of elephant grass plants grown under proportions of produced water (WS, 25%, 50%, 75%, and 100% produced water).

The highest stem diameter values (Figure 11) were recorded in the treatments with 25% (14.54 cm) and 75% (13.37 cm) of PW. The treatments with WS, 50%, and 100% presented lower values, with 11.73 cm, 12.74 cm, and 12.85 cm, respectively, but without statistical difference between them. Although a linear response pattern was not observed, the results indicate that elephant grass exhibited structural stability under different saline conditions.

The observed stability can be explained by the plants ability to adjust biomass allocation in response to environmental stimuli without compromising the integrity of the stem structure. The literature shows that elephant grass has moderate tolerance to salinity, but morphophysiological responses may vary depending on the genotype and environment. This response is observed by Dantas *et al*. (2006), who evaluated *Penissetum* clones under saline stress and identified that some are more resistant to salinity than others.

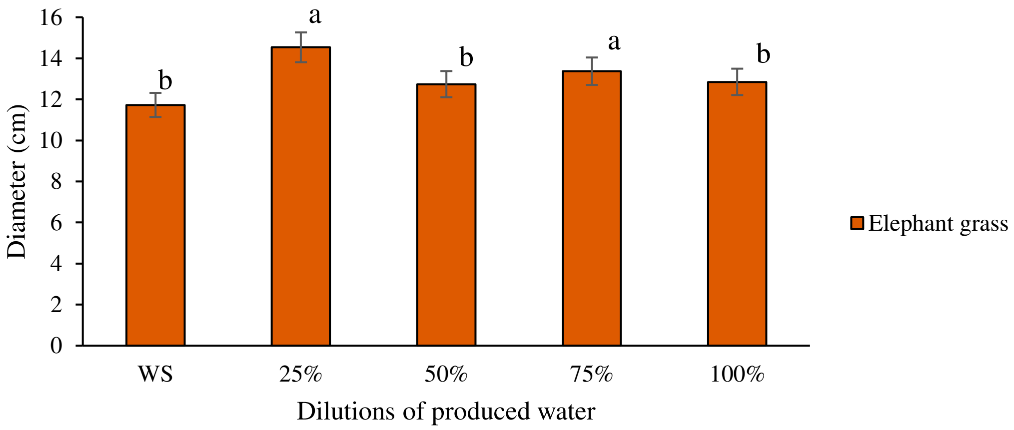

Figure 123. Diameter of elephant grass plants grown under produced water dilutions (WS, 25%, 50%, 75%, and 100% produced water).

Dry matter production, as shown in Figure 12, shows that treatments with 25%, 50%, and 75% PW resulted in the highest biomass accumulation in the leaf, stem, root, and total compartments. Root dry mass responded significantly to concentrations between 25% and 75%, with values between 108.99 g and 112.00 g, higher than WS (46.42 g) and 100% PW (95.89 g). This suggests a physiological adaptation to the presence of salts in moderate concentrations, favoring root growth. Similar results were found by Santos *et al*. (2019), who evaluated the biomass production of elephant grass and found that this attribute was not affected when irrigated with saline water up to 2.5 dS m^{-1}, recommending the use of mixtures with better quality water.

The exclusive use of PW (100%) caused a significant reduction in total biomass compared to the 25% to 75% treatments, but still significantly exceeded the control (WS). This response may be related to the plants ability to respond positively to a moderate level of salt stress, as long as it does not exceed its physiological threshold. The reduction in biomass with 100% PW is consistent with the negative effects of salt stress, as pointed out by Vale and Azevedo (2013) and Santos *et al*. (2019).

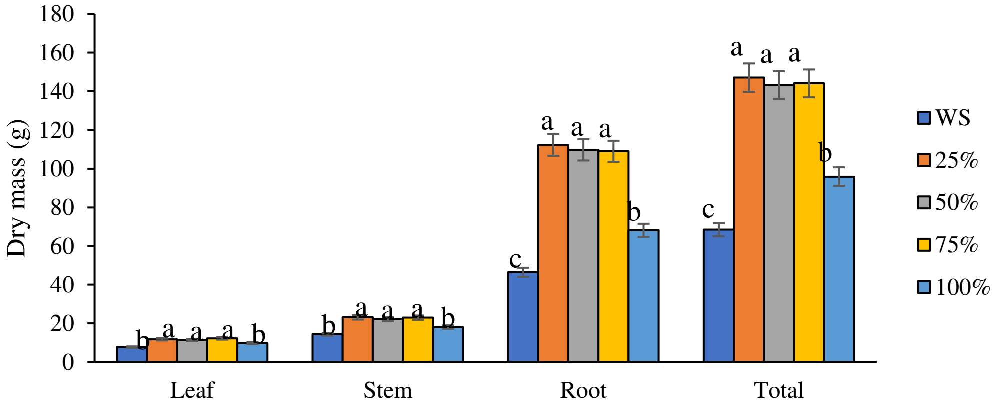

Figure 24. Dry mass of leaves, stems, roots, and total elephant grass plants grown under produced water dilutions (WS, 25%, 50%, 75%, and 100% produced water).

The morphological and productive analysis of elephant grass demonstrates that irrigation with up to 75% PW is agronomically viable, characterizing the crop as a promising alternative for use in areas irrigated with saline water, provided that it is associated with management strategies such as salinity monitoring, the use of plant cover, and, when necessary, soil washing to control salt accumulation. Visual assessment of elephant grass plants (Figure 13) demonstrated the stability of growth observed in the morphological data, even under the highest concentrations of PW. The plants have preserved leaf structure, illustrating the ability of elephant grass to grow consistently even under conditions of high salinity.

Figure 25. Elephant grass plants at 90 days of cultivation under irrigation with dilutions of produced water (WS, 25%, 50%, 75%, and 100% produced water).

3.3.3 Cotton (*Gossypium hirsutum* L.)

Cotton cultivation showed variable behavior in the morphological parameters evaluated. Regarding height (Figure 14), no statistical differences were observed between treatments, with values ranging from 57.0 cm (100%) to 64.2 cm (75%), indicating maintenance of initial vertical growth. These results suggest evidence of crop tolerance to salinity in the early stages, although other variables, such as stem diameter and biomass, showed differences between treatments.

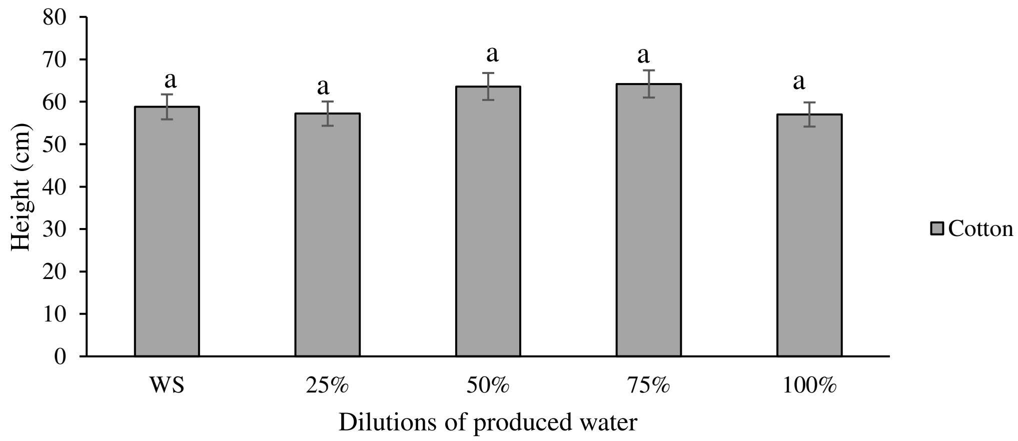

Figure 26. Height of cotton plants grown under proportions of produced water (WS, 25%, 50%, 75%, and 100% produced water).

The tendency for soil salinization in environments irrigated with wastewater was also described by Chaganti *et al*. (2020) and Tian *et al.* (2022), who pointed out the importance of this strategy in semi-arid regions or regions with water scarcity. Similar results were also reported by Ren *et al.* (2021), who highlighted the stability of cotton development under mild to moderate salt stress, with no significant impact on stem height or thickness.

Regarding stem diameter (Figure 15), the treatment with 100% PW presented the highest mean value (5.64 cm), being statistically superior to the others. The treatments with WS at 75% did not differ from each other, with values ranging from 4.35 cm to 4.90 cm. At higher concentrations, the salts and nutrients present in produced water can have a positive effect on stem thickening. Similar results were reported by Ren *et al.* (2021), who observed stability in cotton development under mild to moderate salt stress, with no negative impact on stem height or diameter.

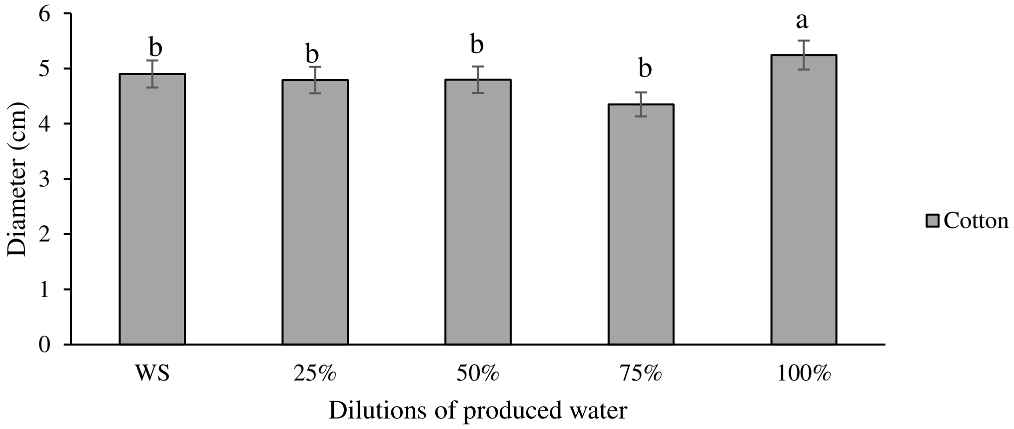

Figure 27. Diameter of cotton plants grown under produced water dilutions (WS, 25%, 50%, 75%, and 100% produced water).

Regarding total dry matter (Figure 16), the treatments with WS, 75%, and 100% PW showed higher values, with no significant difference between them, and were superior to the treatments with 25% and 50%. The crop response indicates that cotton was able to maintain biomass production under higher PW concentrations, demonstrating tolerance to salt stress. The reduction observed in the 25% and 50% treatments may reflect variations in nutrient availability or osmotic effects associated with intermediate salinity.

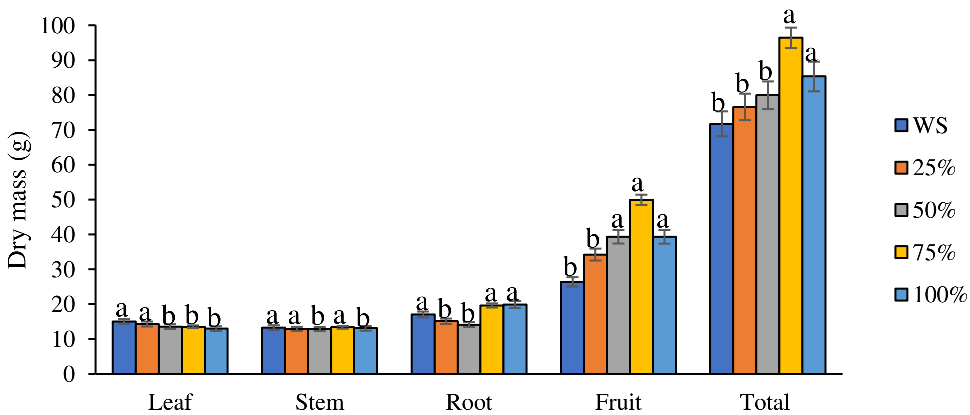

Figure 28. Dry mass of leaves, stems, roots, and total cotton plants grown under produced water dilutions (WS, 25%, 50%, 75%, and 100% produced water).

Thus, the results indicate that cotton is a promising crop for agricultural systems that use treated produced water as an alternative source of irrigation. The highlight for stem diameter in the 100% PW treatment suggests an efficient adaptive capacity to salinity, provided that the soil is adequately monitored to avoid excessive salt accumulation over time.

Figure 17 shows the visual appearance of cotton plants grown under PW dilutions. In general, it can be observed that the plants maintained similar development between treatments, with small variations in leaf supply and architecture. The image serves as a complementary illustrative resource, reinforcing the morphological tolerance of cotton plants to the use of produced water under controlled conditions.

Figure 29. Cotton plants at 90 days of cultivation under irrigation with dilutions of produced water (WS, 25%, 50%, 75%, and 100% produced water).

The maintenance of growth, diameter, and biomass production under the conditions evaluated reinforces the potential of cotton as a strategic crop for agricultural systems that integrate water reuse, especially in semi-arid regions. This approach is aligned with sustainability strategies, as it allows for the rational use of water resources, the utilization of industrial waste, and the production of crops with economic and energy value in environments with low agricultural suitability.

3.4 Agronomic and environmental feasibility of irrigation with produced water

The results obtained in this research demonstrate the technical, agronomic, and environmental potential of using treated petroleum PW as an alternative source of irrigation for strategic crops such as sorghum, elephant grass, and cotton. The three species showed viable development under PW dilutions, albeit with specific responses to soil and plant growth parameters, reflecting their different tolerances to salinity and the chemical composition of the water resource. Sorghum and elephant grass, recognized for their greater rusticity and high biomass production potential, showed promise in environments irrigated with saline water.

The reuse of PW in agriculture is an effective water sustainability strategy, reducing dependence on conventional sources and contributing to the conservation of natural resources in semi-arid regions. This practice also contributes to the valorization of marginal areas and reinforces the principles of the circular economy by transforming waste from the oil industry into a productive input, mitigating the environmental impacts associated with the improper disposal of this effluent. In addition, the cultivation of bioenergy species under this model promotes synergies with the energy transition by associating the reuse of resources with the production of raw materials for biofuels, contributing to the reduction of the carbon footprint and the fulfillment of decarbonization goals.

The maintenance of biomass indices under PW dilutions demonstrates the suitability of sorghum and elephant grass for integration into sustainable energy production systems, even under saline conditions. The gradual accumulation of sodium in the soil, especially in the surface layers, indicates the need for caution regarding the prolonged use of the produced water.

Irrigation with PW showed agronomic and environmental viability in sustainable agricultural systems, considering the initial development of the crops evaluated. This approach represents a concrete alternative to increase water and energy security in contexts of scarcity, in line with the Sustainable Development Goals (SDGs). It is important to emphasize the need to adopt appropriate management practices, monitor water and soil quality, and use adapted crops. Table 12 presents a direct and objective compilation of the observed effects and recommended management practices for improving productivity when the use of produced water is considered.

Based on the advances of this study, it is recommended that research continue through complementary studies that cover the complete crop cycle and evaluate the long-term effects on soil, productivity, and the quality of the biomass produced, consolidating the use of PW as a viable and safe resource on a productive scale.

Table 12. Effects observed in plants versus recommended management interventions.

Culture	Observed effects	Recommended management interventions
Sorghum	Reduced production with increased salinity; sensitive to Na^+ accumulation.	Surface gypsum application to mitigate sodification; choice of more tolerant cultivars; potassium correction.
Elephant grass	High tolerance to salinity; good biomass production even with 100% PW.	Salinity monitoring; potassium fertilization; use of organic matter to improve soil structure.
Cotton	Greater sensitivity to salinity; marked reduction in biomass; more sodified soil.	Limit PW use to up to 25%; prior use of corrective agents (gypsum); drainage and balanced fertilization.

4. CONCLUSION

The results showed that the use of treated PW in irrigation promoted changes in the chemical attributes of the soil, especially in salinity and sodicity, with greater intensity in treatments with high concentrations. The species showed good agronomic performance, even under moderate levels of salinity, high rates of macro and micronutrients, and some heavy metals. The species confirm their potential as bioenergy crops when PW is used as part of the water resource, maintaining acceptable biomass production at intermediate concentrations, indicating viability under proper management. Despite the observed benefits, such as nutrient reuse and reduced dependence on fresh water, the risks of salt and metal accumulation reinforce the importance of continuous monitoring and the adoption of conservation management practices.

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GENERAL CONCLUSIONS

This thesis demonstrated the potential of produced water as a strategic resource for sustainable agriculture and the energy transition. The bibliometric analysis highlighted its growing relevance in global research, while the review emphasized both challenges and opportunities for its safe agricultural reuse in Brazil. The experimental results confirmed the technical feasibility of using produced water to irrigate bioenergy crops such as sorghum, elephant grass, and cotton, provided that management practices address salinity and sodicity risks. Overall, the findings reinforce that produced water, when properly treated and managed, can contribute to water security, resilient production systems, and climate change mitigation.