



Produced Water in New Mexico: A Critical Review of Recent Toxicity and Risk Assessment Literature

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Abstract

This report critically evaluates the state of scientific research on the toxicity and risk assessment of produced water. Produced water refers to wastewater from oil and gas extraction operations, including hydraulic fracturing. It contains saline water as well as natural and man-made hydrocarbons, drilling fluids, and constituents originating from the rocks from which petroleum is extracted. In recent years, water scarcity and challenges associated with ongoing produced water disposal in New Mexico have led to state-sponsored research and regulatory initiatives and industry proposals for permitting discharge of treated produced water to surface water and groundwater. Currently, that discharge is prohibited and produced water is instead disposed of via deep underground injection or exported out of state for treatment and disposal. Under authority granted in the 2019 New Mexico Produced Water Act, the New Mexico Water Quality Control Commission (WQCC) has promulgated regulations that allow for pilot projects and research related to potential re-use of produced water but do not currently allow discharge to surface water and groundwater. A recent petition to the WQCC aims to reconsider surface water and groundwater discharge based on the assertion that recent advances in scientific research support doing so safely.

The following sections of this report closely evaluate several recent publications from the New Mexico Produced Water Research Consortium. These publications are cited by industry as constituting a body of scientific research demonstrating the potential for safe discharge of produced water to surface and groundwater. Each publication is evaluated based on whether it addresses the following key information gaps:

- Toxicity/risk of known contaminants;
- Toxicity/risk of unknown contaminants;
- Toxicity/risk to aquatic species;
- Toxicity/risk to terrestrial species;
- Toxicity/risk to mammals, toxicity/risk to humans;
- Bioaccumulation/long-term effects;
- Spatial/temporal variability of constituents; and
- Environmental fate and transport.

Although the recent publications have incrementally advanced our understanding of treatment alternatives for produced water, as well as residual toxicity and constituents that may persist through various treatment and “post-treatment” processes, gaps persist. These gaps relate to characterizing unknown produced water constituents, advancing knowledge of the toxicity and risk of known substances in produced water, understanding the risks posed by the variability of constituents (and concentrations) in produced waters, and the fate and transport of residual constituents in treated and “post-treated” waters when they are released to the environment. The current *status quo* prohibition on the discharge of treated produced water to surface and groundwater allows for pilot projects and scientific research and advancements. In light of the lingering gaps described in this report, and other lingering gaps not addressed herein, maintaining the *status quo* prohibition will allow ongoing research and testing to proceed without posing an undue risk to the environment and the public.

Introduction

Produced water is a liquid waste from the drilling or production of oil and gas. In the State of New Mexico, it is defined as “a fluid that is an incidental byproduct from drilling for or the production of oil and gas” New Mexico Statutes Annotated 1978, § 74-6-2(S); 20.6.8.7.P(5) New Mexico Administrative Code (NMAC). In 2019, the New Mexico Produced Water Act (House Bill 546) delegated authority to regulate the reuse of produced water outside the oil and gas field to the New Mexico Environment Department (NMED). This was followed by the establishment of a Memorandum of Understanding between NMED and New Mexico State University (NMSU) to create the New Mexico Produced Water Research Consortium (NMPWRC) to “better understand the scientific and technical challenges and opportunities surrounding produced water” and “to fill scientific and technical gaps related to produced water” (NMED and NMSU 2019, p.1).

In December 2023, NMED filed a rulemaking petition before the New Mexico Water Quality Control Commission (WQCC) to regulate discharge of untreated or raw and treated produced water to New Mexico surface water and groundwater (NMED 2024). At that time, Amigos Bravos, Sierra Club, and Western Environmental Law Center retained Industrial Economics, Incorporated (IEc) to provide analysis and testimony from Dr. Christopher Lewis before the WQCC on the human health and ecological risks related to the potential discharge of raw and treated produced water into surface water and groundwater (Lewis 2024). Following a two-week evidentiary hearing in 2024, the WQCC voted in May 2025 to adopt rules prohibiting discharge of treated and untreated produced water to surface water and groundwater and to allow non-discharging pilot projects of any size to move forward with the aim of advancing the science of produced water treatment (WQCC 2025a). The rules, codified at 20.6.8 NMAC, became effective in July 2025.

In June 2025, the Water Access Treatment & Reuse (WATR) Alliance petitioned the WQCC to reverse the prohibition and allow reuse and discharge of treated produced water to surface water and groundwater (WATR 2025). The WQCC dismissed the petition in November 2025 (WQCC 2025b). In March 2026, the WATR Alliance (and other entities) filed a second petition with the WQCC to allow reuse and discharge of treated produced water (WATR et al. 2026), which the WQCC voted to hear (WQCC 2026). The hearing has not been scheduled because the WATR Alliance has not filed a complete petition (WQCC 2026). The WATR Alliance’s second petition asserts that “Assertions that...the rule adopted by the Commission in May 2025 was informed by the most current scientific record, do not reflect the timing or scope of available science” (WATR et al. 2026, p. 10) and that scientific research on the part of the NMPWRC “has demonstrated that treated produced water can be used in various reuse applications without adverse impact to aquatic species, soils and plants, or human cells” (WATR et al. 2026, p. 8).

The purpose of this report, conducted under contract with Amigos Bravos, is to critically evaluate the state of the current scientific research on treated produced water toxicity and risk, focusing on research published by the NMPWRC since the 2024 rulemaking hearing.

Background

This section provides background information on produced water constituents and toxicity, produced water treatment, and the risks associated with treated produced water. It draws from Dr. Lewis’ previous testimony before the WQCC, publicly available information on the NMPWRC, and the WATR Alliance’s second petition (Lewis 2024, NMPWRC 2026, WATR et al. 2026).

Produced Water Constituents

Produced water is a mixture of naturally occurring water from oil and gas formations and liquids introduced into the formation during the oil and gas extraction process. It contains saline water as well as natural and man-made hydrocarbons, drilling fluids, and constituents originating from the rocks from which petroleum is extracted

(Alley et al. 2011). The salinity of produced water can vary from less than one percent to greater than 30 percent, or roughly 10 times the salinity of the ocean (Neff et al. 2011). A study of produced water from five locations in the Permian Basin in New Mexico found salinity ranged from about 10 to 20 percent, or between 100,000 and 200,000 mg/L (Jiang et al. 2022a). Drilling fluids, which can include hydraulic fracturing fluids, are primarily clay-based but can contain a variety of known and proprietary additives. Finally, it is also possible that new chemicals are created during the drilling or operation of oil and gas wells through chemical transformation of known and unknown constituents in produced water (Jiang et al. 2022b, Wollin et al. 2020, Hoelzer et al. 2016).

Considering these variable sources, produced water can contain hundreds of known and unknown constituents. Constituents from the environment that may be present in produced water can include hydrocarbons, salts, metals, and radionuclides. Danforth et al. (2020) documented more than 1,198 known chemical constituents in produced waters nationwide. A follow-up presentation reviewing additional data sources suggests more than 2,800 unique compounds may be present in produced water (Thimons et al. 2023). In addition, many constituents are proprietary, and therefore their basic chemical structure is unknown to the public, let alone their potential toxicity. A 2015 U.S. Environmental Protection Agency (US EPA) study identified 692 unique ingredients in hydraulic fracturing fluids, 11 percent of which were designated as confidential business information (US EPA 2015).

Academic and government studies have shown that concentrations of known chemical constituents in produced water also can vary greatly (Danforth et al. 2020, US EPA 2020, Folkerts et al. 2020). For example, based on data from the U.S. Geological Survey (USGS) National Produced Waters Geochemical Database, barium and strontium concentrations in produced water ranged from less than 10 micrograms per liter ($\mu\text{g/L}$) to more than 10 grams per liter (g/L). Similarly, radium activities ranged from less than 0.1 picocuries per liter (pCi/L) to greater than 10,000 pCi/L (US EPA 2020). The study from five locations in the Permian Basin discussed above showed radium activities in a slightly narrower range from less than 1 pCi/L to greater than 1,000 pCi/L (Jiang et al. 2022a).

Produced Water Toxicity

Many constituents found in untreated produced water are known hazards; for example: arsenic, barium, bromide, mercury, as well as benzene, toluene, ethylbenzene, and xylenes (BTEX). These constituents have the potential to cause carcinogenic, developmental, reproductive, and other adverse effects in humans and other biological organisms (Wollin et al. 2020). In addition, the salts in raw produced waters are high enough to be toxic to freshwater organisms (Folkerts et al. 2020). This means that raw produced water discharged into freshwater poses a risk of harming aquatic ecosystems.

Investigations of the composition of produced water indicate that metal concentrations can be orders of magnitude above US EPA acute and chronic criteria for the protection of aquatic life, and that pH can range from 3.4 to 10.1, which is well outside the range of natural freshwaters (Folkerts et al. 2020). Such metals concentrations and extreme pH values would be expected to cause toxicity to biological organisms living in freshwater systems. Danforth et al. (2020) found maximum concentrations in produced water were 0.035 milligrams per liter (mg/L) for benzo(a)pyrene, 860 mg/L for benzene, and 16,800 mg/L for toluene (Danforth et al. 2020). For reference, ambient freshwater quality criteria for the protection of aquatic life developed by the US EPA for benzene and toluene are 5.3 mg/L and 17.5 mg/L , respectively (US EPA 1980a, 1980b). The federal maximum contaminant levels (MCLs) for drinking water for these three chemicals are 0.0002, 0.005, and 1 mg/L , respectively (US EPA 2024). These thresholds are multiple orders of magnitude lower than the observed concentrations. Both benzene and benzo(a)pyrene are carcinogenic (ATSDR 1995, 2007) and their maximum contaminant level goals are both zero (US EPA 2024). Because there is no threshold for effects of

carcinogenic compounds, this means that any exposure to these constituents would be expected to increase one's risk of developing cancer.

Of the 1,198 chemicals identified in produced water by Danforth et al. (2020), only 167 had corresponding toxicity information suitable for risk assessment. Of those 167, 23 were highlighted as being of particular toxicological concern, based on their maximum observed concentrations in produced water and toxicological information on lower bound effects thresholds from laboratory- and field-based ecological toxicity studies or toxicological screening assays. The authors also identified 36 chemicals as occurring on US EPA's Priority Pollutant List (Danforth et al. 2020). This means that out of only the small fraction of produced water constituents about which we know something of their potential hazards and concentrations, dozens would be expected to pose a risk to human or environmental receptors if those receptors were exposed to produced water.

Researchers have also published studies of the direct toxicity of produced water constituents or of produced water itself to ecological receptors. For example, a review by Folkerts et al. (2020) first identified specific adverse toxicological effects to aquatic organisms caused by individual produced water constituents including salts, metals, and organics such as polycyclic aromatic hydrocarbons at concentrations observed in produced waters. The authors then synthesized studies of the toxicity of produced water tested directly on aquatic organisms or of the toxicity of laboratory-generated "reconstituted" produced water containing mixtures of some of the known constituents of produced water. Observed toxicological responses included immunological, endocrine, metabolic, developmental, and mortality responses in aquatic organisms (Folkerts et al. 2020). Similarly, a study of Permian Basin produced water taken from near Carlsbad, New Mexico showed that even diluted and treated produced water induced toxicity in three toxicity screening assays. The authors of that study highlighted that salinity was the primary driver of toxicity but that organic constituents may play a role in the observed toxicity and raised the possibility that produced water constituents may cause synergistic toxicity (Hu et al. 2022). As discussed further below, more recent studies have corroborated such results showing that untreated and even treated produced water is highly toxic. These studies demonstrate that specific characterized constituents in produced water, as well as raw produced water itself, may pose a risk to human health and the environment.

A Note About Non-Targeted Analysis

To address concerns raised about unknown constituents in produced water, researchers have raised the prospect of using non-targeted analysis. Although non-targeted analysis is at the forefront of analytical chemistry technology and is advancing our understanding of unknown constituents in environmental samples, it is important to understand what non-targeted analysis is and what it can, and cannot, do:

- In contrast to traditional chemical analysis techniques that target a pre-defined set of compounds using known standards, **non-targeted analysis involves the use of specialized analytical equipment to separate chemicals within an analytical sample based on chemical characteristics such as mass and polarity.**
- Non-targeted analysis is useful for identifying classes of compounds for further study.
- Non-targeted analysis does not generate a concentration of a given constituent.
- Due to its broad focus, non-targeted analysis may not be able to detect low levels of specific chemicals.
- Non-targeted analysis does not, independently, address the potential toxicity of a given compound or set of compounds. Toxicity must be assessed separately using toxicity testing protocols.

For more information on non-targeted analysis, see: <https://www.epa.gov/chemical-research/non-targeted-analysis-research>.

Produced Water Treatment

Different technologies are effective at removing different contaminants from water. For example, chemicals can be added to water to react with contaminants and cause them to precipitate out of solution, bioreactors can address high levels of organic carbon, carbon filtration can be used to filter out hydrophobic organic contaminants, and irradiation with ultraviolet light can be used to remove bacteria. Given the wide variety of contaminants in produced water, multiple treatment technologies have been documented to address different needs. Treatment technologies generally can be organized based on the classes of contaminants they are meant to target. For example, hydrocyclones, oil-water separators, floatation, and coagulation and flocculation have been used to remove suspended particles and oil droplets; adsorption and cation and anion exchange membranes have been used to remove metals; and activated sludge, advanced oxidation, and ozonation have been used to address organic contaminants (Adeptian et al. 2026, Amakiri et al. 2022, Igunnu and Chen 2014). More recently, as discussed further below, treatment trains involving the use of various treatment technologies paired with “post-treatment” processes involving the use of granulated activated carbon (GAC) and zeolite have been shown to be effective at removing significant amounts of targeted constituents (Tarazona et al. 2024, 2026; Wijekoon et al. 2025, Edirisooriya et al. 2026a, 2026b).

Although many of the traditional approaches can remove upwards of 80, 90, or even 95 percent of oil, grease, suspended solids and metals, the reality is that most approaches are not 100 percent effective at removing even targeted contaminants, may not address non-targeted contaminants, and are subject to failure. As discussed in detail herein, even treated produced water effluents undergoing “post-treatment” processes may contain residual concentrations of constituents and, in some circumstances, the treatment process itself may introduce contaminants. Even small quantities of residual contamination may be of concern. For example, if the concentration of a constituent is 100 times greater than the threshold of concern, removing all but five percent, or even two percent, will still result in an exceedance of the threshold. One particular problem is the incomplete removal of aromatic compounds such as benzene, toluene, ethylbenzene and xylene (often referred to and analyzed as a group; BTEX), which are difficult to remove in industrial water treatment settings (Amakiri et al. 2022, Igunnu and Chen 2014). To ensure removal of the various constituents that may be present in produced water, a more thorough and complete understanding of which constituents are included in produced water needs to be developed so treatment techniques targeting those contaminants may be employed. Further, multiple treatments in series are necessary, and treatment train effluents should be tested to confirm removal.

Risks Associated with Treated Produced Water

Given the highly heterogeneous nature of produced water and the presence of both known and unknown constituents, assessing its environmental risks is very difficult. The very nature of its highly variable constituents means that produced water from one well may pose a significantly different risk than produced water from another well. Nevertheless, researchers have aimed to evaluate such risks.

In environmental risk assessment, risk is based on the concentration of a stressor in the environment, dose-response information about how increasing concentrations cause increasing adverse effects, and the extent to which a given human or ecological receptor comes into contact, or might be expected to come into contact, with relevant concentrations in the environment. Since treatment systems are not 100 percent effective and only reduce the concentrations of produced water constituents, the risks associated with produced water constituents may be reduced through treatment, but treatment does not fully eliminate risk. Lingering risk stems from two key factors.

First, treatment does not equate to complete removal of a contaminant from a wastewater stream. Even low concentrations of hazardous substances in discharged treated produced water may continue to pose a risk because they may accumulate in the environment downstream of wastewater treatment facilities or may not be removed to below levels of concern. If wastewater-receiving streams or aquifers are hydrologically connected to or themselves used as a source of drinking water, any contaminants that pass through the drinking water treatment process may then pose a risk to the public consuming that water (see text box). Furthermore, carcinogens do not have a safe level of exposure, so even a very small concentration of carcinogenic contaminants may pose a risk. For example, radium is a known contaminant in produced water from the Permian Basin in New Mexico (Thakur et al. 2022). Studies of stream sediments in Pennsylvania near centralized waste treatment facilities treating wastewater from oil and gas extraction operations showed increased radium at the facility outfalls and downstream of the outfalls relative to upstream (Van Sice et al. 2018).

Second, since the full suite of contaminants that may be present in produced water has not been characterized, it is possible, if not likely, that unknown hazards may be present in treated produced water. Of the 1,198 chemicals identified as being present in produced water based on the literature reviewed by Danforth et al. (2020), only 290, or 24 percent, can be identified using standard analytical methods. Further, most of these constituents have not been evaluated to determine whether they are hazardous or not: 56 percent of the known chemical constituents in produced water had no corresponding dose-response data available, and, as stated above, only 167 constituents, or 14 percent, had known toxicity data suitable for risk assessment available (Danforth et al. 2020). Another study reviewed the available toxicity information for chemicals in produced water and hydraulic fracturing fluids, which may be a contaminant in produced water. Yost et al. (2016) found that 62 percent of the 134 chemicals reported as being present in produced water and only eight percent of the 1,072 chemicals reported in hydraulic fracturing fluids had chronic oral reference values. Oral slope factors, which describe the carcinogenicity of a chemical, were almost universally unavailable (Yost et al. 2016). Without information on whether a contaminant is present in produced water, or without information about whether a contaminant is a hazard, one cannot assess risk at all.

Therefore, although the magnitude of risk posed by treated produced water is dependent on the actual dose and route of exposure, given the uncertainties in the makeup of produced water and its treatment, it is nearly certain that there would be some risk associated with discharge of produced water to the environment. Said another way, to the extent that produced water is effectively treated and known hazardous constituents removed (or their concentrations substantially reduced), the risks posed by known constituents would be reduced, but they likely would not be fully eliminated. Finally, the potential risks posed by unknown produced water constituents, particularly if they are left untreated, remain unknown, and unknowable unless and until research has elucidated what those constituents are and the extent to which they are toxic to human and environmental receptors.

The Risks Posed by Untreated Substances: The Example of Pharmaceuticals and Personal Care Products

Incomplete water treatment – particularly of non-target compounds – is not a problem unique to the petroleum industry or the treatment of produced water. It was most strikingly shown by two USGS studies published in the early 2000s, which first documented numerous pharmaceuticals and personal care products (PPCPs) in U.S. streams and led to widespread public health concern regarding the persistence of these chemicals in drinking water (Kolpin et al. 2002, Stackelberg et al. 2004). The first study by Kolpin et al. (2002) documented potentially hazardous substances in streams throughout the U.S. This was followed by a study that documented that a wide variety of contaminants were found to pass through the treatment train in a drinking water facility (Stackelberg et al. 2004). These two studies, together, were groundbreaking in the field of environmental health specifically because they demonstrated that measurable quantities of known hazards were passing through public wastewater and drinking water treatment facilities and posing a potential risk to the environment and the public. Since their publication, the US EPA has placed a greater emphasis on source control—keeping PPCPs out of wastewater streams—as well as promoting use of more advanced treatment technologies by wastewater treatment facilities.

The Recent Produced Water Toxicity and Risk Literature: The State of the Science

The subsections that follow describe the key recent publications highlighted by the NMPWRC as relevant to the toxicity of, and human and ecological health risks associated with, treated produced water (NMPWRC 2026). For each publication, we summarize the research findings and discuss the paper's contributions and limitations in filling knowledge gaps on the safety and risks of reusing treated produced water outside of the oil and gas industry. In addition, we evaluate each paper qualitatively on the extent to which it addresses each gap. The knowledge gaps targeted in this review include:

- **Toxicity/risk of known contaminants**
- **Toxicity/risk of unknown contaminants**
- **Toxicity/risk to aquatic species**
- **Toxicity/risk to terrestrial species**
- **Toxicity/risk to mammals**
- **Toxicity/risk to humans**
- **Bioaccumulation/long-term effects**
- **Spatial/temporal variability of constituents**
- **Environmental fate and transport**

This list represents key gaps related to toxicity and risk assessment when considering the pathways of release of treated produced water to surface and groundwater. It is not the full list of potential knowledge gaps that would need to be filled to allow for the safe treatment and reuse of produced water outside of the oil and gas industry. For example, it does not fully address knowledge gaps associated with the potential use of treated produced water in agriculture, for livestock watering, or for use in dust suppression on roads, among other proposed reuses. Note also that although produced water treatment is discussed in this report, since treatment may reduce exposure and is the subject of several recent papers in the literature, the efficacy, scalability, costs, challenges, and other implications of specific treatment technologies are not addressed herein. Though such challenges are relevant to toxicity assessment since effluents from pilot-scale studies are unlikely to be fully representative of effluents from full-scale treatment facilities, none of the studies reviewed herein directly address toxicity from full-scale treatment facilities. Finally, it is worth reiterating that the discussion below centers around the toxicity and risks associated with treated produced water; it does not address the toxicity and risks associated with raw produced water, potential accidental releases and exposure, or concentrated waste streams that may be generated through treatment.

Tarazona et al. 2024, Title: Benchmarking produced water treatment strategies for non-toxic effluents: Integrating thermal distillation with granular activated carbon and zeolite post-treatment

Summary

The researchers evaluated the efficacy of the treatment of Permian Basin produced water using a pilot system relying on low-temperature thermal distillation. The treated produced water was subsequently run through a “post-treatment” system further treating the water with GAC, which is used to remove organic compounds and metals, and zeolite, which is used to remove ammonia. These “post-treatments” were applied individually and in series. Concentrations of 45 constituents in the treated and “post-treated” water were measured, including standard water quality parameters (i.e., total dissolved solids [TDS], electrical conductivity, pH, hardness, and alkalinity), volatile and semi-volatile organics (VOCs and SVOCs, respectively), total organic carbon, total petroleum hydrocarbons (TPH), nitrogen-containing compounds (i.e., ammonia, nitrate, and nitrite), and

selected ions and metals. The toxicities of the effluents were assessed using three whole effluent toxicity (WET) tests exposing: a green algal species (*Raphidocelis subcapitata*) for four days, an aquatic invertebrate—the water flea (*Ceriodaphnia dubia*) for two days, and zebrafish (*Danio rerio*) for four days. In addition, toxicity was further evaluated using a Microtox screening assay, a bioluminescence inhibition test using the bacterium *Vibrio fischeri* wherein the degree of bioluminescence corresponds to the viability of the bacterium. Various dilutions of the treated and “post-treated” effluents were tested. Toxicity was observed in both the treated and “post-treated” waters, though the iterative treatments resulted in effluents with sequentially decreased toxicity. The greatest reduction in toxicity was observed for effluents treated with both the GAC and zeolite “post-treatments”. Of note, the authors highlighted that “These findings highlight the presence of residual stressors in the post-treated distillate when GAC and zeolite post-treatments are used as an individual treatment process” (p. 5) but “the GAC+Zeolite post-treatment was successful in surpassing the [test of significant toxicity], not only meeting both acute and chronic [regulatory management decision] thresholds but also achieving the low-risk [regulatory management decision] benchmark (mean effect less than 10%) for *R. subcapitata*, *C. dubia* and *D. rerio*” (p. 10). The concentrations of many measured constituents in the effluents similarly were reduced with subsequent treatment steps, and the authors credited removal of specific compounds for reducing observed toxicity, though not all contaminants targeted for analysis were reduced to below their respective detection limits (including unresolved total organic matter). Surprisingly, the concentrations of some substances increased, particularly cadmium, copper, and sodium in “post-treated” effluents, potentially due to contamination resulting from the treatment process itself (i.e., leaching from the zeolite).

Contributions

The paper’s primary contributions to demonstrating safe reuse of produced water outside the oil and gas industry are related to its use of WET testing using standard test organisms and use of multiple toxicity endpoints spanning three taxa. Further, the study effectively used both positive and negative controls, by demonstrating toxicity of the treated pilot effluent and by using clean control samples in toxicity tests, which validate the observed toxicity reductions. The paper also demonstrates the promise of a pilot treatment train approach to treating Permian Basin produced water.

Limitations

Limitations of the research discussed specifically by the authors include the focus on acute mortality endpoints (and the need for testing of chronic toxicity and sublethal endpoints) and their focus on a limited suite of chemical analytes. The authors note “Given the potential risks and the limitations associated with [residual uncharacterized organics] characterization, the uncharacterized fraction of organics should be considered a “potential stressor”, and a treatment unit aiming to remove organics should be considered as the next step” (p. 13). Though not addressed by the authors, the work also does not address potential human toxicity or potential toxicity to any number of non-standard biological receptors. Although reduced constituent concentrations and toxicity were observed, not all constituents were removed and residual toxicity, though not statistically significant, was present, even in “post-treated” water, highlighting the complexity of produced water treatment. Additional caveats relevant to this work include the complexities of scaling the treatment train used and whether the treatment train could adequately address the variability of constituent concentrations observed in Permian Basin produced waters. Finally, this work does not address the potential accumulation of residual contaminants in the environment from discharged effluents.

Gaps Assessment

Knowledge Gap	Gap Addressed?	Notes
Toxicity/risk of known contaminants	Partially	Produced water chemically tested, but only 45 known constituents measured.
Toxicity/risk of unknown contaminants	Partially	Use of raw, treated, and “post-treated” whole produced water in toxicity testing using WET tests targeting three species plus microtox, but no detailed evaluation of unresolved organic carbon.
Toxicity/risk to aquatic environments/species	Partially	Toxicity assessed using WET tests targeting three species plus microtox addresses acute toxicity only, to a subset of species, from a single treated and “post-treated” produced water constituent mixture.
Toxicity/risk to terrestrial environments/species	No	No tests on terrestrial endpoints.
Toxicity/risk to mammals	No	No tests on mammalian endpoints.
Toxicity/risk to humans	No	No tests on human endpoints.
Bioaccumulation/long-term effects	No	Tissues/bioaccumulation not tested, no chronic toxicity testing conducted.
Spatial/temporal variability of constituents	No	Only one batch of produced water tested.
Environmental fate and transport	No	No testing or evaluation of environmental fate or transport.

Wijekoon et al. 2025, Title: Comprehensive cytotoxicity assessment of treated produced water from thermal distillation using human cell lines

Summary

This paper is a follow-up to the Tarazona et al. 2024 paper, produced by most of the same authors, employing a similar overall research approach. The primary difference is the suite of toxicological endpoints measured. In this work, the researchers evaluated the lethal and sublethal toxicity of Permian Basin produced water at various dilutions to human cell lines, before and after treatment and “post-treatment” using several different human tissue types. They also similarly measured constituent concentrations in effluents, though only present results for 24 water quality characteristics and individual constituents (i.e., pH, ammonia, total organic carbon, total dissolved solids, total petroleum hydrocarbons, numerous ions, and a short list of volatile organic compounds). In this case the authors evaluated two different thermal treatment techniques, along with GAC and zeolite in series as the “post-treatment step”. Chemical results showed that salinity was effectively reduced with treatment but VOC concentrations actually increased. Subsequent “post-treatment” steps further reduced targeted constituents, including ammonia and VOCs in most cases to below the analytical detection limits. Notably, however, total organic carbon, total petroleum hydrocarbons, and ions were still present in one or more of the “post-treated” effluents. Across the battery of human cell line toxicity tests, the researchers generally observed toxicity in the untreated produced water, observed reduced toxicity in the treated effluents, and saw further reduced toxicity in the “post-treated” effluents.

Contributions

The paper's primary contribution is in partially addressing the information gap related to the question of whether treated produced water is toxic to humans, and not just to standard aquatic test organisms. Further, in applying a battery of human cell line toxicity tests, the authors were able to test both lethal and sublethal endpoints. Similar to the Tarazona et al. 2024 paper, the experimental design also facilitated both positive and negative controls, in that the authors demonstrated that the tests used were sensitive to the toxicity of raw produced water but also did not show toxicity using test-specific controls.

Limitations

The limitations of this work are similar to those of Tarazona et al. 2024, in that this paper did not address the ability of the treatment process to handle variable constituent concentrations in produced water, or whether the treatment or "post-treatment" processes used could be reasonably scaled. Nor did it address concerns related to the accumulation of contaminants in the environment from effluents. Of particular concern, however, was the increase in VOCs measured in the treated effluent, though those results further emphasize the importance of the use of treatment trains and the additional "post-treatment" steps the authors employ. Further, despite the battery of toxicity tests used, though standard, they rely on immortal or cancer cell lines, the use of which has been criticized for having reduced applicability to healthy human cells in the body (Li et al. 2024). Ultimately, such human cell line toxicity tests are one line of evidence among several that toxicologists consider when assessing human toxicity (e.g., among other lines of evidence including epidemiological studies, animal studies, and modeling tools).

Gaps Assessment

Knowledge Gap	Gap Addressed?	Notes
Toxicity/risk of known contaminants	Partially	Produced water chemically tested, but only 24 known constituents measured.
Toxicity/risk of unknown contaminants	Partially	Use of raw, treated, and "post-treated" whole produced water in toxicity testing, but no detailed evaluation of unresolved organic carbon.
Toxicity/risk to aquatic environments/species	No	No tests on aquatic endpoints.
Toxicity/risk to terrestrial environments/species	No	No tests on terrestrial endpoints.
Toxicity/risk to mammals	Partially	Toxicity assessed using human cell lines, but no other mammalian tests conducted.
Toxicity/risk to humans	Partially	Toxicity assessed using human cell lines, but structure-activity modeling conducted.
Bioaccumulation/long-term effects	No	Tissues/bioaccumulation not tested, no chronic testing conducted.
Spatial/temporal variability of constituents	No	Only one batch of produced water tested.
Environmental fate and transport	No	No testing or evaluation of environmental fate or transport.

Senanayake et al. 2025, Title: Plant growth, ion dynamics, and microbial communities in soils irrigated with treated produced water for sustainable agriculture

Summary

Senanayake et al. studied plant growth in greenhouse experiments, irrigating the plants with multiple dilutions of treated produced water. The key variables were TDS concentration, species, and soil type. The paper ultimately focuses on the alfalfa, a moderately salt-tolerant forage plant, grown in either loamy, clay-rich, or a mixture of both soil types with results for the other plants (Mexican feather grass, red yucca honey, mesquite) presented in supplemental materials. The authors also evaluated soil microbial health and measured and reported on concentrations of a suite of chemical parameters in the produced water, including water quality characteristics, some organic contaminants including TPH, and major and minor ions and other elements. With the focus on alfalfa, a battery of plant attributes related to nutritional value (e.g., fiber and protein content) were measured, and microbial communities were assessed based on DNA sequencing to assess diversity. Finally, overall soil health was tracked based on the soil quality index, which measures soil health based on pH, conductivity, TDS, and sodium absorption. The study was run for a total of 40 weeks. Research findings were generally consistent with expected results based on the soils literature, with the clayey soils accumulating ions nearer to the surface and the loamy soils demonstrating leaching with increased salt exposure to deeper soils. Although changes in ion profiles in soils were observed across all treatment groups, the authors concluded that only the lowest dilution (highest concentration) of produced water of approximately 1,500 mg/L TDS would lead to “pronounced salt accumulation” and related adverse effects on soils (p. 9). Study conclusions were that (1) treated produced water with TDS concentrations in the range of 1,500 mg/L exhibited measurable adverse effects to plant, microbial community, and soil health, (2) nutritional content of the alfalfa varied across all of the produced water treatment but irrigation of alfalfa with water at a TDS concentration in the range of 1,000 mg/L improved alfalfa nutritional content when grown in loamy soils, and (3) soil quality and microbial effects were predominantly dictated by soil type.

Contributions

This paper demonstrated that irrigation with diluted, treated and then reconstituted produced water at salinity of approximately 1,500 mg/L caused adverse changes to soil, plant, and microbial health. However, if sufficiently diluted (i.e., to a salinity of approximately 1,000 mg/L, or approximately 100:1 assuming a TDS concentration of 100,000 to 200,000 mg/L in raw Permian Basin produced water; Jiang et al. 2022a), alfalfa growth can be supported. The research also furthered understanding of the potential influences of soil type on soil chemistry and associated microbial dynamics. The authors themselves highlight the paper’s contributions as advancing “understanding of plant growth, ion dynamics, and microbial community responses in soils irrigated with [treated produced water] of varying salinities” and its potential “as an alternative irrigation source, offering critical guidance for promoting long-term soil health, microbial stability, and sustainable agricultural practices in water-scarce regions” (p. 13).

Limitations

Other than focusing on a limited set of plants and soil types, notable shortcomings of the research include the fact that both the control and produced water-irrigated soils were contaminated with TPH, putting into question firm conclusions related to toxicity and the microbial community.¹ The study was also limited in duration (less than one year) so did not address longer-term impacts of irrigation with diluted produced water on either soils or plants, and did not assess uptake of contaminants into plant tissues. In discussing the paper’s contributions, the

¹ The authors note, however, that TPH concentrations were below risk-based and remedial thresholds in all soils.

authors provide the key caveat that “Future extended field application across successive growing seasons is recommended to further validate [treated produced water’s] long-term viability and investigate the potential progressive accumulation of residual salts and trace organic constituents in [treated produced water] on soil physicochemical characteristics and microbial dynamics, thereby influencing soil health and crop productivity” (p. 13).

Gaps Assessment

Knowledge Gap	Gap Addressed?	Notes
Toxicity/risk of known contaminants	Partially	Produced water chemically tested, but only 35 known constituents measured.
Toxicity/risk of unknown contaminants	Partially	Use of treated but then reconstituted (using permeate and concentrate) produced water in toxicity testing, but no detailed evaluation of unresolved organic carbon.
Toxicity/risk to aquatic environments/species	No	No tests on aquatic endpoints.
Toxicity/risk to terrestrial environments/species	Partially	Variety of plant species tested. No terrestrial animals tested.
Toxicity/risk to mammals	No	No tests on mammalian endpoints.
Toxicity/risk to humans	No	No tests on human endpoints.
Bioaccumulation/long-term effects	No	Bioaccumulation not tested (tissues tested but only for nutritional content), testing conducted over a nine-month period.
Spatial/temporal variability of constituents	No	Only one batch of produced water tested.
Environmental fate and transport	No	No testing or evaluation of environmental fate or transport.

Tarazona et al. 2026, Title: Advancing produced water quality via integrated mechanical vapor recompression: Chemical and toxicological characterization, hazard identification and mitigation

Summary

One of the most recent papers from NMPWRC researchers, this is a follow up paper to both Tarazona et al. (2024) and Wijekoon et al. (2025), among others. In this case, the researchers similarly treated Permian Basin produced water, apparently from the same source as used in the earlier papers. However, samples were more thoroughly chemically evaluated and additional toxicological tests performed. In this case, over 400 known chemical constituents were targeted for analysis and tracked through the treatment and “post-treatment” processes (though a subset were detected). Results of these additional tests mirrored those of earlier papers by the same authors, with the raw and treated produced water exhibiting toxicity and the “post-treated” water not showing toxicity with the selected tests. As observed in previous small-scale studies, the combination of treatment and “post-treatment” with granulated activated carbon and zeolite were highly effective at removing the constituents evaluated (i.e., upwards of 95 percent). However, small quantities of some constituents persisted in “post-treatment” effluents and some constituents actually increased at certain stages of the treatment train, likely as a result of the treatment itself. This included VOCs, which increased through the distillation process,

and per- and polyfluoroalkyl substances (PFAS), which increased in the “post-treated” water. These findings highlight the complexities and challenges of managing a treatment train to remove such a wide variety of constituents.² Finally, although radium isotopes and gross alpha were reduced by between approximately 96 and 99 percent through the whole treatment and “post-treatment” process, gross beta radiation was detected at 1.25 pCi/L in the “post-treatment” effluent, exhibiting an increase over the activity observed in the treated samples (but still an overall decrease relative to the raw water). Toxicological tests performed mirrored those presented in Tarazona et al. (2024), with *R. subcapitata*, *C. dubia*, *V. fischeri* (Microtox), and *D. rerio* (zebrafish) as the standard lab test organisms used across both papers. Toxicological findings were also similar, with raw and treated produced water exhibiting variable toxicity, but “post-treated” water exhibiting no toxicity statistically significantly different from controls.

Contributions

The key contributions provided by this paper to the produced water literature were the findings from toxicological tests evaluating sublethal effects, including tests on zebrafish embryos and gross measures of development and metabolism through gene expression. The use of WET tests and toxicity screenings in combination with both positive and negative controls demonstrate the selected treatment train’s ability to effectively remove the vast majority of measured produced water constituents and reduce, if not eliminate, the toxicity of the “post-treated” effluent. In addition, the longer list of target analytes for chemical analysis provides additional insights into the presence and concentrations range of known constituents.

Limitations

The limitations of the work are generally similar to those of other studies by the same authors discussed above. Key risk-related uncertainties were not addressed, including chronic effects to higher trophic-level organisms—including those related to bioaccumulation of known and unknown substances, as well as the potential accumulation of recalcitrant substances in the environment. For example, PFAS compounds were detected in the “post-treated” effluents, which are both toxic and long-lived in the environment. In addition, in some cases, sample sizes may have been limited. For example, in the case of some of the genetic tests the researchers performed, differences between the produced water and controls were noted but were not found to be statistically significantly different. This included a test for Aromatase A (*cyp19a1a*) expression for which the “post-treated” produced water produced a roughly 2.5-fold increase in gene activity relative to the control even though this enhancement was not statistically significant. In the case of the RNA assays, the authors highlighted that samples needed to be pooled and “a future study is needed to examine individual embryos/ larvae with a larger sample size” (p. 15). In discussing their research findings, the authors themselves note that “WET tests are designed to measure the combined toxic effects of all constituents present in an effluent; reductions in [produced water] effluent toxicity after treatment should be interpreted as reduced mixture hazard rather than definitive removal of a single toxicant. In addition, long-term exposure studies using both aquatic organisms and mammalian models are warranted to further improve our understanding of the safety of treated PW for both direct and indirect receptors” (p. 16). Finally, the paper did not address the potential variability of constituents in produced water and how that could affect treatment efficacy or toxicity.

² Although it is beyond the scope of this review, the scalability of the removal technologies used was not directly discussed in this paper; the authors noted that the GAC system used for “post-treatment” operated at a flow rate of 14 L/day.

Gaps Assessment

Knowledge Gap	Gap Addressed?	Notes
Toxicity/risk of known contaminants	Partially	Produced water chemically tested, but only 400 known constituents measured.
Toxicity/risk of unknown contaminants	Partially	Use of raw, treated, and “post-treated” whole produced water in toxicity testing, but no detailed evaluation of unresolved organic carbon.
Toxicity/risk to aquatic environments/species	Partially	Toxicity assessed using WET tests targeting aquatic species plus gene expression address acute (and to a limited extent, chronic) toxicity to a subset of species, from a single treated and “post-treated” produced water constituent mixture.
Toxicity/risk to terrestrial environments/species	No	No tests on terrestrial endpoints.
Toxicity/risk to mammals	No	No tests on mammalian endpoints.
Toxicity/risk to humans	No	No tests on human endpoints.
Bioaccumulation/long-term effects	Partially	Bioaccumulation not tested, but some chronic and sublethal endpoints tested.
Spatial/temporal variability of constituents	No	Only one batch of produced water tested.
Environmental fate and transport	No	No testing or evaluation of environmental fate or transport.

Edirisooriya et al. 2026a, Title: Pilot-scale evaluation of hypersaline produced water treatment and reuse via freeze desalination and seawater reverse osmosis: Organic removal, aquatic and human cell line toxicity studies

Summary

This study represents one of the most comprehensive chemical evaluations of constituents in Permian Basin produced water, in that the researchers targeted 360 organic constituents, of which 53 were detected. Further, chemical analysis was performed on raw produced water from four separate samples taken over a roughly seven-month period from one produced water disposal facility (though a total of five samples were collected over a roughly nine-month period, raw water from the final sample was not analyzed). Most samples were collected from more than one collection point, though, so appear to be composite samples. The analytical chemistry results nevertheless somewhat reflect the temporal variability (and potentially spatial variability, though this cannot be confirmed) of raw Permian Basin produced waters, and to some degree a range of treated effluent chemistries. While the first three samples were treated with granulated activated carbon and reverse osmosis only, later samples also used freeze desalination as a pretreatment step or also employed an additional “post-treatment” polishing step using another pass through granulated activated carbon. The study presents the analytical results of primarily organic constituents while a separate paper by the same lead author, which does not address produced water toxicity, presents results of primarily inorganic constituents (Edirisooriya 2026b, not discussed herein). Importantly, this paper also presents results from toxicity tests using both human cell lines and chronic WET tests on *R. subcapitata*, *C. dubia*, and *P. promelas* (fathead minnow). However, it appears that the human cell line toxicity tests were only performed on raw and treated waters collected during the penultimate sampling event. In addition, the produced water used in the WET tests was treated further with

zeolite or granulated activated carbon “post-treatment” steps prior to use; no toxicity tests were performed on raw or treated produced water (without “post-treatment”). Finally, a subset of constituent concentrations measured in the treated and “post-treated” produced waters were compared to several regulatory criteria the authors identified as being relevant to potential reuse outside of the oil and gas field (i.e., beneficial use standards for land application from the Texas Railroad Commission, New Mexico Administrative Code ground and surface water standards, and California irrigation standards, and U.S. Environmental Protection Agency MCLs).

Results showed that the treatment processes evaluated, when combined with additional “post-treatment” steps analogous to those discussed above (i.e., GAC and zeolite), effectively reduced all of the measured organic contaminants targeted for analysis to below their respective laboratory detection limits. Similar to findings from the studies discussed above, despite treatment reducing most measured constituents to below their respective detection limits, various constituents were found to pass through the various treatment stages, except for the most rigorously treated and “post-treated” treatment train (which involved a pre-treatment freeze desalination step, treatment with granulated activated carbon and reverse osmosis, and “post-treatment” with granulated activated carbon). For example, a total organic carbon residue of 1.52 mg/L remained in the effluent of even the most rigorously treated and “post-treated” produced water. Results of the toxicity tests were similar to those presented in the papers discussed above by other NMPWRC authors; namely that raw produced water induced toxicity, treatment reduced that toxicity but did not eliminate it, and “post-treated” effluents were not found to be toxic compared to controls (though some non-statistically significant toxicity was observed). Finally, the subset of the known constituents that were both measured in treated and “post-treated” effluents and which had beneficial use standards were generally found to have residual concentrations less than the listed standards.³ However, the authors caveat this comparison by highlighting that “Many of the detected organic compounds lack established regulatory limits, making it challenging to fully evaluate their impact” (p. 13).

Contributions

Results of the chemical analyses demonstrate the variable constituent concentrations in raw produced water. In addition, this paper expands the list of toxicity test endpoints used to evaluate treated and “post-treated” produced waters to additional human cell lines and aquatic test organisms. This paper also introduces the concept of comparing residual concentrations of known constituents to regulatory beneficial use criteria and demonstrates, for a small number of constituents measured after “post-treatment” which had criteria, that concentrations were below the respective criteria.

Limitations

Despite being one of the most recent papers produced by the NMPWRC, the authors themselves highlight many shortcomings of their research in identifying a wide range of work left to do to ensure safe discharge of treated

³ The exception was polychlorinated biphenyls, the detection limit for which was listed as 0.000530 mg/L, which is higher than the NMAC irrigation standard and maximum contaminant level (both of which are 0.005 mg/L). Note that Edirisooriya et al. (2026b), which presents results of a similar comparison, but for inorganic constituents, similarly claimed that “The measured concentrations of inorganic constituents after posttreatment complied with all relevant water quality criteria” (p. 10). However, the detection limit for cadmium was 0.002 mg/L, which is higher than the acute (0.00072 mg/L) and chronic (0.0018 mg/L) ambient water quality criteria.

produced water to the environment.⁴ In the paper's final sentence, the authors write "This study highlights the critical need for advanced analytical approaches, such as non-targeted analysis and suspect screening coupled with effect-directed analysis, to link chemical composition, unknown compounds, and transformation products interactions to toxicological outcomes" (p. 16). Earlier in the paper, the authors identify more specific studies that are needed, including studies "to identify the specific constituents responsible for the residual cytotoxicity observed in treated [produced water] by preparing synthetic solutions with specific constituents" (p. 12) and "evaluating multiple cell lines and biological endpoints" to "clarify the mechanisms of toxicity and improve risk assessment for potential [produced water] reuse applications" (p. 13). They also note that "future studies will be needed to further explore subtle molecular and logical alterations from unidentified chemical mixtures present in treated [produced water] using enzyme assays and advanced molecular tools" (p. 13). Regarding the authors' findings related to their comparisons of residual constituents in treated and "post-treated" effluents to regulatory criteria for reuse, the authors note that "The absence of regulatory criteria for many of the detected compounds requires a comprehensive assessment of the purified [produced water's] suitability for beneficial reuse, including non-targeted chemical characterization and toxicological assays (p. 16).

Gaps Assessment

Knowledge Gap	Gap Addressed?	Notes
Toxicity/risk of known contaminants	Partially	Produced water chemically tested, only organic constituents tested addressed.
Toxicity/risk of unknown contaminants	Partially	Use of raw, treated, and "post-treated" whole produced water in toxicity testing, but no detailed evaluation of unresolved organic carbon.
Toxicity/risk to aquatic environments/species	Partially	Toxicity assessed using WET tests targeting a subset of aquatic species, from a single treated and "post-treated" produced water constituent mixture.
Toxicity/risk to terrestrial environments/species	No	No tests on terrestrial endpoints.
Toxicity/risk to mammals	Partially	Toxicity tests on four human cell lines were performed using a single treated and produced water constituent mixture.
Toxicity/risk to humans	Partially	Toxicity tests on four human cell lines were performed using a single treated and produced water constituent mixture.
Bioaccumulation/long-term effects	Partially	Bioaccumulation not tested, but chronic tests on standard aquatic laboratory organisms conducted.
Spatial/temporal variability of constituents	Partially	Four raw produced water samples taken for chemical analysis over a seven-month period, but use of water from a treatment facility and composite sampling masked spatial heterogeneity. Further, only subset of the multiple samples were used for toxicity testing.
Environmental fate and transport	No	No testing or evaluation of environmental fate or transport.

⁴ Although it is beyond the scope of this review, the authors also cautioned against the ease with which the treatment train could be reasonably scaled. In discussing the treatment system used in this case, the authors state "While this [freeze desalination-reverse osmosis] pilot study demonstrates that high-quality water recovery from hypersaline [produced water] is technically feasible, the transition to industrial-scale deployment involves significant operational improvements. Unlike mature thermal technologies...the current pilot-scale process faces operational complexity challenges" (p. 10-11).

Summary of Findings and Persistent Knowledge Gaps

The papers discussed above, published for the most part since the 2024 WQCC rulemaking hearing, have targeted several of the key information gaps identified prior to and during the rulemaking hearing. Research efforts have focused on the toxicity assessment of produced water treated and “post-treated” using intensive treatment trains and have included the performance of WET tests using standard laboratory toxicity testing organisms and human cell lines, as well as the evaluation plant and soil health following irrigation with treated produced water. By using WET tests, the authors have advanced our understanding of the potential toxicity of known constituents and residual uncharacterized constituents in treated produced water, though none of the papers produced to-date have attempted to further characterize the unresolved organic matter that may persist in treated effluents. Further, the studies have employed a mix of acute and chronic tests, used multiple test species and life stages, and used both positive and negative controls in their experiments, principally by testing combinations and dilutions of raw, treated, and “post-treated” waters. The scientific methods employed have been rigorous and have addressed, to some degree, questions related to species-specific sensitivity and certain modes of toxicity, as well as the efficacy of the range of specific treatment technologies evaluated.

Each of the reviewed studies generally confirmed the existing body of produced water toxicity literature, which has shown conclusively that raw and even treated produced water (that has not undergone subsequent significant “post-treatment”) is toxic to humans and ecological receptors. The primary scientific contributions of these papers thus relate to the lack of observed toxicity in produced water treated (in a variety of ways) and “post-treated” (using a combination of GAC and zeolite). The conclusions discussed below therefore aim to address the threshold question of whether the papers constitute a “body” of scientific literature that demonstrates that treated (and/or “post-treated”) produced water can be discharged safely into surface and groundwater. Ultimately, the incremental advances in scientific knowledge accomplished by the NMPWRC in the past several years, while commendable, still fall short of addressing a number of information gaps that would need to be filled to fully assess the human and ecological risks of discharging “post-treated” produced water to surface or groundwater.

The introduction to one of the most recent NMPWRC papers, by Tarazona et al. (2026), summarizes several of the lingering knowledge gaps in the produced water literature, noting:

[F]undamental knowledge gaps persist regarding the chemical safety of thermally desalinated [treated] [produced water, PW]. Previous research has focused on a limited set of chemical analytes, raising concerns about whether such characterization efforts can adequately evaluate the quality of PW and ensure the chemical safety of thermally treated PW, particularly given the potential for unknown organic compounds to partition into the distillate [7,13]. Furthermore, most toxicological evaluations of PW effluents have primarily relied on conventional acute and chronic endpoints or in-silico toxicity predictions, which are often insufficient for comprehensive hazard identification. Although these tests can capture the effects of PW-associated chemicals on mortality, reproduction, and growth inhibition, they fail to detect subtle molecular and physiological perturbations arising from low-dose exposures or from complex and largely unidentified chemical mixtures present in PW [14,15]. (p. 2)

While the authors claim that their study addresses these fundamental knowledge gaps, it is frankly impossible for a single publication to comprehensively address such significant gaps. From a regulatory risk assessment perspective, the gaps that have been addressed by recent papers pertaining to “post-treated” water have not been reproduced by third parties and do not, even in aggregate, reflect a comprehensive toxicity or risk evaluation. Considering the papers in aggregate, and within the context of the broader produced water toxicity and risk assessment literature, the subsections that follow address each of the persisting knowledge gaps.

Toxicity/risk of known contaminants

The NMPWRC states that it has tested 75 Permian Basin produced water samples for 600 unique analytes and identified 290 (74 of which were found to persist in the “post-treated” water) (NMPWRC 2026). This compares to the roughly 1,200 substances that have been documented in produced water nationwide (Danforth et al. 2020). Whether Permian Basin produced water lacks the balance of these substances is unknown. A specific evaluation of the toxicity information available (or not) for the 290 constituents identified was beyond the scope of this white paper. Information presented in the papers discussed above generally confirms the broader produced water literature in finding that the high total dissolved solids (salts), petroleum constituents and other volatile organic compounds, and ammonia contained in produced water are likely major contributors to toxicity. However, whether additional unmeasured constituents (known to be toxic, or whose toxicity has not been individually characterized) contribute to toxicity remains a significant knowledge gap.

Toxicity/risk of unknown contaminants

As stated above in the introduction to this paper, standard methods are not available to measure the vast majority of chemicals that have been identified in produced water, and of those that have been identified, nearly half lack information on which an assessment of risk may be based (Danforth et al. 2020). This includes substances that may be carcinogenic, for which no level of exposure would be considered safe. These knowledge gaps persist (Ariana et al. 2025). While WET tests are useful because they can assess toxicity without direct characterization of what is causing that toxicity, they are just one line of evidence used by risk assessors to identify hazards and assess risk. To appropriately assess the risks posed by residual produced water constituents, it is necessary to understand what constituents are present. Lack of transparency on the part of the oil and gas industry regarding what chemicals are used, insufficient analytical methods, challenges associated with chemical interference in chemical analysis, and the potential for chemicals to undergo changes during the production process continue to further complicate chemical characterization of produced water constituents. This problem extends to produced waters that have been “post-treated”. As noted above, “post-treated” effluents were found to contain measurable concentrations of numerous known substances as well as unresolved organic matter and dissolved solids. The most recent papers by NMPWRC researchers specifically identify the potential risks posed by unknown constituents contained within unresolved organic matter as an area in need of further study. Tarazona et al. (2024), in discussing a framework developed to evaluate risks posed by produced water notes that “Given the potential risks and the limitations associated with [residual uncharacterized organics] characterization, the uncharacterized fraction of organics should be considered a “potential stressor”, and a treatment unit aiming to remove organics should be considered as the next step” (p. 13). Two years later, most recently, Edirisooriya et al. (2026a) write “This study highlights the critical need for advanced analytical approaches, such as non-targeted analysis and suspect screening coupled with effect-directed analysis, to link chemical composition, unknown compounds, and transformation products interactions to toxicological outcomes” (p. 16). Despite significant contributions to the literature made by recent publications, our ability to understand the potential human and ecological risks posed by produced water constituents that may pass through the treatment process remains limited by our understanding of those constituents, themselves.

Toxicity/risk to aquatic species

A variety of standard aquatic laboratory test organisms have been targeted for analyses in the broader produced water literature, and within the papers discussed above. This has included organisms selected because of their sensitivity to environmental contamination. As noted above, a wide variety of toxicological effects have been shown to result from exposure to raw and even treated produced water, and the primary contributions of the papers above comprise the authors' findings related to a lack of observed toxicity caused by "post-treated" produced water. A lack of toxicity to sensitive laboratory test organisms has traditionally been seen as a way to ensure the protection of the range of organisms in the environment. However, outliers may occur and safety can only be assured by repeated toxicological testing under a range of field and laboratory conditions and test species (see text box). It is only through repeated and varied toxicity testing over time, in field and laboratory settings, using different test organisms and alternative approaches to toxicity evaluation (e.g., modeling, use of quantitative structure activity relationships, field studies, etc.), that chemical safety can be reasonably assured. In the case of the recently published "post-treated" produced water studies by the NMPWRC, the species tested represent only a subset of the potentially susceptible biota that should be studied to ensure the safety of treated produced water.

When Standard Laboratory Toxicity Testing Fails: the Example of 6PPD-Quinone

Standard laboratory toxicity testing does not ensure safety in all cases. An example of this is the substance 6PPD-quinone, a chemical that is created when the preservative 6PPD (used in car tires) reacts with ozone in the environment. Only in recent years have scientists learned that 6PPD-quinone is the ubiquitous contaminant responsible for the long-recognized Urban Runoff Mortality Syndrome, particularly prevalent in coho salmon. The compound is highly toxic to certain Salmonidae (salmon and trout species), especially coho. Not only are Salmonidae a family not typically used in laboratory toxicity testing, but it is unlikely that an ozone degradation product like 6PPD-quinone would be evaluated during standard toxicity testing.

Toxicity/risk to terrestrial species

Risks to human and ecological health may be posed directly by produced water used to irrigate agriculture or in applications such as spreading on roads, or indirectly if produced water is discharged to surface or groundwater used for terrestrial applications. However, produced water discharged to surface water or groundwater may pose a risk to a variety of terrestrial ecological receptors that come into contact with those waters. Only one of the papers discussed above aims to address the toxicity of produced water to terrestrial species—in this case several plant species. Although the paper demonstrates that alfalfa may be grown in produced water, it does not fully address concerns related to the accumulation of produced water constituents in plant tissues that may be consumed by humans, livestock, or wildlife. It also does not address the potential long-term effects of exposure to low concentrations of hazardous substances (see discussion of Bioaccumulation/long-term effects, below) or accumulation of salts in soils over time (see Environmental fate and transport, below). Finally, the several plant species tested represent only a small fraction of the myriad terrestrial biota that could be exposed to produced water if released into the environment. Thus, the addition of the Senanayake et al. (2025) paper to the literature falls short of demonstrating that treated produced water poses no risks to terrestrial biological receptors.

Toxicity/risk to mammals

Although a series of studies within the broader produced water literature has documented the toxicity of hydraulic fracturing fluid constituents and produced water to mammalian test organisms (Ariana et al. 2025), none of the papers discussed above directly address this topic. This includes, principally, a lack of oral dosing studies with treated or "post-treated" water. In fact, Tarazona et al. (2026) specifically highlights that "long-term exposure studies using both aquatic organisms and mammalian models are warranted to further improve our understanding of the safety of treated [produced water] for both direct and indirect receptors" (p. 16).

Toxicity/risk to humans

Similar to the discussion of standard laboratory toxicity tests immediately above, use of a limited number of human cell assays, while informative, represents an incomplete evaluation of the potential toxicity of “post-treated” produced water to humans. A more thorough evaluation would require a more complete understanding of the full range of known and unknown constituents in produced water (including those that remain after the treatment and “post-treatment”) and their toxicity, both as individual contaminants and in aggregate, as contaminant mixtures that have synergistic effects. This information is crucial since laboratory testing cannot be ethically performed on humans. While risk to humans is often inferred from mammalian toxicity testing, those studies too are lacking (see above). Finally, while it is also possible that epidemiological studies (e.g., evaluations of the health effects of workers exposed to produced water) could be informative in this regard, a recent study by Aker et al. (2024) evaluating the state of the epidemiological literature in Canada on the human health effects of hydraulic fracturing identified a dearth of such studies.

Bioaccumulation/long-term effects

A key information gap in the broader produced water toxicity and risk assessment literature, which is also relevant to the toxicity and risks associated with “post-treated” water, pertains to the potential adverse effects of long-term exposure. This includes effects from accumulation of produced water constituents both in biological organisms and the environment over time. This gap persists despite the fact that a number of known produced water constituents are known to bioaccumulate (e.g., PFAS, mercury, selenium, etc.) and have shown the potential for environmental accumulation (Lauer et al. 2018, Van Sice et al. 2018, Ariana et al. 2025) or have been inconclusive in this regard (Mendietta 2024). To address this gap, laboratory studies specifically testing biota over longer exposure durations, assessing bioaccumulation, and evaluating the potential for environmental accumulation (e.g., in artificial environments such as sediment tanks and in agricultural pilot studies) are needed.

Spatial/temporal variability of constituents

The NMPWRC papers discussed above principally focus on produced water from the Permian Basin. This is appropriate and relevant since the Permian basin extends into southern New Mexico. However, constituents in produced water from different formations, different areas of the same formation, and even from the same well can vary significantly over space and time. In addition, different chemicals may be added to produced water by different wellfield operators. None of the papers discussed above specifically address this challenge, and only one (Edirisooriya et al. 2026a) took multiple samples over time for chemical analysis. As noted above, NMPWRC (2026) highlights that their researchers have evaluated a total of 75 produced water samples during laboratory and pilot testing in the Permian Basin. Whether these 75 samples are representative of the vast quantities of produced water generated in New Mexico on an annual basis is unknown. The variability of produced water combined with the fact that its constituents are not fully characterized presents a unique challenge to toxicologists and risk assessors. While the treatment and toxicity evaluations described in the papers above may show a lack of toxicity to a set of “post-treated” produced water samples, there are no assurances that a different produced water sample would yield the same results. To address this gap, toxicological testing needs to be performed using treated (and “post-treated”) waters representative of the variability of produced water sources in the State.

Environmental fate and transport

Despite significant chemical removal rates demonstrated by the NMPWRC papers, in most instances, some measurable contaminants and unresolved organic constituents remained even in “post-treated” effluents. The behavior, fate, and transport dynamics of uncharacterized chemicals (as well as some known but understudied chemicals) are unknown. Further, chemicals can change once they are released into the environment (see

discussion of 6PPD-quinone, above). Finally, in some cases, even known contaminants (e.g., radium) have already been shown to have a propensity to accumulate in the environment (Lauer et al. 2018, Van Sice et al. 2018). These uncertainties complicate the assessment of the risks produced water constituents pose in the environment. None of the recent literature addresses crucial questions about the fate and transport of either the known or unknown constituents once they are released into the environment—information which is needed to more thoroughly assess human and ecological risk. To address this gap, additional research to characterize unknown constituents in produced water is needed, as are studies to assess the movement, fate, and consequences of potential accumulation of produced water constituents in the environment.

Conclusion

The NMPWRC has conducted multiple research projects over the past several years that have incrementally advanced our understanding of treatment alternatives for produced water, as well as residual toxicity and constituents that may persist through various treatment and “post-treatment” processes. In their research papers, NMPWRC scientists themselves suggest that there is still work to do. Additional work not addressed by the this recent literature is still needed, particularly related to characterizing unknown produced water constituents, advancing knowledge related to the toxicity and risk of known substances found to be present in produced water, understanding the risks posed by the variability of constituents (and concentrations) in produced waters, and the fate and transport of residual constituents in treated and “post-treated” waters when they are released to the environment. Materials circulated by the NMPWRC as recently as June of 2026 highlight that “Current scientific evidence suggests that properly treated PW can achieve substantial reductions in toxicity, but continued monitoring and validation remain essential” (p. 3). “[K]ey knowledge gaps” identified in these materials include the “long-term ecological impacts of treated PW reuse”, “fate, transport, and bioaccumulation of residual compounds”, and “management of waste streams generated during treatment”. The current *status quo* prohibition on the discharge of treated produced water to surface and groundwater allows for pilot projects and scientific research and advancements. In light of the lingering gaps described in this report, and other lingering gaps not addressed herein, maintaining the *status quo* prohibition will allow ongoing research and testing to proceed without posing an undue risk to the environment and the public.

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