

# Monitoring and Treatment of Water in an Intensive Treatment Unit Dialysis Service in the Municipality of Macapá/Brazil

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## Abstract

The state of Amapá has one of the most precarious indicators of basic sanitation in Brazil, directly affecting the public health system. This research evaluated the monitoring of water quality and its treatment in a compact and isolated water treatment plant (WTPci) in a dialysis clinic in Macapá/Amapá/Brazil, evaluating raw water abstraction, operational units and medicinal destination. The objective of the research was to evaluate the physicochemical and microbiological quality of the water in the WTPci. The methodological stage consisted of: a) analysis of water quality data acquired monthly during 25 months totaling ≈ 1100 analyses of different physical-chemical and microbiological parameters provided by legislation; b) evaluation of the conformity and efficiency of the treatment process of the WTPci. In the post-osmosis (PO) and dialysis solution (SD) stages, heterotrophic bacteria count, pathogen research, presence of endotoxins and metal content (Al, Hg, Se, etc.) were included. The results indicated bacterial contamination in at least 2 monitoring points, with the presence of heterotrophic bacteria (HET). Concentrations of metals above the legal limits were found in only 1.14% of the samples collected for the Ca parameter, exceeding the allowed limits. Electrical conductivity showed non-compliance in 11.20% of the samples, followed by pH (13.02%), color (0.26%), total chlorine (4.95%) and turbidity (0.52%). There were no conformities for the other parameters (Al, Sb, Ba, Be). The parameters were compared with the legal limits established by the Ministry of Health and National Health Surveillance Agency (ANVISA), which regulates conventional hemodialysis services in Brazil. The results show the importance of water quality monitoring to avoid

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health vulnerability in the operation of the WTPci and as an instrument to support decision-making in the operational management, ensuring health safety of patients.

## Keywords

Sanitation, Water Treatment, Isolated System, Parameters, Renal Dialysis

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## 1. Introduction

Hemodialysis (HD) is a treatment of paramount importance for patients with chronic kidney disease (CKD) or acute renal failure (AKI), situations in which the kidneys are unable to eliminate waste products from cellular metabolism or perform their normal regulatory functions (Siviero et al., 2014; Jesus et al., 2021). For example, endotoxins are common contaminants in aqueous and physiological solutions, and their detection and removal are critical to ensuring patient safety during HD, due to the various biological effects they can cause. In other words, the inadequate quality of the water used in HD can result in serious complications for patients, including inflammatory reactions, infections, and even mortality (Coulliette & Arduino, 2013).

Contaminants such as aluminum (Al), chlorine (Cl), and endotoxins can cause endotoxemia and allergic reactions, compromising the effectiveness of the treatment and the patient's health. An aggravating factor is that the presence of bacteria and other microorganisms can also lead to serious systemic infections. Compliance with rigorous standards, such as those set by the Association for the Advancement of Medical Instrumentation (AAMI) and the International Organization for Standardization (ISO), is essential to prevent such complications and ensure patient safety (Coulliette & Arduino, 2013).

Kidney dialysis is a form of therapy that artificially replaces kidney function, and can be performed through transplantation or by two modalities: peritoneal dialysis and hemodialysis (Smeltzer et al., 2017). HD consists of filtering waste from the blood by means of a dialyzer machine, thus assuming the functions normally performed by the kidneys (Rocha, Cockroach, & Braz, 2019). Therefore, as water is an essential resource in hospitals and clinics with HD units, its treatment is one of the most critical stages of this process, as water quality has a direct impact on all phases of the process, requiring systematic and rigorously controlled monitoring to reduce risks to the health of patients (Zanette et al., 2024).

On the other hand, it is known that the states of the Northern Region of Brazil have been considered the most precarious and lacking in investments in basic sanitation infrastructures compared to the other geographic regions of the country. For example, the states of Acre, Amapá, Pará and Rondônia have the worst basic sanitation and health indicators in the Amazon (Viegas et al., 2024). The mapping carried out by these authors statistically correlated 22 sanitary indicators and 5

health indicators, concluding that for some health and sanitary variables, there were significant correlations ( $p < 0.05$ ), with Roraima being the one that advanced the most among the former federal territories in relation to water supply and sewage indicators. The ranking is followed by Rondônia, Acre, and, finally, Amapá, suggesting high health inequality, even between these states and between different municipalities in these states (Araújo et al., 2021; Flores et al., 2022; de Vilhena Amanajás Miranda et al., 2022; De Sousa et al., 2024).

In Macapá, the capital of the state of Amapá/Brazil, the sanitary problem is so critical that the water source of the hemodialysis clinic, object of the present study, is isolated and underground. This is because the source of collection is located within the private area of the clinic, currently operating without any external connection with the water supply system of the current concessionaire (Sanitation Company of the State of Amapá, CSA). This scenario remained throughout the process of collecting and monitoring the water quality of the present study. Therefore, the operation of water collection and treatment studied is of an isolated character (i) and of a compact system (c), hereinafter referred to as WTPic. Such characteristics have been a current conjunctural reflection of precariousness and significant deficiency of local sanitary infrastructure in the state of Amapá, and can be considered systemic, evidencing serious deficiencies in the four dimensions of basic sanitation: a) water supply (Amaral & Cunha, 2022; Araújo et al., 2021), b) sanitary sewage (Viegas et al., 2021; Viegas et al., 2024; Medeiros de Abreu et al., 2024; De Sousa et al., 2024), c) rainwater and drainage systems (Pacheco et al., 2023; Sousa et al., 2022) and solid waste (Flores et al., 2022; de Vilhena Amanajás Miranda et al., 2022).

Isolated collection and treatment (WTPic) is both a reflection and a need generated by the scenario of increased health threats related to surface and underground water sources, with the systemic presence of potential pollutants and contaminants that could eventually contaminate the underground source of the water treatment plant (Sousa et al., 2023; Araújo et al., 2021; Grott et al., 2018). In general, pollutants or contaminants are organic and inorganic and of urban origin, that is, domestic sewage and polluted rainwater. And, even in minimal quantities, they represent potential threats to the health of patients, generating concerns for professionals who work in these areas (Faria, 2018; Coulliette & Arduino, 2013; Grott et al., 2018).

In this context, water quality monitoring is the main support factor for dialysis services, being important in comparison with results legally recommended by the Health Surveillance Agency (ANVISA). The specific parameters provided for in the legislation also serve to assess the level of efficiency of the treatment and legal compliance (management of the WTPci). For example, the implementation of comprehensive and enforceable regulation at the national level would make the work of health enforcement agencies more effective and ensure more safety for patients (Zanette et al., 2024; Scavazini & Américo-Pinheiro, 2020; Bentes & Meschede, 2021).

The quality of the water used in HD systems can also be influenced throughout the different stages of water treatment in the WTP (collection, disinfection, distribution and storage). Therefore, to ensure that the water quality control program is effective in treatment clinics, it is important not only that the technology used and the distribution are adequate, but also that the storage system in the clinic is efficient and safe. The care taken in the treatment of water at the treatment plant will be compromised when storage is not carried out correctly (Drewes & Fox, 2000; Brasil, 2000).

The present research aims to evaluate the quality of the monitored raw and treated water of the WTPci of an intensive treatment unit dialysis service located in Macapá/Amapá/Brazil. The monitoring period was two continuous years and one month, observing legal compliance and the limits of the parameters established by ANVISA (RDC N°. 11/2014 and RDC N°. 154/2004) and the Ministry of Health (GM/MS, N°. 888/2021) (Brasil, 2004, 2011, 2021a, 2021b). It is also noteworthy that the monitored indicators are essential to ensure legal compliance with the use of water in accordance with the safety standards specifically required in the treatment of HD patients. Therefore, an eventual failure in the storage or treatment process of the water can compromise its entire efficiency, safety and the quality of the product (Pinheiro et al., 2010; Tristão, 2014; Ramirez, 2009; Zanette et al., 2024).

Considering the sanitary context of the WTPic in Macapá, we raised the following hypotheses: 1) in a total of 25 continuous monthly water quality monitoring campaigns, at least 95% of the physical-chemical, microbiological and metal parameters were in legal compliance with RDC No. 11/2014 (Brasil, 2014) and RDC No. 154/2004 (Brasil, 2021a), of ANVISA, and the Ordinance GM/MS, No. 888, of May 4, 2021, of Ministry of Health (Brasil, 2021a, 2021b); 2) based on statistical tests, in multiple comparisons, there are indications of significant variations between the physicochemical, metals and microbiological parameters analyzed in the different stages of treatment identified by the monitoring ( $p < 0.05$ ). 3) Variation is critical in the reverse osmosis stage in the WTPic; 4) the four main treatment steps of the WTPic present different levels of efficiency ( $p < 0.05$ ) in relation to the legal compliance of water quality, regardless of the operational unit resulting from the redundancy of the treatment in two parallel phases.

To test these hypotheses, we present the following specific objectives: 1) to evaluate the general conformity of the historical series of physicochemical and microbiological quality of water in the WTPi cover 25 months in the intensive care clinic of the municipality of Macapá/Amapá/Brazil; 2) to elaborate multiple statistical comparisons between physicochemical and microbiological parameters of water quality (pH, Conductivity, *E. coli*, Metals, etc.) throughout the different stages of treatment of the WTP ( $p < 0.05$ ); 3) test the temporal statistical significance for each of the different water quality parameters (physicochemical, metals and microbiological) ( $p < 0.05$ ) in the same specific stages of treatment of the WTPic; 4) evaluate efficiency and level of legal compliance in the different operational stages

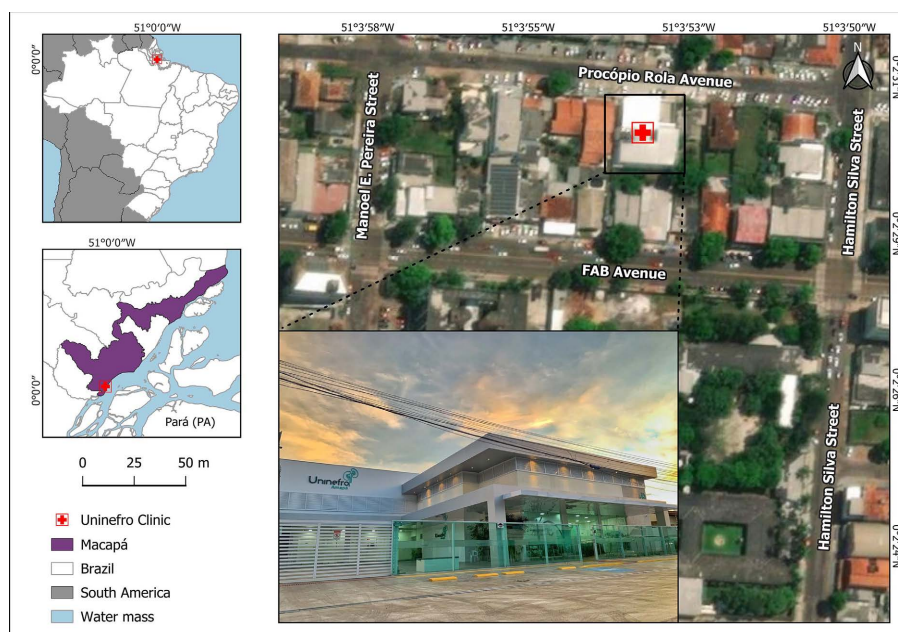
of WTPic.

## 2. Materials and Methods

### 2.1. Study Area

The site of investigation was the hemodialysis (HD) clinic located in the city of Macapá, in the state of Amapá/Brazil. The study period took place between August 2022 to August 2024. During this period, the physicochemical, metallic and microbiological parameters were monitored and analyzed monthly and continuously. The data obtained for the present study were kindly provided by the company Clínica Uninefro Amapá Ltda, established in Macapá since 2018. The company operates in the area of Nephrology and provides HD services.

During the visits to the clinic, all the equipment used in the HD process was freely registered, with permission. **Figure 1** shows the map with the location of the HD clinic where the WTPic is in Macapá/Amapá/Brazil.



**Figure 1.** Aerial and frontal view of the Hemodialysis Clinic of Macapá/Brazil. Legend: The white and yellow rectangles refer to the location of the clinic in relation to the urban area.

Data and information on each of the operational stages and the quality of raw water, or obtained in the different stages of treatment of the WTPic, were obtained from monthly reports throughout the period. These monthly reports contained detailed information on each water quality parameter, as indicated in **Table 1**. Among the relevant data, we highlight the concentration of total chlorine, electrical conductivity, apparent color, pH at 25 °C, turbidity, total coliforms, heterotrophic bacteria count (endotox), HET and the presence of Total Thermotolerant Coliforms and *Escherichia coli*.

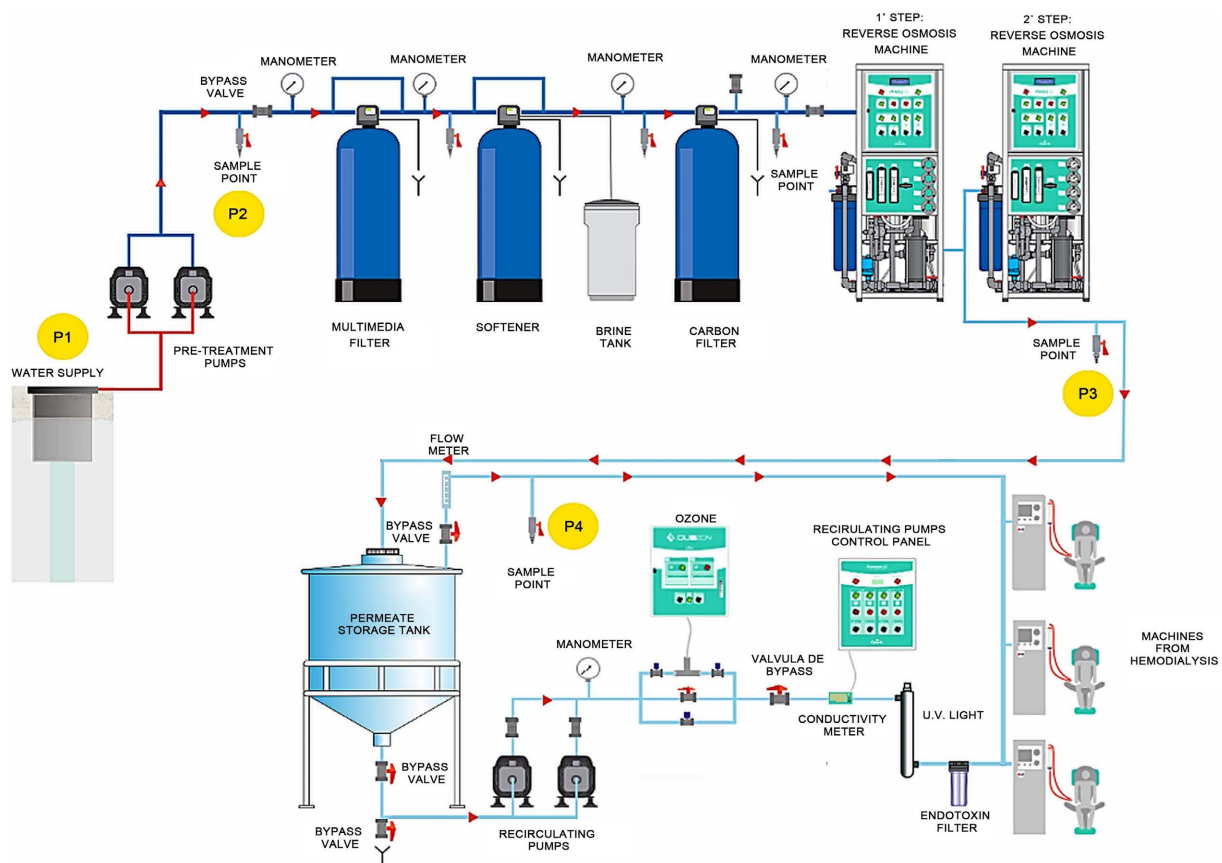
**Table 1.** Water quality parameters monitored monthly by WTPic-Clinic of Macapá/Amapá/Brazil (2022 to 2024).

Parameter	Justification for analysis	Tolerated limits (RDC, 2014)
pH	Indicates the acidity or alkalinity of the water; essential to ensure potability and protect infrastructure.	6.0 to 9.5
Total chlorine (Cl)	Necessary for disinfection and microbiological control of water.	Maximum: 0.1 mg/L
Aluminum (Al)	High levels can be toxic and interfere with water treatment.	Maximum: 0.2 mg/L
Iron (Fe)	Can cause stains and alter the taste of water; also affects piping systems.	Maximum: 0.3 mg/L
<i>E. coli</i>	Indicates recent fecal contamination and risk of waterborne diseases.	Absent in 100 mL
HET	Count of heterotrophic bacteria to monitor the specific microbiological quality of the water.	Maximum: 100 CFU/mL
Electrical Conductivity	Measures the water's ability to conduct electricity, indicating the presence of dissolved salts.	Variable, depending on the water source
Turbidity	Assesses suspended particles in the water, which may harbor microorganisms.	Maximum: 5 NTU
Apparent color	Indicates the presence of organic and inorganic materials that affect the aesthetics and quality of the water.	Maximum: 15 uH
Salinity	Related to salt concentration, affecting the potability and corrosiveness of the water.	Maximum: 250 mg/L (Chloride)
Nitrate (NO <sub>3</sub> )	Assessment of agricultural or sewage contamination, with health risks such as methemoglobinemia.	Maximum: 10 mg/L
Fluoride (F)	Important for preventing cavities, but in excess can cause fluorosis. This parameter is currently not included in the legislation.	0.6 to 1.5 mg/L
Lead (Pb)	Toxic heavy metal, with impacts on human health, especially on the nervous system.	Maximum: 0.01 mg/L
Mercury (Hg)	Highly toxic; can cause neurological damage and chronic poisoning.	Maximum: 0.001 mg/L
Endotoxins	Indicator of gram-negative microorganisms, capable of causing fevers and toxic reactions.	Absent in 100 mL

Source: Adapted from RDC No. 11/2014.

The general list of physicochemical and microbiological parameters monitored includes the following: total aluminum (Al), total antonym (Sb), total barium (Ba), beryllium (Be), cadmium (Cd), calcium (Ca), total chlorine (Cl), copper (Cu), chromium (Cr), fluorine (F), magnesium (Mg), mercury (Hg), nitrates (NO<sub>3</sub>), potassium (K), silver (Ag), selenium (Se), sodium (Na), sulfate (SO<sub>4</sub>), Thallium (Tl), zinc (Zn), chlorine (Cl), cerium (EC), apparent color, total iron (Fe), electrical conductivity (EC), salinity, turbidity, pH, total coliforms, heterotrophic bacteria count, *Escherichia coli* (*E. coli*) and endotoxins.

**Figure 2** represents a schematic flowchart of the process of the water treatment stages of the WTP. The flowchart serves to visualize the critical and representative operational components of the water treatment phases. The Pi points that are highlighted in yellow ( $i = 1, 2, 3,$  and  $4$ ) represent each of the critical points of the water treatment process, from which the WTPci water quality monitoring data series were obtained. The critical monitoring points were defined as follows: P1 indicates the underground collection point (currently isolated from the conventional supply network of the CSA concessionaire). Therefore, the treatment process begins at this first point, representing the capture of water directly from an underground tubular well of approximately 40 m deep. Point P2 indicates the point of sampling of the water quality before the treatment process begins. This is where the water effectively enters the pretreatment system (STDAH), and which comprises the step aimed at removing particles and impurities that may compromise the operation of the posterior reverse osmosis system, ensuring that the water is suitable for the next step. Point P3 lists the filtration processes (stages in series 1 and 2) and reverse osmosis (stages in series 1 and 2). Point P4 indicates the point of final use of the water for medicinal purposes of the treated water (dialysis HD).



**Figure 2.** Flowchart of treatment and detailing of WTPic equipment of the type of double filtration and reverse osmosis; process of ozonation and use of ultraviolet light and recirculation of treated water through recirculating pumping through the storage tank. Source: Adapted from Saubern (2025).

After the pre-treatment of filtration and reverse osmosis, the water goes from point P3, where the system removes dissolved contaminants and other impurities, resulting in treated water ready for other specific applications. At point P4, the treated water is subjected to two other processes for the purpose of disinfection certification, after recirculation and passage through the storage tank: a) ozonation and b) ultraviolet light. Only after these last two procedures is the treated water directed to the hemodialysis machine (HD). After the entire treatment process indicated in the flowchart, the water used would be potentially safe for the medical procedure to have the legally necessary quality, also ensuring the safety of patients during hemodialysis treatment (Zanette et al., 2024; Schleicher, 2013).

In the Amazon region, a rare study on this topic was also conducted, titled “Water quality used in hemodialysis services before and after the treatment system in Santarém, Western Pará, Amazon” (Bentes & Meschede, 2021). Similarly, the objective was to analyze changes in the quality of water collected from an underground source and to assess the treatment efficiency to meet the requirements of a hemodialysis clinic.

A third case, like the present study, was documented in the literature in the southern region of Brazil. The referred study was conducted by Zanette et al. (2024), who assessed the efficiency of the water treatment process in a hemodialysis clinic in Criciúma, Santa Catarina. Similarly, the study focused on evaluating the efficiency of the water treatment process using reverse osmosis, a technology employed as the primary purification operation to ensure the safety of the clinic’s patients.

## 2.2. Water Sample Collection Procedure

According to the flowchart, the treatment process begins with the capture of groundwater. The first collection point (P1) represents an isolated semi-artesian tubular well approximately 40 m deep. This source consists of an exclusive groundwater collection system for the clinic, ensuring that the water used comes from a “protected and controlled” source. The water collected undergoes an initial analysis to check for the presence of contaminants such as heavy metals, bacteria and other components that may compromise the quality from the beginning of the process (Zanette et al., 2024).

At the second collection point (P2), the water pumped to the Water Treatment System for Hemodialysis (STDAH) goes through pre-treatment. This pretreatment includes processes such as filtration, dechlorination and “softening” (reduction of excessive water hardness,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$  and  $\text{Mg}^+$ ) and which are also necessary to remove suspended particles and free chlorine. The goal of step 2 is to protect the sensitive components of the most advanced treatment systems, such as reverse osmosis (first filtration at P2). The water is then sent to the reverse osmosis unit (second filtration at P3), which is an essential purification process to remove dissolved ions, bacteria, viruses, and endotoxins (HET), ensuring that the water meets the stringent standards required for hemodialysis (Zanette et al., 2024).

The third point (P3) represents post-reverse osmosis water, which already has high purity and is suitable for use in HD. However, to ensure maximum safety, the water undergoes a final stage of disinfection and microbiological control (P3) before being directed to the collection point (P4). At this last point (P4), the water is ready to be used in the HD procedure and is supplied directly to the dialysis machine (P4), where it will come into contact with the patient's blood.

It is important to emphasize that the water in this final stage meets the quality specifications, as any residual contamination (Brasil, 2004) (Brasil, 2014) can pose a significant risk to the patient's health. The implementation of the reverse osmosis system requires special attention to the pretreatment and composition of the water (Farrugia, 2013). Pretreatment is essential to reduce particles and contaminants that can damage the membrane or high-pressure pump (Frischkorn, 2016). The composition of the water is also crucial, as the desalination process concentrates the salts, which can lead to saturation and precipitate generation. And, if precipitation occurs, salt fouling may occur in the reverse osmosis membrane and chemical cleaning will be necessary (Farrugia, 2013). These problems can lead to a reduction in the useful life of the equipment and generate additional maintenance costs throughout the treatment process of the WTPic.

From a methodological perspective of water sampling, ANVISA Resolution RDC No. 11/2014 (Brasil, 2014) mandates at least two distinct points in the treatment system: the return of the distribution loop and a point in the processing room. The regulation also requires that the water used be potable, with daily quality monitoring at the inlet, conducted by a qualified technician responsible for the operation and maintenance of the system. Furthermore, the STDAH design must comply with specific standards, and the treated water must meet strict criteria, verified through analyses conducted by a certified laboratory. The results of these analyses must be readily available.

Although RDC No. 11/2014 (Brasil, 2014) establishes a mandatory minimum, the sampling strategy adopted by the clinic is more robust and comprehensive, even recommending the inclusion of additional critical points in the treatment and distribution system. The objective is to provide a more precise and reliable assessment of the historical series of water quality used in treatment. This recommendation tends to ensure greater safety for patients.

In addition to the sample collection and analysis conducted in the present study (ETAic in Macapá-AP), the National Health Surveillance Agency (ANVISA) has played a crucial role in ensuring water quality in healthcare services, including dialysis cases. These procedures involve the collection and analysis of samples to verify compliance with sanitary regulations and to proactively protect public health. This type of procedure and ANVISA's approach—through inspections and sample collection for laboratory analysis—was also observed in the study by Jesus et al. (2021), who evaluated the quality of water used in mobile dialysis services in ICUs in Rio de Janeiro. In that case, the authors applied a sampling methodology integrated with health surveillance inspections, aiming to obtain representative

data on the actual conditions of treated water usage (Jesus et al., 2021)

### 2.3. Statistical Analysis of Water Quality and Operational Efficiency

A series of tests and statistical analyses were developed to evaluate the impact of each treatment step on the expected efficiency of WTPic. For example, we initially developed a descriptive statistical analysis, followed by hypothesis of normality tests (Shapiro-Wilk), homoscedasticity of variances and variation of residuals, paired Wilcoxon tests for non-parametric double-entry comparisons, and simple and multiple regression analysis tests. For this purpose, we use the R 4.0.3 software, as recommended by Crawley (2007) and R Development Core Team (2020).

### 2.4. Legal Limits of Physicochemical, Microbiological and Metal Parameters

The physicochemical and microbiological parameters evaluated in the present research were as follows: total aluminum (Al), total antonym (Sb), total barium (Ba), beryllium (Be), cadmium (Cd), calcium (Ca), total chlorine (Cl), copper (Cu), chromium (Cr), fluorine (F), magnesium (Mg), mercury (Hg), nitrates (NO<sub>3</sub>), potassium (K), silver (Ag), selenium (Se), sodium (Na), sulfuric acid (SO<sub>4</sub>), Thallium (Tl), zinc (Zn), chlorine (Cl), cerium (EC), apparent color, total iron (Fe), electrical conductivity, salinity, turbidity, pH, total coliforms, heterotrophic bacteria count, *Escherichia coli* (*E. coli*) and endotoxins.

RDC No. 11/2022 presents an established water quality standard for hemodialysis, as presented in Table 2, containing the recommended limits for the concentration of various elements in the water. This ensures safety and compliance with the required quality standards.

**Table 2.** Quality standard for hemodialysis water established by RDC No. 11/2022.

Parameter	Maximum allowed concentration (mg/L)	Parameter	Maximum allowed concentration (mg/L)
Aluminum (Al)	0.01	Fluoride (F)	0.2
Antimony (Sb)	0.006	Magnesium (Mg)	4
Arsenic (As)	0.005	Mercury (Hg)	0.0002
Barium (Ba)	0.1	Nitrate (NO <sub>3</sub> )	2
Beryllium (Be)	0.0004	Potassium (K)	8
Cadmium (Cd)	0.001	Silver (Ag)	0.005
Calcium (Ca)	2	Selenium (Se)	0.09
Lead (Pb)	0.005	Sodium (Na)	70
Total chlorine (Cl)	0.1	Sulfate (SO <sub>4</sub> )	100
Copper (Cu)	0.1	Thallium (Tl)	0.002
Chromium (Cr)	0.014	Zinc (Zn)	0.1

Source: Adapted from RDC No. 11/22 (Brasil, 2014).

## 2.5. WTPic and Water Quality Monitoring and Comparisons with Legislation

A photographic record of the WTPic water treatment system was made for HD during one of the technical visits (**Figure 3**). The entire operation of equipment, especially the reverse osmosis stage, is recorded in the reports as *Reverse Osmosis Pura-2, da Saubern (2025)*.



**Figure 3.** WTPic infrastructure, equipment arrangement and state of conservation of the nephrology clinic system, in 2024.

The monthly water quality reports were made available, tabulated and later statistically analyzed. The results were compared with the legally regulated parameters in order to verify their legal compliance, where the maximum allowed limits for chemical and microbiological contaminants were specified. ANVISA's RDC No. 11/2014 (Brasil, 2014) establishes that water for dialysis must be free of toxic substances and have an endotoxin content of less than 0.25 endotoxic units per milliliter (EU/mL). This limit avoids risks to the health of patients. Thus, RDC No. 154/2007 (Brasil, 2021a) defines the technical regulation for the operation of dialysis services. It is noteworthy that the risk to the health of patients undergoing hemodialysis, associated with the use of drinking water in the procedures, is reduced if these established criteria are applied. The DRC is associated with strict water quality standards, making the use of reverse osmosis techniques mandatory (**Figure 2**) to comply with established minimum quality requirements (Zanette et al., 2024).

As pointed out by Ribeiro, Sanches-Pagliaruss and Ribeiro (2016), physico-chemical analyses are essential tools for monitoring the water used in dialysis, and should be carried out regularly to evaluate the performance of reverse osmosis membranes. According to Scavazini and Américo-Pinheiro (2020), hemodialysis treatment involves the use of large amounts of water, requiring rigorous treatment

and continuous monitoring (Ribeiro, Sanches-Pagliaruss, & Ribeiro, 2016; Scavazini & Américo-Pinheiro, 2020).

Both RDC No. 11/2014 (Brasil, 2014) and Ordinance GM/MS No. 888, of May 4, 2021 (Brasil, 2021a, 2021b), update the parameters and standards for the potability of water intended for human consumption, reflecting the safety and quality guidelines that also apply to the control of water used in health services. Ordinance GM/MS No. 888 defines the maximum values allowed for a wide range of chemical, microbiological and physicochemical substances in the water supply, which serve as a reference to ensure the safety of the treatment process, from the capture of raw water to the final use in hemodialysis (Brazil, 2021a, 2021b; Zanette et al., 2024).

## 2.6. Statistical Analysis of WTPic HD Water Quality Parameters

The data were organized and tabulated using the Excel@ software as a basis for preparation for the statistical analysis stage in the R-Project software (R Core Team, 2020). An acronym was assigned to each parameter to facilitate the organization and understanding of statistical analysis. Table 3 shows the applications of hypothesis tests for the time series of each parameter in the period studied (Friedman's non-parametric multicomparison test) (Crawley, 2007; R Core Team, 2020). Descriptive statistics were represented by means (medians), standard deviation, maximum and minimum values (Table 1 Supplementary). The most evident results were compared with the limits stipulated by ANVISA's RDC No. 11/2014 (Brasil, 2014), to assess whether the water used in the clinic's hemodialysis system was in compliance with the required standards. Table 3 shows the parameters with a degree of significance ( $p < 0.05$ ), represented by the symbol “\*” and the non-significant “NS”.

**Table 3.** Results of Friedman's non-parametric hypothesis tests<sup>(1,2)</sup>.

Parameter	Medians	Friedman chi-square $\chi^2$	df (degrees of freedom)	p-value
CIP1	0.01			
CIP2	0.21	20.5410	3	0.0001***
CIP3	0.01			
CIP4	0.01			
CondP1	420.0			
CondP2	396.00	50,8860	3	<0.001*
CondP3	7.36			
CondP4	7.7			
CorapP1	2			
CorapP2	2	0.8182	1	NS
<i>E. coli</i> P1	0	-	1	NS
<i>E. coli</i> P2	0			

**Continued**

HETP1	25			
HETP2	1	10.34	3	<b>0.0160*</b>
HETP3	1			
HETP4	1			
pHP1	4.975			
pHP2	5.520	44.88	3	<b>&lt;0.001***</b>
pHP3	6.305			
pHP4	6.240			
TurbP1	1.5	0.33	1	<b>NS</b>
TurbP2	1.1			

\*Note 1: The symbol “\*” indicates significance at  $p$ -value  $< 0.05$ , NS = Not significant and NA = Not analyzed. \*Note 2: The following symbols were applied only to the parameters that showed significance at each stage of the water treatment at WTPic: **ClPi** indicates the chlorine concentration, **CondPi** indicates the electrical conductivity, **CorPi** indicates the color, **E. coliPi** indicates the concentration of *E. coli* bacteria per 100 mL, **HETPi** indicates the number of heterotrophic cells, **pHPi** the acidity level or pH and **TubPi** indicates the turbidity level.

## 2.7. Compliance of Water Quality with ANVISA Standards

To assess the compliance of water quality in hemodialysis services, a systematic analysis of the positive (compliance) and negative (non-conforming) frequencies of the parameters in the monthly reports provided by the treatment clinic (monitoring and analysis of time series) was performed. The quality parameters considered included the physicochemical and microbiological aspects established by ANVISA RDC No. 11/2014 (Brasil, 2014), Ordinance GM/MS No. 888, of May 4, 2021 (Brasil, 2021a, 2021b), and Ordinance No. 2, 914/2011 (Brasil, 2011).

The parameters analyzed were chosen based on the requirements of the aforementioned regulations. RDC No. 11/2014 (Brasil, 2014) is specific for water used in hemodialysis, which must have a maximum endotoxin concentration of 0.25 endotoxic units per milliliter (EU/mL) and a bacterial count of up to 100 colony-forming units per milliliter (CFU/mL). We considered the limits established in Ordinance GM/MS No. 888 for heavy metals, such as 0.01 mg/L for mercury, 0.2 mg/L for aluminum, 0.001 mg/L for lead and for the absence of total coliforms and *Escherichia coli* in 100 mL samples.

The analysis of the reports was carried out based on samples collected monthly, totaling 836 samples over the period from August 2022 to August 2024. The compliance of the parameters with the regulatory standards was verified in each monthly sample. In addition, it was suggested to increase the frequency of analysis, considering the criteria established by Ordinance No. 2914/2011 (Brasil, 2011), which recommends weekly monitoring in situations where the results present significant variations or proximity to regulatory limits.

The evaluated data consider the analyses regarding compliance with the maxi-

imum allowed limits, observing any non-conformities and their respective collection points, including the operations of raw water collection, pre-treatment, post-reverse osmosis and dialysis machine entry. The analysis of the reports considered the frequency and consistency of the parameters, identifying any trends that could indicate the need for adjustments in the treatment system or in the periodicity of the analyses.

### 3. Results

#### 3.1. Metals

The results of the metal concentrations revealed that 98.86% of the parameters were in legal compliance with the hemodialysis water quality standard established by RDC No. 11/2014 (Brasil, 2014) and Ordinance MS 2914/2011 888/2021 (Brasil, 2021a, 2021b). These results corroborate the main research hypothesis. That is, there was compliance with frequencies greater than 95% of the samples collected. In addition, the remaining 1.14%, in non-compliance, corresponds exclusively to the first point (P1) that represents the underground source (isolated tubular well). One of the non-compliant parameters was calcium (Ca) verified both in November 2023 and May 2024, with values above 2 mg/L. Tables 4-6 show these values highlighted in bold and the percentage of compliance.

**Table 4.** Parameters of WTPic's microbiological analysis in 2022. Uninefro Amapá, 2024.

Metal parameters (mg/L)	No. of samples	Mean ± SD (mg/L)	MPL <sup>(1)</sup>	In compliance (% of samples)	Metal parameters (mg/L)	No. of samples	Mean ± SD (mg/L)	MPL <sup>(1)</sup>	In compliance (% of samples)
Al	2	0.001 ± 0	0.2 <sup>(2)</sup>		F	2	0.1 ± 0	1.5 <sup>(2)</sup>	
Sb	2	0.001 ± 0	0.006 <sup>(1)</sup>		Mg	2	1.1 ± 1.24	4 <sup>(1)</sup>	
As	2	0.005 ± 0	0.01 <sup>(2)</sup>		Hg	2	0.0002 ± 0	0.0002 <sup>(1)</sup>	
Ba	2	0.045 ± 0.02	0.7 <sup>(2)</sup>		N	2	0.6 ± 0.806	10 <sup>(2)</sup>	
Be	2	0.0001 ± 0	0.0004 <sup>(1)</sup>		K	2	1.155 ± 1.619	8 <sup>(1)</sup>	
Cd	2	0.001 ± 0	0.003 <sup>(2)</sup>	<b>100</b>	Ag	2	0.0035 ± 0.002	0.005 <sup>(1)</sup>	<b>100</b>
Ca	2	1.65 ± 0.49	2 <sup>(1)</sup>		Se	2	0.001 ± 0	0.04 <sup>(2)</sup>	
Pb	2	0.002 ± 0	0.01 <sup>(2)</sup>		Na	2	23.8 ± 32.88	200 <sup>(2)</sup>	
Total Cl	2	0.0355 ± 0.05	0.1 <sup>(1)</sup>		SO <sub>4</sub>	2	3.5 ± 3.536	250 <sup>(2)</sup>	
Cu	2	0.0045 ± 0.01	2 <sup>(2)</sup>		TI	2	0.001 ± 0	0.002 <sup>(1)</sup>	
Cr	2	0.001 ± 0	0.05 <sup>(2)</sup>		Zn	2	0.07 ± 0	5 <sup>(2)</sup>	

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-Brazilian Health Regulatory Agency (ANVISA); Note: <sup>(2)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum. Permitted Level. Source: Authors (2025).

#### 3.2. Physicochemical Parameters

The physicochemical analysis contained in the water quality reports indicated that 70.05% of the parameters evaluated were in accordance with the current standard. On the other hand, the remaining 29.95% did not meet the criteria

**Table 5.** WTPic's microbiological analysis parameters in 2023. Uninefro Amapá, 2024.

Metal parameters (mg/L)	No. of samples	Mean ± SD (mg/L)	MPL <sup>(1)</sup>	In compliance (% of samples)	Metal parameters (mg/L)	No. of samples	Mean ± SD (mg/L)	MPL <sup>(1)</sup>	In compliance (% of samples)
Al	4	0.005 ± 0.002	0.2 <sup>(2)</sup>	<b>100</b>	F	4	0.1 ± 0	1.5 <sup>(2)</sup>	
Sb	4	0.001 ± 0	0.006 <sup>(1)</sup>		Mg	4	3.5 ± 1	4 <sup>(1)</sup>	
As	4	0.005 ± 0	0.01 <sup>(2)</sup>		Hg	4	0.000175 ± 0.00005	0.001 <sup>(2)</sup>	
Ba	4	0.055 ± 0.013	0.7 <sup>(2)</sup>		N	4	0.5 ± 0.48	10 <sup>(2)</sup>	
Be	4	0.0001 ± 0	0.0004 <sup>(1)</sup>		K	4	0.73 ± 1.20	8 <sup>(1)</sup>	
Cd	4	0.001 ± 0	0.003 <sup>(2)</sup>		Ag	4	0.005 ± 0	0.005 <sup>(1)</sup>	<b>100</b>
Ca	4	2.125 ± 0.629	2 <sup>(1)</sup>		Se	4	0.001 ± 0	0.04 <sup>(2)</sup>	
Pb	4	0.002 ± 0	0.01 <sup>(2)</sup>		Na	4	35.9 ± 40.86	200 <sup>(2)</sup>	
Total Cl	4	0.02 ± 0.02	0.1 <sup>(1)</sup>		SO <sub>4</sub>	4	1.3 ± 0.5	250 <sup>(2)</sup>	
Cu	4	0.055 ± 0.013	2 <sup>(2)</sup>		TI	4	0.001 ± 0	0.002 <sup>(1)</sup>	
Cr	4	0.001 ± 0	0.05 <sup>(2)</sup>	Zn	4	0.07 ± 0	5 <sup>(2)</sup>		

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-Brazilian Health Regulatory Agency (ANVISA); Note: <sup>(2)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum; Permitted Level. Source: Authors (2025).

**Table 6.** Parameters of WTPic's microbiological analysis in the year 2024. Uninefro Amapá, 2024.

Metal parameters (mg/L)	No. of samples	Mean ± SD (mg/L)	MPL <sup>(1)</sup>	In compliance (% of samples)	Metal parameters (mg/L)	No. of samples	Mean ± SD (mg/L)	MPL <sup>(1)</sup>	In compliance (% of samples)
Al	2	0.009 ± 0	0.2 <sup>(2)</sup>	<b>100</b>	F	2	0.1 ± 0	1.5 <sup>(2)</sup>	
Sb	2	0.001 ± 0	0.006 <sup>(1)</sup>		Mg	2	4 ± 0	4 <sup>(1)</sup>	
As	2	0.005 ± 0	0.01 <sup>(2)</sup>		Hg	2	0.0002 ± 0	0.001 <sup>(2)</sup>	
Ba	2	0.08 ± 0.01	0.7 <sup>(2)</sup>		N	2	2.1 ± 2.66	10 <sup>(2)</sup>	
Be	2	0.0001 ± 0	0.0004 <sup>(1)</sup>		K	2	1.71 ± 2.40	8 <sup>(1)</sup>	
Cd	2	0.001 ± 0	0.003 <sup>(2)</sup>		Ag	2	0.005 ± 0	0.005 <sup>(1)</sup>	<b>100</b>
Ca	2	3.5 ± 2.12	2 <sup>(1)</sup>		Se	2	0.001 ± 0	0.04 <sup>(2)</sup>	
Pb	2	0.002 ± 0	0.01 <sup>(2)</sup>		Na	2	42.5 ± 55.86	200 <sup>(2)</sup>	
Total Cl	2	0.02 ± 0.01	0.1 <sup>(1)</sup>		SO <sub>4</sub>	2	7.5 ± 9.19	250 <sup>(2)</sup>	
Cu	2	0.065 ± 0.02	2 <sup>(2)</sup>		TI	2	0.001 ± 0	0.002 <sup>(1)</sup>	
Cr	2	0.001 ± 0	0.05 <sup>(2)</sup>	Zn	2	0.47 ± 0.56	5 <sup>(2)</sup>		

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-Brazilian Health Regulatory Agency (ANVISA); Note: <sup>(2)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum; Permitted Level. Source: Authors (2025).

established by Resolution RDC No. 11/2014. Among those that stood out, electrical conductivity corresponded to 11.20% of non-compliance at points (P1), which represents an isolated well, and (P2), which represents the water pumped to the Water Treatment System for Hemodialysis (STDAH) in the sampling period. As

indicated in **Table 7** and **Table 8**, the most restrictive compliance values observed were the electrical conductivity of the water, respectively, with 52.63% at point P1 in 2023 and at point P2 with 52.17% in 2024.

The total chlorine parameter registered 4.95% of non-conformities, corresponding to August 2022 in point P1, and in the months of September, October and November in point P2. In 2023, the same occurred in January, at point P1, and in January, March, and from June to November, at point P2. In March and May 2024, it occurred at point (P1) and in the months of February, March, June and August at point P2. The turbidity parameter was 0.52% in January and October 2023 at point P1 (**Table 8**).

The apparent color parameter was more critical in August 2022 at point P1 (**Table 7**), resulting in 0.26% of non-conformities (above 15 uH), that is, outside the norm established by Ordinance MS 2.914/2011 888/2021.

The pH parameter recorded 13.02% of non-conformities, corresponding to point P1, in February, March, April, May, June, July, August, September, October and December 2023. The same occurred in February, May, June, August, October, November and December at point P2. However, there were also non-conformities in December 2024, in points P3 and P4. The same result occurred in point P1, in the months of January to August, and in point P2, in January, February, March, May, June, July and August 2024. In addition, the same sequence of results occurred at points P3 and P4, in January, February, March, May, June and July 2024 (**Table 9**).

**Table 7.** Results of the parameters of the physicochemical analysis of WTPic in the year 2022. Uninefro Amapá, 2024.

Physicochemical Parameters	No. of samples	Mean ± SD (P <sub>1</sub> )	Mean ± SD (P <sub>2</sub> )	Mean ± SD (P <sub>3</sub> )	Mean ± SD (P <sub>4</sub> )	MPL <sup>(1)</sup>	MPL <sup>(2)</sup>	In compliance (% of samples)
Total chlorine (mg/L)	20	0.20 ± 0.39	0.24 ± 0.29	0.03 ± 0.04	0.02 ± 0.03	0.1 <sup>(1)</sup>	-	<b>80</b>
Electrical conductivity (µS/cm)	19	280.4 ± 107.32	277.8 ± 117.49	8.3 ± 1.13	8.3 ± 0.76	10 <sup>(1)</sup>	-	<b>52.63</b>
Apparent color (uH)	9	8.6 ± 10.69	2 ± 0	-	-	Colorless	15 <sup>(2)</sup>	<b>88.89</b>
Salinity	1	275 ± 0	-	-	-	-	-	-
Turbidity (NTU)	9	1.6 ± 0.89	1 ± 0	-	-	-	5 <sup>(2)</sup>	<b>100</b>
pH at 25 °C	19	5.70 ± 1.06	6.36 ± 0.27	6.70 ± 0.34	6.72 ± 0.26	6 - 9.5 <sup>(1)</sup>	6 - 9 <sup>(2)</sup>	<b>78.95</b>

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-National Health Surveillance Agency (ANVISA); Note: <sup>(2)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum Permitted Level. Source: Authors (2025).

**Table 8.** Parameters of the physicochemical analysis of WTPic in the year 2023. Uninefro Amapá, 2024.

Physicochemical Parameters	No. of samples	Mean ± SD (P <sub>1</sub> )	Mean ± SD (P <sub>2</sub> )	Mean ± SD (P <sub>3</sub> )	Mean ± SD (P <sub>4</sub> )	MPL <sup>(1)</sup>	MPL <sup>(2)</sup>	In compliance (% of samples)
Total chlorine (mg/L)	46	0.07 ± 0.18	0.38 ± 0.34	0.03 ± 0.03	0.03 ± 0.04	0.1 <sup>(1)</sup>	-	<b>86.96</b>
Electrical conductivity (µS/cm)	46	472.4 ± 108.23	457.9 ± 77.76	7.27 ± 0.81	8.05 ± 0.71	10 <sup>(1)</sup>	-	<b>52.17</b>
Apparent color (uH)	22	6.2 ± 5.67	3.4 ± 2.29	-	-	Colorless	15 <sup>(2)</sup>	<b>100</b>

**Continued**

Iron (mg/L)	2	0.04 ± 0.04	-	-	-	-	0.3 <sup>(1)</sup>	<b>100</b>
Salinity	2	0.3 ± 0	-	-	-	-	-	-
Turbidity (NTU)	21	4.2 ± 3.42	2.7 ± 1.71	-	-	-	5 <sup>(2)</sup>	<b>90.48</b>
pH at 25°C	45	5.01 ± 0.46	5.54 ± 0.61	6.48 ± 0.50	6.37 ± 0.56	6 - 9.5 <sup>(1)</sup>	6 - 9 <sup>(2)</sup>	<b>57.78</b>

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-National Health Surveillance Agency (ANVISA); Note: <sup>(2)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum Permitted Level. Source: Authors (2025).

**Table 9.** Parameters of WTPic's microbiological analysis in the year 2024. Uninefro Amapá, 2024.

Physicochemical Parameters	No. of samples	Mean ± SD (P <sub>1</sub> )	Mean ± SD (P <sub>2</sub> )	Mean ± SD (P <sub>3</sub> )	Mean ± SD (P <sub>4</sub> )	MPL <sup>(1)</sup>	MPL <sup>(2)</sup>	In compliance (% of samples)
Total chlorine (mg/L)	31	0.08 ± 0.12	0.21 ± 0.20	0.03 ± 0.04	0.02 ± 0.02	0.1 <sup>(1)</sup>	0.1 <sup>(2)</sup>	<b>80.65</b>
Electrical conductivity (µS/cm)	31	357.3 ± 280.95	246.6 ± 249.48	7 ± 1.76	6.1 ± 1.16	10 <sup>(1)</sup>	-	<b>61.29</b>
Apparent color (uH)	15	3.6 ± 3.54	5 ± 4.04	-	-	Colorless	15 <sup>(2)</sup>	<b>100</b>
Turbidity (NTU)	15	2.3 ± 1.39	2.4 ± 1.62	-	-	-	5 <sup>(2)</sup>	<b>100</b>
pH	31	4.68 ± 0.44	4.75 ± 0.67	5.67 ± 0.58	5.68 ± 0.70	6 - 9.5 <sup>(1)</sup>	6 - 9 <sup>(2)</sup>	<b>12.90</b>

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-National Health Surveillance Agency (ANVISA); Note: <sup>(2)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum Permitted Level. Source: Authors (2025).

### 3.3. Microbiological Parameters

The results of the microbiological analysis contained in the WTPic water reports indicated that the parameters presented almost all legal compliance with water quality. This indicator was in the order of 97.46%, and in accordance with Resolution RDC No. 11/2014 (Brasil, 2014) and Ordinance GM/MS 888, of May 2021 (Brasil, 2021a, 2021b). On the other hand, the remaining 2.54% did not meet the legal requirements. This corresponds mainly to the results of heterotrophic bacteria parameters (HET, up to 100 CFU/mL). These records occurred in December 2022, May 2023, July 2023 and June 2024, specifically at the first point P1. Similarly, heterotrophic bacteria (HET) showed non-compliance at the entry point of P2 pre-treatment, between August 2022 and July 2023. Thus, although 100% of the results of the endotoxin parameter at the post-reverse osmosis (P3) water point were legally compliant (up to 0.25 EU/mL), these results were very similar over the 25 months of the study (Tables 10-12). However, this scenario seemed to us probabilistically unexpected.

Tables 10-12 summarize the data recorded on microbiological parameters in the periods of 2022, 2023, and 2024. The microbiological compliance values of the samples that met the potability standard required by Resolution RDC No. 11/2014 (Brasil, 2014) and Ordinance GM/MS 888, of May 2021 (Brasil, 2021a, 2021b) are marked in bold. It is noteworthy that there is a greater number of samples in 2023, and that the data present favorable results mostly in terms of compliance with current standards.

## 4. Discussion

### 4.1. Metals

Regarding metals, there was full legal compliance in 2022. That is, the records of

**Table 10.** Parameters of WTPic's microbiological analysis in 2022. Uninefro Amapá, 2024.

Microbiological Parameters	No. of samples	Mean ± SD (P <sub>1</sub> )	Mean ± SD (P <sub>2</sub> )	Mean ± SD (P <sub>3</sub> )	Mean ± SD (P <sub>4</sub> )	MPL <sup>(1)</sup>	MPL <sup>(2,3)</sup>	In compliance (% of samples)
Heterotrophic bacteria count	20	47.4 ± 50.78	164.8 ± 294.97	6.2 ± 7.16	14.2 ± 24.43	Absent in 100 mL <sup>(1)</sup>	500 UFC/mL <sup>(3)</sup>	95
Total coliforms	20	0 ± 0	0 ± 0	0 ± 0	0 ± 0	Absent in 100 mL <sup>(1)</sup>	Absent in 100 mL <sup>(2)</sup>	
<i>E. coli</i>	10	0 ± 0	0 ± 0	-	-	-	Absent in 100 mL <sup>(2)</sup>	100
Endotoxins (EU/mL)	5	-	-	0.25 ± 0	-	0.25 <sup>(1)</sup>	-	

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-National Health Surveillance Agency (ANVISA); Note: <sup>(2,3)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum Permitted Level. Source: Authors (2025).

**Table 11.** WTPic's microbiological analysis parameters in 2023. Uninefro Amapá, 2024.

Microbiological Parameters	No. of samples	Mean ± SD (P <sub>1</sub> )	Mean ± SD (P <sub>2</sub> )	Mean ± SD (P <sub>3</sub> )	Mean ± SD (P <sub>4</sub> )	MPL <sup>(1)</sup>	MPL <sup>(2,3)</sup>	In compliance (% of samples)
Heterotrophic bacteria count	48	137.20 ± 252.61	62.50 ± 197.76	9.4 ± 23.74	22.8 ± 25.66	Absent in 100 mL <sup>(1)</sup>	500 UFC/mL <sup>(3)</sup>	93.75
Total coliforms	48	0 ± 0	0 ± 0	0 ± 0	0 ± 0	Absent in 100 mL <sup>(1)</sup>	Absent in 100 mL <sup>(2)</sup>	
<i>E. coli</i>	24	0 ± 0	0 ± 0	-	-	-	Absent in 100 mL <sup>(2)</sup>	100
Endotoxins (EU/mL)	13	-	-	0.25 ± 0	-	0.25 <sup>(1)</sup>	-	

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-National Health Surveillance Agency (ANVISA); Note: <sup>(2,3)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum Permitted Level. Source: Authors (2025).

**Table 12.** Parameters of WTPic's microbiological analysis in the year 2024. Uninefro Amapá, 2024.

Microbiological Parameters	No. of samples	Mean ± SD (P <sub>1</sub> )	Mean ± SD (P <sub>2</sub> )	Mean ± SD (P <sub>3</sub> )	Mean ± SD (P <sub>4</sub> )	MPL <sup>(1)</sup>	MPL <sup>(2,3)</sup>	In compliance (% of samples)
Heterotrophic bacteria count	32	80.4 ± 195.40	89.8 ± 220.13	3.4 ± 6.72	1.1 ± 0.35	Absent in 100 mL <sup>(1)</sup>	500 UFC/mL <sup>(3)</sup>	93.75
Total coliforms	32	0 ± 0	0 ± 0	0 ± 0	0 ± 0	Absent in 100 mL <sup>(1)</sup>	Absent in 100 mL <sup>(2)</sup>	
<i>E. coli</i>	16	0 ± 0	0 ± 0	-	-	-	Absent in 100 mL <sup>(2)</sup>	100
Endotoxins (EU/mL)	8	-	-	0.25 ± 0	-	0.25 <sup>(1)</sup>	-	

Note: <sup>(1)</sup>RDC No. 11 of March 13, 2014-National Health Surveillance Agency (ANVISA); Note: <sup>(2,3)</sup>Ordinance GM/MS No. 888, of May 4, 2021; SD = Standard Deviation; MPL = Maximum Permitted Level. Source: Authors (2025).

comparative analysis with the established standards presented values in accordance with 100% of the samples analyzed, without any inconsistency. However, in 2023 and 2024, only the calcium (Ca) parameter showed values below 100%. These results correspond only to the samples from the first point P1, at the point of water

collection from the semi-artesian well.

Studies in the literature, such as the one developed by Abdalla et al. (2010), describe calcium ion values in the rainy season between 4.81 mg/L and 30.06 mg/L. The authors' analyses dealt with the hardness and concentrations of calcium and magnesium in the groundwater of wells in the municipality of Rosario in the state of Maranhão.

Da Silva et al. (2023) observed higher values of calcium concentration in the water of underground wells in the municipality of Vitória da Conquista, state of Bahia, with concentrations ranging from 2.1 mg/L to 200 mg/L. These results presented by the aforementioned authors exceeded those of the present study for this ion. That is, the concentrations observed in the semi-artesian well of the WTPic, with maximum concentrations of calcium (Ca) ranging between 3 mg/L and 5 mg/L. However, it is necessary to consider that the quality of the water analyzed in the WTPic well was restricted in not distinguishing the samples throughout different seasons of the year, as can be previously illustrated by the authors, since this is usually a determining factor of influence or divergences of values over time. However, it is known that groundwater quality parameters in Macapá have significant seasonality (Grott et al., 2018) and are highly sensitive to the environmental characteristics of the surroundings (Sousa et al., 2023).

## 4.2. Physicochemical

In the present analysis, it was observed that the total chlorine parameter was examined in two different reports. The first was obtained from the report of metal parameters and the second from the physicochemical report. With this distinction, it was possible to compare values on the time axis and on the collection points mentioned in the duplicate and to examine correspondences between them. However, these were different samples for the same points, also resulting in different values.

With this fact, in December 2022, we obtained concentration values for the identified metals in the order of 0.001 (mg/L) in P1 and 0.07 (mg/L) in P3. On the other hand, in the same month and year, in the physicochemical analysis report, the results of total chlorine concentration were 0.01 (mg/L) in P1 and 0.01 (mg/L) in P3. A similar situation for the analysis of metals occurred in May 2023, where the total chlorine at point P1 was equal to 0.05 (mg/L). On the other hand, in the physicochemical analysis, a value of 0.01 (mg/L) was recorded at the same point. In November of the same year, a value of 0.01 (mg/L) was recorded in the analysis of metals at point P3, while in the physicochemical analysis, this value was 0.04 (mg/L). In May 2024, the records showed a concentration equal to 0.01 (mg/L) in P1 and 0.03 (mg/L) in P3, in relation to metals. However, in the physicochemical analysis, different values were observed, of 0.03 (mg/L) in P1 and 0.01 (mg/L) in P3.

Although this episode occurred, the values observed were in accordance with the established norms, being useful for comparison between both samples. It is

noteworthy that there are studies that show that this type of inconsistency is frequent, but that still include total chlorine values adopted in Resolution RDC No. 11/2014 (Brasil, 2014). Thus, for legal comparative purposes, the World Health Organization (WHO) serves as a reference to frame maximum permitted concentration values.

The electrical conductivity parameter represented the highest indicators of non-conformity in the physicochemical analysis in the present research, especially in the raw water of the semi-artesian well. However, a significant drop in the values of electrical conductivity was observed at points P3 and P4, both in accordance with RDC No. 11/2014 of up to 10 ( $\mu\text{S}/\text{cm}$ ). This shows that the different phases of water treatment progressively impact its quality, but justifies the probable discrepancy in values between different monitoring points. Despite the scarcity of information in the literature regarding the limitations of information that discusses high electrical conductivity in well water used for hemodialysis water treatment, it was possible to find studies that discuss high values for the parameter mentioned in other different approaches. For example, Vasconcelos et al. (2019) analyzed the application of water electrical conductivity in hydrogeological studies of the northeastern region of Brazil. The authors classified three levels of behavior of electrical conductivity in the water column of a tubular well. The first in the range 25 to 36 m (287  $\mu\text{S}/\text{cm}$  to 497  $\mu\text{S}/\text{cm}$ ), whose values are close to those found in the present study. However, on the other hand, these are even higher than those of the second band, at the level of 38 to 25 m (995 and 1082  $\mu\text{S}/\text{cm}$ ) and in the third, at the level of 55 to 59 m (1082  $\mu\text{S}/\text{cm}$  to 5565  $\mu\text{S}/\text{cm}$ ). According to the aforementioned authors, the high values of electrical conductivity may be related to the variation in the depth of the water depth of the well.

Da Silva & Gomes (2021) also observed high values of electrical conductivity in at least five samples of water from wells, whose concentrations ranged from 310.4  $\mu\text{S}/\text{cm}$  to 1898  $\mu\text{S}/\text{cm}$  in the village of Alegria, a rural area of the municipality of Teresina-PI. This was probably due to the direct relationship between these high values of electrical conductivity of water and high concentration of total dissolved solids present in water. As the amount of dissolved solids in water increases, electrical conductivity is expected to increase in the same proportion.

Lages et al. (2022) observed electrical conductivity values between 9.90  $\mu\text{S}/\text{cm}$  and 406.33  $\mu\text{S}/\text{cm}$  in water samples collected in the Educandos Watershed in the municipality of Manaus, AM, and found values similar to those monitored in the WTPic-AP. According to the aforementioned authors, the highest values of this parameter were related to the receipt of high loads of domestic sewage when the volume of water from the well was lower, indicating the existence of a significant influence of pollution sources that altered the concentrations in the analyzed samples. On the other hand, the lowest values of electrical conductivity were associated with a single sample collected in a well-wooded place and protected from industrial waste. This protection contributed to the maintenance of water quality, resulting in lower levels of conductivity. Water dilution and concentration influ-

enced the results, leading to lower electrical conductivity values, suggesting that environmental factors and the presence of vegetation may play an important role in water quality (Grott et al., 2018; Sousa et al., 2023).

Regarding salinity, the samples from the WTPic semi-artesian well collected at point P1 indicate a significant variation in salinity levels over time. In September 2022, an alarming value of 275 (%) was recorded, while in January and August, this value dropped to approximately 0.3 (%). Because it is groundwater, the salinity variable was not considered for comparative purposes. In addition, there is no specific legal unit of measurement as a reference. And, even though Resolution No. 357, of March 17, 2005, classifies fresh waters, they still have salinity equal to or less than 0.5%. Brackish waters have salinity between 0.5% and 30% and saline waters have values equal to or greater than 30%. At WTPic, the drastic change in values suggests probable analysis errors, requiring verification in the monitoring of the water quality of the well. Thus, the value recorded in September 2022 would classify this water sample as saline, something unlikely in the present situation, which could result in significant implications for its use.

The apparent color parameter is an important indicator of water quality, reflecting the presence of possible contaminants. At point P1, in only a single sample from August 2022, the concentration exceeded the limit allowed by Ordinance MS 2914/2011 888/2021. Lima et al. (2024) studied the water quality in semi-artesian wells in the District of Santo Antônio do Matupi, in Manicoré/AM, observing a high value of 22.1 uH. According to the authors cited, this concentration exceeds the legal limit, being a warning sign for water quality, requiring detailed investigation to identify the source of the alteration of this indicator. In the present study, the turbidity in the WTPic was analyzed only at points P1 and P2. In this sense, in January and October 2023, non-conformities occurred only in samples of point P1.

The turbidity variation in the TECic was of the order of 10 and 11 uT. However, Ordinance GM/MS No. 888, of May 4, 2021, establishes a maximum allowed value of 5 uT (MPL). According to Silva et al. (2021), in an analysis of groundwater from the western region of the state of Santa Catarina, in samples analyzed in the municipality of Luzerna, turbidity exceeded the maximum value by 1.14 times. According to the aforementioned authors, this was due to the low depth of the well and its location being close to a crop area.

The pH indicator was one of the indicators with the highest frequency of non-compliance, being above 70% in 2024. In addition, variations in pH non-conformities were observed between 5.70 and 6.72 in 2022, between 5.01 and 6.37 in 2023, and between 4.68 and 5.68 in 2024, suggesting considerable water acidity throughout the period. Thus, even in the reverse osmosis phase and in the distribution phase, where water should be seen as suitable for HD, in general, this means that the pH of the water can vary considerably from P1 to the final stage of the WTPic process. RDC Resolution No. 11/2014 (Brasil, 2014) does not recommend the use of water with a pH outside the range between 6 and 9.5, which would be unsuitable for human consumption and even for HD treatment.

Bento Chaves Santana et al. (2016) analyzed samples of water distributed for human consumption in the state of Amazonas from the Surveillance of Water Quality for Human Consumption (Sisagua) information system, finding pH values lower than 6, with a median of 5.78, similar to those found in the present study (WTPic). These authors suggest that the acidity of water is associated with the concentration of soluble organic substances and less presence of minerals in the water. This fact converges with other similar studies in the Amazon, where the soil is generally naturally acidic, influencing the pH values of water in underground springs (Grott et al., 2018). In addition, Ferreira et al. (2021) also observed minimum pH values, around 4.80 in the dry season, and maximum values of 6.30, in the rainy season. Those studies took place in rural wells in the municipality of Humaitá-AM. In the latter case, the authors considered that these values can be explained by the presence of dissolved carbon dioxide (CO<sub>2</sub>) and alkalinity (Al), a result of leaching of soil and rocks by rainfall.

### 4.3. Microbiological

Surprisingly, only heterotrophic bacteria were in non-compliance with the current legislation, considering that the highest values occurred only at points P1 and P2, ranging from concentrations of 520 CFU/mL to 800 CFU/mL. In contrast to previous expectations, the concentrations for points P3 and P4 ranged from 1 CFU/mL to 84 CFU/mL, showing no change.

The presence of these bacteria in the water is an indication of contamination originating from non-fecal sources. A situation that compromises the potability of water and can lead to problems of corrosion and formation of biofilms in the pipes, in addition to suggesting failures in the storage system and proximity to places where organic waste is disposed of (Gomes de Siqueira et al., 2022).

When analyzing the potability of water from artesian wells in rural communities in the Sergipe countryside, Gomes de Siqueira et al. (2022) found the presence of heterotrophic bacteria in wells, which have values between 43 CFU/mL and <1000 CFU/mL. Reis Santos et al. (2024) analyzed the water from artesian wells in the municipality of Itabaiana-SE, and found values between 276 CFU/mL and even higher than 6000 (CFU/mL). Thus, the authors justify that the significant presence of contamination suggests that the amount of free residual chlorine was not adequate for the eradication of the microorganisms detected and resulting from the lack of basic sanitation.

In the present study, however, the monitoring results demonstrate a consistent pattern of compliance for microbiological parameters. Thus, it is possible to confirm the hypothesis that the microbiological indicators were fully in legal compliance. So much so that some percentage values of compliance were in the order of up to 100% in the other parameters analyzed (Tables 10-12).

## 5. Conclusion

Although most of the parameters were in accordance with the established stand-

ards (>95% of the sampling frequency), it was possible to confirm the research hypotheses that the monitoring indicated high reliability and efficiency of the WTPic.

However, there were some inconsistencies in the monitoring regarding the excessive similarities of some parameters, as some results showed high similarity, above the probabilistically expected, for the aforementioned randomized frequencies. In this aspect, significant similarities in the variation of the parameters were expected only in a small fraction of the monitored time series, such as resulting from the hydrological seasonal effects, that is, only between the rainy, transition and dry seasonal periods, with greater influence of the rainy period, than in the transitional or dry periods. This analysis was due to the fact of the relatively low depth of the well (in the order of 40 m), most likely influenced by the variation in the level of the water table within a very urbanized area of the city of Macapá-AP.

In these cases, in relation to the hypotheses raised, it is possible to report the following situations: a) the quality of the water from the well would be unexpectedly “very stable”, to the point that most of the parameters would present values or concentrations that are often constant (very repeated), reflecting on a “constancy” observed in most of the values and standards of water quality monitored; b) despite the relatively low depth of the underground water source (up to 40 m), it is still possible to assume low variability and high protection capacity of the water source in the current situation, which acts in favor of safety; c) ultimately, it would also be expected that there would have been inconsistencies and/or technical failures (systematic errors) in the experimental conduct of water quality collection and monitoring.

The systematic constancy of some water quality parameters throughout the historical series could characterize evidence of systematic monitoring inconsistencies or failures. Therefore, it would serve as a “wake-up call” to improve the quality and frequency of collection for the purpose of counter-evidence in the different stages of water quality monitoring. These recommendations could, in theory, reduce inconsistencies and/or potential failures, and consequently reduce risks inherent to the production of water used in HD. This procedure would improve the safety of water quality management and its noble use in HD procedures.

Overall, the custom-designed system proved to be robust and potentially safe in view of its rigorous and efficient treatment capacity (WTPic). The infrastructure and monitoring of each treatment stage were considered sufficient to maintain legal compliance of water quality, with a frequency greater than 95% of the total samples of the physicochemical (pH, color, turbidity, metals, etc.) and microbiological total coliforms and *E. coli*, and heterotrophic (HET) parameters.

On the other hand, the fact that the WTPic system is considered isolated, without the benefit of a regular source of the water supply network of the Amapá Sanitation Concessionaire (CSA), required a considerable technical and investment effort to enable efficient operations for the treatment of raw groundwater. So that there was a minimum safety and protection necessary for its operation. In this

case, we observed that, if the natural underground source were replaced by the concessionaire's public water supply, there would be room for several improvements in the quality of the WTPic's inlet water (spring). In addition, the probable current operational, infrastructural and maintenance costs would greatly reduce the potential risks and vulnerability to the efficiency of treatment of WTPic.

Therefore, the economic, technical and environmental costs of WTPic, in the way it is currently operated, are probably related to the quality of the underground source and the associated potential risks it offers, in addition to the general context of basic sanitation existing in the capital of Macapá/Amapá. In addition, this scenario also seems to have repercussions not only on the current situation of basic sanitation and public health in the municipality of Macapá, but is probably a limiting factor for other municipalities in the state of Amapá/Brazil.

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### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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