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A FRAMEWORK FOR ASSESSING INDIGENOUS WATER SECURITY ALIGNED WITH THE PRINCIPLES OF THE BRAZILIAN UNIFIED HEALTH SYSTEM (SUS)

UMA ESTRUTURA PARA AVALIAÇÃO DA SEGURANÇA HÍDRICA INDÍGENA ALINHADA COM OS PRINCÍPIOS DO SISTEMA ÚNICO DE SAÚDE (SUS) BRASILEIRO

UN MARCO PARA LA EVALUACIÓN DE LA SEGURIDAD HÍDRICA INDÍGENA ALINEADO CON LOS PRINCIPIOS DEL SISTEMA ÚNICO DE SALUD BRASILEÑO (SUS)

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ABSTRACT

This paper presents framework for assessing water safety in Indigenous Communities within the Brazilian Amazonian Region. The framework follows the principles of Special Secretariat of Indigenous Health (SESAI) within the Brazilian Unified Health System (SUS). The first contribution of this paper is that it presents a literature review comprising works published internationally between 2015 and 2025 including studied of indigenous public health, natural resource management and indigenous peoples in the state of Para. The second contribution is that the framework reported can support assessments of water safety according to set of Key Performance indicators (KPIs) specified reflect Brazilian public policy. The KPIs enables the assessment of water safety by integrating technical, environmental, and socio-cultural dimensions. Besides it takes into account the Brazilian guidelines, it also taken into account international recommendations from the Organization for Economic Co-operation and Development (OECD) and the World Health Organization (WHO). By the end an illustrative application is an illustrative application of the assessment procedure introduced based on

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real public open data, and it discusses research insights and opportunities are also highlighted.

Keywords: Indigenous Peoples. Water Security. Performance Evaluation. Assessment Framework. Brazilian Amazon.

RESUMO

Este artigo apresenta uma estrutura para avaliar a segurança hídrica em comunidades indígenas na Amazônia brasileira. A estrutura segue os princípios da Secretaria Especial de Saúde Indígena (SESAI) do Sistema Único de Saúde (SUS). A primeira contribuição deste artigo é a apresentação de uma revisão bibliográfica abrangendo trabalhos publicados internacionalmente entre 2015 e 2025, incluindo estudos sobre saúde pública indígena, gestão de recursos naturais e povos indígenas no estado do Pará. A segunda contribuição é que a estrutura relatada pode subsidiar avaliações da segurança hídrica de acordo com um conjunto de Key Performance Indicators (KPIs) especificados, que refletem as políticas públicas brasileiras. Os KPIs permitem a avaliação da segurança hídrica integrando dimensões técnicas, ambientais e socioculturais. Além de levar em consideração as diretrizes brasileiras, também considera as recomendações internacionais da Organização para a Cooperação e Desenvolvimento Econômico (OCDE) e da Organização Mundial da Saúde (OMS). Ao final, uma aplicação ilustrativa do procedimento de avaliação introduzido com base em dados públicos abertos reais é apresentada, e são discutidos insights e oportunidades de pesquisa, que também são destacados.

Palavras-chave: Povos Originários. Segurança Hídrica. Avaliação de Desempenho. Framework de Avaliação. Amazônia Brasileira.

RESUMEN

Este artículo presenta un marco para evaluar la seguridad hídrica en comunidades indígenas de la Amazonia brasileña. El marco sigue los principios de la Secretaría Especial de Salud Indígena (SESAI) del Sistema Único de Salud (SUS). La primera contribución del artículo es la presentación de una revisión bibliográfica que abarca trabajos publicados internacionalmente entre 2015 y 2025, incluyendo estudios sobre salud pública indígena, gestión de recursos naturales y pueblos indígenas en el estado de Pará. La segunda contribución es que el marco presentado puede respaldar las evaluaciones de la seguridad hídrica basadas en un conjunto de Indicadores Clave de Desempeño (KPI) específicos que reflejan las políticas públicas brasileñas. Los KPI permiten evaluar la seguridad hídrica integrando dimensiones técnicas, ambientales y socioculturales. Además de considerar las directrices brasileñas, también considera las recomendaciones internacionales de la Organización para la Cooperación y el Desarrollo Económicos (OCDE) y la Organización Mundial de la Salud (OMS). Finalmente, se presenta una aplicación ilustrativa del procedimiento de evaluación introducido, basada en datos públicos reales y abiertos, y se destacan perspectivas y oportunidades de investigación.

Palabras clave: Pueblos Indígenas. Seguridad Hídrica. Evaluación del Desempeño. Marco de Evaluación. Amazonía Brasileña.

1 INTRODUCTION

This paper presents the development of a framework for assessing water safety in Indigenous Communities within the Brazilian Amazonian Region. The framework follows the principles of Special Secretariat of Indigenous Health (SESAI) within the Brazilian Unified Health System (SUS). This effort is part of the broader activities under Arandu Network Project. The content presented here aims to support ongoing research activities and contribute to the systematization of knowledge oriented to sustainable development including public health, natural resource management and indigenous peoples in the state of Para.

The proposed framework seeks to quantify and assess the state of water safety by integrating technical, environmental, and socio-cultural dimensions. Specifically, it is designed to incorporate physical-chemical, microbiological, and infrastructure-related parameters, while also acknowledging community-based values regarding water use and public health outcomes. The methodological approach follows structured scientific protocols aligned with both national and international guidelines, notably those issued by the Organisation for Economic Co-operation and Development (OECD) and the World Health Organization (WHO).

Internationally recommended practices and statistical techniques are employed to guide data treatment and normalization. The development of this framework follows a logical sequence: from the collection and structuring of relevant data, through the definition of evaluation criteria, to the construction of composite indicators that enable integrated, comparative analyses across different Indigenous territories.

The structure of this article is as follows. Section 2 provides a literature review, summarizing conceptual developments, empirical evidence, and assessment strategies related to water safety in Indigenous contexts. Section 3 outlines the methodology adopted in the construction of the framework, including theoretical underpinnings. Section 4 introduces the assessment framework, including criteria recommended by World Health Organization (WHO) and the Key performance Indicators formulae specified specifically for this sort of assessment, based on the data availability of Special Secretariat of Indigenous Health (SESAI). The Framework considers multiple dimensions of indigenous water safety discusses the findings and outlines recommendations for improving water safety monitoring and policy planning in culturally sensitive and logistically complex settings. Section 5 discusses an illustrative application of the assessment procedure introduced based on real public open data. Finally, Section 6 presents some research insights and opportunities are also highlighted.

2 LITERATURE REVIEW

This literature review has the objective to map the research body of water safety of Indigenous communities. Special attention was dedicated to review research regarding water safety frameworks, discussions on governance, public health implications, and proposed assessment procedures. The review process included a systematic search of 62 articles published between 2015 and 2025 across journals indexed in Web of Science (WoS) and Scopus, spanning quartiles Q1 to Q4. Keywords used included: "water safety," "Indigenous communities," "sustainable water management," "access to clean water," "hydrological resilience," "traditional ecological knowledge," "water rights," "environmental justice," "water scarcity," and "integrated water resources management (IWRM)." Inclusion criteria required the articles to explicitly address water safety in Indigenous contexts with attention to physical, chemical, and social aspects. Exclusion criteria ruled out studies unrelated to Indigenous populations or lacking relevance to key water safety dimensions. An additional unstructured search via Google Scholar was conducted to capture relevant works outside of the Boolean strategy. Ultimately, ten articles were selected, mostly focusing on Indigenous groups in Canada and Australia, with two addressing Pan-Amazonian populations in Bolivia and Paraguay.

Across the literature, water safety for Indigenous peoples emerges as a multidimensional challenge encompassing governance, infrastructure, public health, and cultural values. Governance structures are often fragmented. In Canada, for instance, water quality regulations do not uniformly apply to First Nations communities, which suffer from outdated and poorly maintained infrastructure (Galway, 2016; Lucier et al., 2020, Harper et al., 2011).

Cultural aspects are considered fundamental to Indigenous water perspectives. Water is not merely a resource but a sacred entity, essential to health, spirituality, and community identity. Authors such as Bradford et al. (2016a) and Wilson et al. (2019) argue that effective water safety strategies must integrate these cultural dimensions, challenging conventional models that focus solely on physical and chemical metrics. McGregor (2012) and Patrick et al. (2019) advocate for incorporating Indigenous worldviews and traditional knowledge into the development of culturally respectful water protocols.

Several studies link poor water quality to adverse health outcomes. Research by Bermedo-Carrasco et al. (2018) and Ratelle et al. (2022) found high levels of microbial and chemical contaminants in Indigenous communities, with frequent gastrointestinal illnesses. Distrust of municipal water—often due to taste, odor, or past contamination incidents—leads many to rely on traditional but potentially unsafe sources such as lakes and streams (Harper et al., 2015b; Wilson et al., 2019).

Social inequities are compounded by chronic underfunding and marginalization. Scholars argue for not just technical upgrades but equitable resource redistribution and Indigenous self-determination in water governance (Marshall et al., 2020; Schill & Caxaj, 2019). Community-led water management initiatives show promise, especially when combining ancestral knowledge with modern technology and regulatory tools (Jackson et al., 2012; McGregor, 2012).

Technological approaches also feature prominently. Lane et al. (2022) developed a web-based risk assessment tool for First Nations, enhancing data integration and inter-stakeholder communication, although digital illiteracy and infrastructure gaps pose challenges. Wright et al. (2018) found that even with new water distribution units, community trust and behavioral change remained limited. Similar limitations were observed by Correia (2022) in Paraguay, where political and environmental transformations exacerbate water vulnerability.

Quantitative and probabilistic models, such as the fuzzy evaluation method proposed by Hu et al. (2022), are gaining ground for precise monitoring in remote settings. These models often integrate traditional ecological knowledge (TEK) as emphasized by Cassivi et al. (2023). Balasooriya et al. (2023) and Hu et al. (2022) highlight high contamination levels in Australia and British Columbia, respectively, while Harper et al. (2015) linked poor water quality to gastrointestinal disorders in Canadian Inuit communities.

Finally, shifts in water usage behavior due to perception issues are also documented. Deshpande et al. (2025) and Ratelle et al. (2022) report a trend towards consumption of sweetened and fermented beverages among Indigenous populations in Bolivia and Canada due to distrust in chlorinated tap water.

In summary, the literature identifies five recurring factors critical to water safety in Indigenous contexts: microbiological and chemical quality, accessibility, infrastructure governance, community perception, and public health impacts. These dimensions form the foundation for the KPI framework developed in this study.

3 METHOD

The methodology adopted for the development of the water safety framework is based on the international recommendations of the Organisation for Economic Co-operation and Development (OECD) for composite indicators, specifically the guidelines outlined by Nardo et al. (2008) for the weighting of indicators. It is assumed that all Key Performance Indicators (KPIs) values are already normalized and dimensionless.

The OECD outlines eight structured steps for the construction of composite indicators, which were adapted for the construction of the KPI framework reported in this study. Examples of works published in the 2020s based on these guidelines include Zanella et al (2025), Oliveira et al (2025a); Oliveira et al (2025b)

The eight adapted steps are as follows.

- **Step 1 – Theoretical Framework:** A conceptual model was defined to support the selection and integration of KPIs. This ensures relevance to the multidimensional nature of water safety. Foundational references include the Brazilian Ministry of Health Ordinance No. 888 (2021) and the WHO Guidelines for Drinking-water Quality (2017).
- **Step 2 – Data Selection:** KPIs were developed based on analytical robustness, availability, geographic and thematic coverage, and internal coherence. In cases of limited data availability, proxy variables were considered.
- **Step 3 – Treatment of Missing Data.** Statistical techniques are required to manage missing values. Methods included mean, median, and mode substitution, as well as advanced approaches such as linear/polynomial interpolation, regression modeling, and machine learning algorithms like MICE, KNN, and Random Forest, depending on data characteristics (Wang et al., 2023).
- **Step 4 – Data Structure Analysis.** Exploratory analysis of the dataset informed choices around indicator weighting and aggregation. This ensured methodological transparency and internal consistency.
- **Step 5 – Normalization.** Indicators were normalized to a common scale to enable meaningful comparison. Special care was taken to address skewed distributions and outliers that could bias results.
- **Step 6 – Weighting and Aggregation.** Weights were assigned in alignment with the theoretical model and inter-indicator relationships. Aggregation methods recommended by OECD were considered, including Data Envelopment Analysis (DEA), Analytic Hierarchy Process (AHP), and Principal Component Analysis (PCA).
- **Step 7 – Robustness and Sensitivity Analysis.** Robustness checks were performed to assess how variations in normalization, weighting, and aggregation affect final outcomes. The framework design supports decomposing the index into its constituent components for transparency and interpretability.
- **Step 8 – Presentation and Visualization**. The KPIs and resulting composite scores were visualized using accessible formats that support interpretation by decision-

makers. Graphical outputs such as dashboards allow ranking and comparison between communities based on water safety performance.

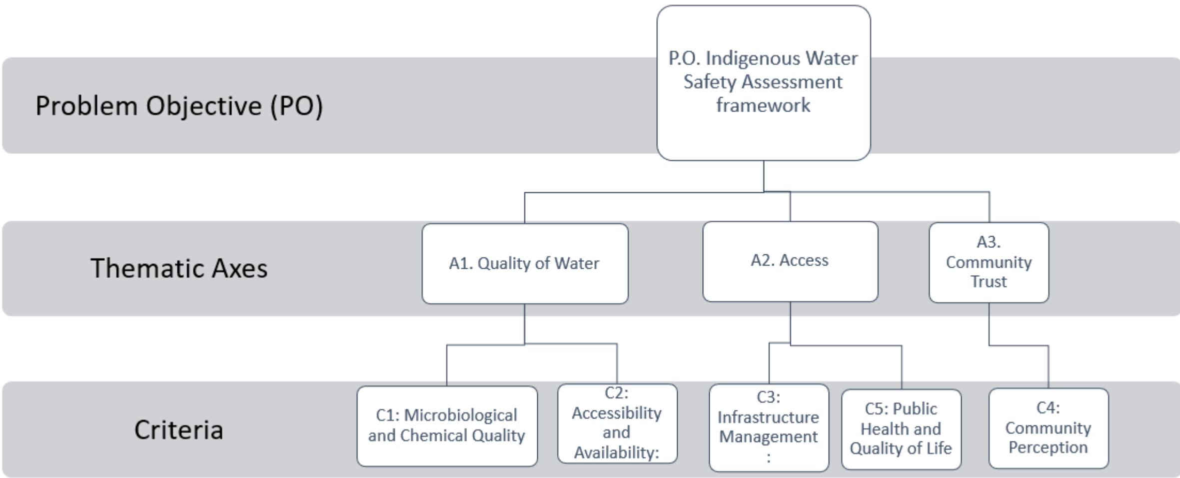
This set of procedures ensures the reliability and applicability of the framework in assessing multidimensional aspects of water safety within Indigenous territories.

4 ASSESSMENT FRAMEWORK OF INDIGENOUS PEOPLES' WATER SAFETY.

The water safety framework reported in this section was specified based on the criteria identified in the literature. Based on the international Standards and the body of research, three thematic axis and five performance criteria are proposed (see Figure 1). They were considered fundamental for this sort of assessment involving public policy health and natural research use according to scholars, SUS and WHO.

Figure 1

Indigenous water safety assessment framework proposed



Source: the Authors (2025).

- Axis 1 is quality of water. It covers studies focused on criteria C1 and C5. There is widespread concern about contaminants and health risks. For example, Hu et al. (2022) highlight heavy metals, focus on fecal coliforms. Climate impacts are also noted (Balasooriya et al., 2023). Sensory perceptions like chlorine odor (Ratelle et al., 2022) influence community acceptance. A Brazilian example of how one can quantify this criteria in KPI can be find in the work of Oliveira et al (2025), who proposed a common set of weights to quantify an alternative Potability Index (IPA) aligned with Brazilian standards.

- Axis 2 is Access. This includes criteria C2 and C3, seen in studies by Black; McBean (2025), Wright et al. (2018), Lane et al. (2022), and Correia (2022), highlighting structural challenges and environmental degradation affecting water availability.
- Axis 3 is Community Trust. It encompasses C4 wherein studies address distrust in municipal water systems, linking it to increased consumption of sweetened drinks (Deshpande et al., 2025). Traditional knowledge plays a crucial role in shaping water perceptions and acceptance of interventions (e.g., Black & McBean, 2017; Cassivi et al., 2023).

The description of criteria and thematic axis are represented in the next paragraphs and in Table 1.

Table 1

Relevance of Criteria in the Literature (2015–2025)

Authors	C1	C2	C3	C4	C5
Balasooriya et Al (2023)	X	X			
Black & McBean (2017)	X	X	X		
Cassivi et al. (2023)	X	X			
Correia (2022)			X		X
Deshpande et al. (2025)				X	X
Harper et al. (2015)	X				X
Hu et al. (2022)	X				
Lane et al. (2022)	X	X	X		
Ratelle et al. (2022)				X	
Wright et al. (2018)				X	X

Source: the Authors (2025).

The five performance criteria are described in the next paragraphs.

- C1: Microbiological and Chemical Quality: Includes evaluation of contaminants such as heavy metals, fecal coliforms, and harmful chemicals.
- C2: Accessibility and Availability: it measures include distance to water sources, supply reliability, and cost.
- C3: Infrastructure and Management: Covers best practices, public policy, local distribution systems, and governance. Especially relevant for urban-adjacent Indigenous communities, this criterion must be adapted for remote areas.
- C4: Community Perception: Reflects trust in water based on sensory attributes and contamination history.

- C5: Public Health and Quality of Life: reflects the incidence of waterborne diseases and chronic exposures.

These findings underline the need for water management strategies that integrate both technical and cultural dimensions to adequately reflect community-specific experiences and needs.

Finally, the set of Key Performance Indicators (KPIs) developed to operationalize the assessment of Indigenous people's water safety is reports in Table 2. Grounded in the criteria in figure 1 each KPI was specified to quantify a specific dimension of water safety: water quality (C1), access (C2), infrastructure coverage (C3), community perception (C4), and public health outcomes (C5). Table 2 outlines the KPIs, their corresponding formulas, and required parameters.

Table 2

KPIs proposed to assess indigenous Water Safety

Criterion	KPI	Formulae developed	Reference values
C1	Water Potability Index (WPI)	$WPI = \sum_{i=1}^{n} w_i \left(\frac{x_i - x_{imin}}{x_{imax} - x_{imin}} \right)$	Where: x_i measured value of contaminant i (e.g., fecal coliforms, nitrates, heavy metals); w_i weight of indicator i, based on health significance; WPI: values range from 1 (excellent quality) to 0 (poor quality).
C2	% Indigenous population access to drinking water (IPDW)	$\% IPDW = \frac{PDW}{total\ community\ population}$	-
	% Truck Supplied Population (TSP)	$\% TSP = \frac{TSP}{total\ community\ population}$	-
C3	% sanitation services area coverage	$\% SSAC = \frac{SSAC}{total\ community\ area}$	-
C4	Community Perception of Potability Index (CPPI)	$CPPI = \frac{R_j}{n \times R_{max}}$	Where: R_j = score of one survey respondent; R_{max} = max possible

			score; n: $number\ os\ responses$
C5	waterborne disease incidence index (WDI)	$WDI = 1 - \frac{I_{community}}{I_{thereshold}}$	Where: $I_{community}$: incidence rate of waterborne disease (cases per 1,000 inhabitants) ; $I_{thereshold}$ reference value.

Source: Oliveira et al (2025).

Together, these KPIs offer a robust and scalable framework for monitoring the state of water security in socio-environmentally vulnerable territories.

5 ILLUSTRATIVE APPLICATION OF THE ASSESSMENT OF INDIGENOUS PEOPLES' WATER SAFETY

This exercise aims to showcase the functionality of the framework and its KPIs. It has as objective to demonstrate the practical implementation of the proposed water safety framework, an illustrative application was developed based on simulated data representing the conditions of a hypothetical Indigenous community located in the Brazilian Amazon. The data collection used in this illustrative example is based on public open data from the Special Secretariat of Indigenous Health (SESAI, 2025) and the Brazilian Institute of Geography and Statistics (IBGE, 2025).

Consider an Indigenous Community settled in the state of Para comprising a population: 1,200 individuals in a territory of 45 km². The main source of water is surface water (river) and they have limited well-based supply.

Table 3

Illustrative Application

Criterion	KPI	Calculated Index
C1	Water Potability Index (WPI)	$WPI = 0{,}42$
C2	% Indigenous population access to drinking water (IPDW)	$\%\, IPDW = 0{,}625$
	% Truck Supplied Population (TSP)	$\%\, TSP = 0{,}275$
C3	% sanitation services area coverage	$\%\, SSAC = 0{,}158$
C4	Community Perception of Potability Index (CPPI)	$CPPI = 0{,}48$
C5	waterborne disease incidence index (WDI)	$WDI = 1 - \left(\frac{97}{120}\right) = 0{,}19$

Source: The Authors (2025).

In this small example, the assessment of water safety reveals potential structural vulnerabilities in all dimensions of the water safety framework. Each KPI was calculated using standardized formulas provided in Table 2. The Water Potability Index (WPI) aggregates normalized values of key contaminants, weighted by health risk. The accessibility indicators (IPDW and TSP) measure the proportion of the population with direct access to clean water or dependent on emergency supply. Infrastructure coverage (SSAC) reflects the physical presence of sanitation systems across the territory. The Community Perception Index (CPPI) quantifies public confidence in water quality through Likert-scale surveys. Lastly, the Waterborne Disease Index (WDI) inversely relates the local incidence of illness to a national reference threshold. Together, these indices enable a holistic interpretation of water safety, combining technical, infrastructural, perceptual, and epidemiological dimensions.

In this illustrative example, the Water Potability Index (WPI) for the community was 0.42, indicating that water quality was below acceptable standards due to the presence of contaminants such as coliforms, nitrates, and chlorine residuals. Regarding accessibility (C2), 62.5% of the population had direct access to water sources (IPDW), while 27.5% relied on truck-supplied water (TSP), revealing limited infrastructure and service reliability. The sanitation coverage indicator (C3) showed that only 15.8% of the territorial area was equipped with sanitation infrastructure, much of which was reportedly outdated or requiring repair. Perception data (C4), collected through a Likert-scale simulation, resulted in a Community Perception of Potability Index (CPPI) of 0.48, indicating widespread dissatisfaction related to taste, color, and reported gastrointestinal discomfort. Finally, health outcomes (C5) were represented by the Waterborne Disease Incidence Index (WDI), calculated as 0.19, based on 97 reported cases of water-related illness per 1,000 people compared to a national reference threshold of 120 cases. This result reflects a high degree of exposure to waterborne health risks.

While the WDI and WPI point to pressing health risks and low water quality, KPIs related to access and infrastructure confirm the operational deficiencies affecting the community.

The community perception KPI reinforces the dichotomy between technical interventions and user confidence on the sanitation services provided. It highlights the importance of addressing both physical and cultural dimensions of water safety.

This illustration validates the potential of the proposed framework to systematically diagnose weaknesses, monitor progress, and inform public interventions tailored to Indigenous realities. Future applications with empirical data will further strengthen the relevance and adaptability of this tool across diverse territories.

6 FINAL CONSIDERATIONS

This study presented the partial outcomes of an ongoing research initiative focused on developing a performance-based framework to assess water safety in Indigenous communities in Brazil. Grounded in national regulations, international standards, and academic literature, the proposed framework integrates five key performance criteria ranging from water quality and infrastructure to public health and community perception. They were organized under three thematic axes. A set of normalized KPIs was developed specifically for this matter, and they structured to enable transparent monitoring and policy-oriented analysis.

The illustrative application using simulated data adapted from SESAI and SIDRA depicted a hypothetical Amazonian community demonstrated the framework's operational potential. Results revealed critical challenges including poor water potability, limited access, outdated infrastructure, low public trust, and high rates of waterborne disease exposure. While these findings are illustrative, they reflect patterns actually observed in real-world Amazonian Indigenous contexts and underline the need for culturally informed, evidence-based responses in water governance

To ensure that this framework becomes a more actionable public health tool, the next stage of the research should involve its empirical application in Indigenous territories. This includes selecting pilot communities, collecting and processing real-world data, and populating the proposed KPIs with inputs from public databases and community-based surveys. The development of an interactive dashboard will facilitate visualization, comparison, and informed decision-making for public managers, Indigenous leaders, and researchers.

Furthermore, the application of statistical techniques such as multivariate analysis (e.g., PCA, DEA, AHP) will allow the refinement and possible aggregation of KPIs into a composite Water Safety Index. This index could be tested for robustness and sensitivity, supporting evidence-based prioritization in contexts of resource scarcity and socio-environmental vulnerability.

Equally essential is the validation of the framework through participatory processes. Workshops and dialogue with Indigenous representatives and health sector stakeholders will help ensure that the criteria and indicators reflect lived realities and cultural values. This step reinforces a commitment to intercultural governance and co-production of knowledge, in line with the principles of the Brazilian Unified Health System (SUS) and international rights frameworks such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP).

Summing up, this study represents an interdisciplinary approach contribution to assessing water safety in Indigenous contexts. Its advancement into practical tools and participatory validation will support more equitable, informed, and culturally appropriate water policies in the Brazilian Amazon and beyond.

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