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Water reuse in Brazilian rice farming: Application of semiquantitative microbiological risk assessment

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ABSTRACT

The current paper presented the Semiquantitative model for microbiological risk assessment for human health, in rice crop production in Brazil. For this purpose, initially, Microbiological Risk Assessment (SqMRA) was divided into four stages: 1) Identification of hazards; 2) Identification of exposure routes for different receptors; 3) Exposure scenarization; 4) Risk characterization. After that, the SqMRA was applied to rice farming in two scenarios, in which the first considers the effluent to be disinfected (Hazard 7), and the second considers the reality of sewage treatment conditions in Brazil (Hazard 9). Thus, it was observed that the reuse of water reuse can be applied in rice farming, with an acceptable global risk, to the receptors involved (farmer, consumer, and neighborhood). Although, it is necessary the relevance of disinfection to minimize the risk in any water reuse application is highlighted.

1. Introduction

Faced with the water insecurity that currently affects the whole world, namely the driest regions of the planet, the use of treated wastewater becomes increasingly present. In this scenario, in addition to providing water from an alternative source for various purposes, the practice of water reuse alleviates regional water pressures, minimizes the impacts of conflicts over water use and water pollution. In addition, in low and middle-income countries, water reuse can encourage the increase in sewage treatment rates and the improvement of operational practices to achieve the desired quality, consequently boosting socioeconomic development [1].

There are several possibilities for water reuse, usually classified as potable and non-potable, which demand different levels of quality, related to the intended uses [2]. However, it is a practice intrinsically associated with the risk of contamination. In the case of agricultural application, the most frequent purpose of the reuse practice in the world, the risk is related to the environment and the health of workers, consumers and the population living in the neighborhood of irrigated areas, due to the microbiological and chemical constituents present in the effluent after the treatment [3]. In general, standards, guidelines, and criteria for the reuse of non-potable water, throughout the world, are based on the quality of water required for a given use [3], but in most cases, they do not involve the direct application of risk assessment methodologies. However, at the European level, risk assessment has become mandatory whenever agricultural irrigation is involved, and in Portugal it is required for any use [4].

Technological advances allow the production of high-quality reclaimed water (RW), which can reliably meet the most demanding standards, including for potable uses [5,6]. If the treatment process is inadequate or unreliable, residual biological and chemical contaminants can pose a risk to human health [7]. This risk can be greater or lesser, the more or less exposed to hazard the receptors are, respectively. This is one of the main factors involved with user rejection [8]. The general public considers RW as a high risk to human health, mainly due to the presence of pathogens that may enter the food chain [9], although the practice has proven technical-scientific reliability [10].

To ensure safety, risk assessment, in particular on human health, is of

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paramount importance [11]. The risk must be evaluated and managed correctly so that the transparency of actions and information provides an adequate level of communication to achieve a sustained relationship with the population and promote a greater acceptance of water reuse projects [12].

The current discussion on different risk assessment approaches can help to establish more informative and comprehensive risk assessment models in future studies on the topic of water reuse, which continues to grow [13]. In this sense, the aim of the current paper is to present an application of the semi-quantitative model for microbiological risk assessment for human health, in rice crop production. This type of crop, generally irrigated by flooding (furrow or flood) is of great importance for agricultural production in Brazil, as it demands the largest amount of water for irrigation in the country.

The relevance of the study also results from the fact that this type of irrigation has already been identified as a potential vector of risk in fresh crops intended for raw consumption [14] but there are studies on risk assessment for crops consumed after cooking.

2. Risk assessment

To guarantee the safety of water reuse, different risk assessment methodologies are adopted. In all of them, four main elements are interrelated to minimize the risk for public health, to acceptable levels. They are: i) Identification of hazards, ii) Identification of exposure routes for different receptors, iii) Exposure scenarios according to the dose; iv) Risk Characterization [4,13,15].

The hazard (i) relates to chemical, biological or physical agents with the potential to cause harm [16]. According to the ISO 20670:2018, a standard on vocabulary for water reuse [17], the hazard is defined as being a "source or situation with a potential for harm in terms of human injury or ill health (both short and long term), damage to property, the environment, soil, and vegetation, or a combination of these".

For public health, the hazard is mostly associated with microorganisms related to waterborne diseases, usually represented by indicators of fecal contamination [13,18]. In the case of irrigation for agricultural purposes, chemical constituents such as compounds of emerging concern can be absorbed by crops in the irrigation process, with this absorption being greater in foliage and roots than in fruits [19]. However, despite still being studied, it is suggested that most contaminants of emerging concern, as well as heavy metals, may not present major health risk concerns [19,20]. Furthermore, according to ISO 16075-1:2020, to date, there is a lack of evidence of adverse effects of contaminants of emerging concern (pharmaceutical residues and personal care products) on human health or the environment from RW irrigation or consumption of irrigated crops with RW [21]. Thus, the hazards inherent to the RW to be made available for irrigation are mainly related to the microbiological content, especially pathogens.

The exposure routes (ii) considered are ingestion, inhalation, or dermal adsorption, are assumed with direct or indirect contact, to different receptors, such as humans, animals (domestic or livestock), landscape vegetation or crops (food or not) [15,22]. The receptors and their respective susceptibilities to hazard are always different in each water reuse project in the irrigation of different types of crops.

The scenarios (iii) should portray, in the greatest possible detail, the potential situations of exposure of receptors to RW. For this reason, it is the most critical stage, which involves subjectivity and uncertainties [4].

The risk characterization (iv) consists of quantifying and prioritizing the risk for human health resulting directly from the factors associated with the hazard, exposure routes, applicable scenarios, and the applied multiple barriers [23].

The World Health Organization (WHO) suggests several risk assessment approaches that can respond to different management needs. These are qualitative and semi-quantitative models or quantitative mathematical methods, in addition to sanitary inspection, which involves a simple and effective approach for small systems [24].

All approaches, in different ways, estimate the possible risks associated with the practice of reuse, to reduce them to a minimum level considered acceptable. Quantitative assessment, known by the acronym QMRA (Quantitative Microbial Risk Assessment) combines scientific knowledge about the presence and nature of pathogens, their potential fate and transport in the water cycle and exposure scenarios referring to the receptor and their health effects that result from such exposure [24]. Qualitative or semi-quantitative assessment is based on the approach of the risk matrix that allows assessing different risks associated with water quality, involving an appraisal of the likelihood of occurrence of exposure to a given hazard and its severity or consequence, if it happens.

Among the different risk assessment methodologies, those that use quantitative mathematical models, similar to QMRA, are complex and have a high uncertainty as they require extensive local data that are not always available for non-potable uses [4]. Besides that, the data limitation ends up requiring many assumptions during the process, absorbing great uncertainties for the result [13]. The quantitative model, due to the characteristics already described, and not because it is difficult to apply in reclaimed water scenarios, has great applicability for risk assessment in potable reuse [25]. In the context of reuse, the quantitative method should only be used for potability purposes (direct or indirect) [13]. On the other hand, the QMRA can be used to assess risk at a specific point in the reuse system, such as the delivery point between the RW production system and the farmer but does not allow the quantification of the risk beyond that [18].

2.1. *Semiquantitative Microbiological Risk Assessment*

For non-potable uses, it was developed a Semiquantitative model, based on the qualitative methodology presented by the ISO 20426:2018 in order to deal with the limitations of quantitative microbiological risk assessment [4,26].

This, along with parts 1 and 2 of the 16075 serie of standards [21,27] form the basis of the Portuguese legislation [28] and the European Union Regulation [29]. The Semiquantitative Microbiological Risk Assessment (SqMRA) comprises the use of an empirical qualitative judgmental approach to assess the relative importance of hazards, exposure routes and contact scenarios, and multi-barriers in place [4]. For this, instead of dealing with complex input data such as those required for the application of QMRA, in the semi-quantitative methodology, the input data can be the possible quality standards that indirectly represent the eventually tolerable doses.

According to this, the regulations that legally enable the practice of water reuse should be taken into account, not only the water quality standards, but also a risk management plan, specifically associated with the project in question, according to a fit-for-purpose approach [4]. This is the purpose indicated by ISO 16075-1:2020, i.e., the use of RW with a quality suitable for the purpose for which it is intended without jeopardizing public health or the environment [21]. In this approach, is possible to combine physical, chemical, or biological barriers to minimize contact between hazards and receptors, and consequently minimize risk. To control microbiological risk, the concept of accredited barrier can also be used, which is a measure that produces a result equivalent to a certain microbiological reduction measured in logarithmic scale [27].

3. Methodology

For the development of this study, the semi-quantitative model of microbiological risk assessment for human health, developed [4] and already adopted in Portugal, following the publication of specific regulations for the water reuse [28] and in the European Union, through the recent *Regulation* (EU) 2020/741 [30], was applied with the aim of ensuring the safety of reuse for agricultural irrigation purposes.

The SqMRA is divided into four stages, corresponding to the successive application of the elements that integrates the methodology: 1) Identification of *hazards*; 2) Identification of *exposure routes* for different *receptors*; 3) *Exposure scenarios*; 4) *Risk* characterization. Each of these stages involves different steps, which must be taken seriously to ensure the successful implementation of a safe reuse practice in irrigation. In Fig. 1, a general flowchart of the SqMRA application is presented, with all stages and steps involved in the process, which are detailed as follows.

Stage 1 - Identification of *hazards*

Initially, the hazard related to the practice of water reuse in irrigation, which configures the microbiological risk, must be identified. In this stage, the possible agents that have the potential to cause adverse effects are identified.

Usually are used indicators of microbial contend in water due to the difficulties to detect and/or quantify all pathogenic agents present in water due to the lack of easy and reliable methods. The *Escherichia coli* (*E. coli*) is the most common indicator for defining the *hazard* associated with human health in RW irrigation practices [13,18,32], although Thermotolerant Coliforms can also be adopted. In this study, *E. coli* was used, instead of fecal coliforms, as it is used in the legal aspects adopted, according to Portuguese legislation, European Union Regulation, and ISO guidelines.

Table 1 shows the hazard classification related to the quality of the RW, considering the *E. coli* pattern, according to the level of wastewater treatment.

Stage 2 - Identification of *exposure routes* for different *receptors*

In this stage, the possible receptors (Step 1) that have susceptibility to exposure are identified, through the following routes: ingestion, inhalation, and dermal adsorption, directly or indirectly. Subsequently, for each identified receptor, is necessary to assign the exposure routes (Step 2).

Step 1 - Identification of receptors

The receptors involved must be identified according to the main characteristics of the analyzed project, such as the irrigation method and systems, culture typology, area location, neighborhood, among others. Potential receptors are those that are susceptible to exposure, especially humans, animals, and vegetation [15]. In the present study, only human receptors were adopted.

Table 1
Hazard level classification based on wastewater treatment options and microbiological quality.

level	*E. coli* (CFU/100 mL)	Hazard	treatment options
V	*E. coli* $\geq 10^4$	9	Secondary
IV	$10^3 <$ *E. coli* $< 10^4$	7	Secondary + disinfection
III	$10^2 <$ *E. coli* $\leq 10^3$	5	Advanced
II	$10^1 <$ *E. coli* $\leq 10^2$	3	Secondary + disinfection + post-chlorination
I	*E. coli* $\leq 10^1$	1	Advanced + post-chlorination

Source: Adapted from Ref. [4].

The human beings can be separated by age group, by function in the production chain, and by adherence to the project [4]. In the case of age group, children, adolescents and the elderly are usually more vulnerable than adults.

Regarding the role in the production chain, farmers and system operators (producers) are more vulnerable than merchant, because the first group is closer to the irrigation event and, consequently, to the RW. Merchants, a group of intermediaries between collection and distribution, must be adopted according to the specificities of each project.

In relation to adherence to the project, consumers and neighbors have different degrees of susceptibility, related to the distance of the irrigation systems and the type of consumption of the crop by consumers.

Step 2 – Definition of exposure routes for each receptor

The routes of exposure (ingestion, inhalation, and dermal adsorption) and their occurrences (direct or indirect) can be combined in different ways [4]. For instance, ingestion can occur directly, and can be intentional, accidental, by lack of information about the non-potability of water, inadvertently due to the ingestion of microdroplets during sprinkler irrigation, hand to mouth, among others.

Inhalation by human beings occurs directly by inhalation of the RW, for example, in cases of sprinkler irrigation; and indirectly, through domestic animals that carry the droplets to these environments. Adsorption, on the other hand, occurs through contact with wet or damp surfaces,

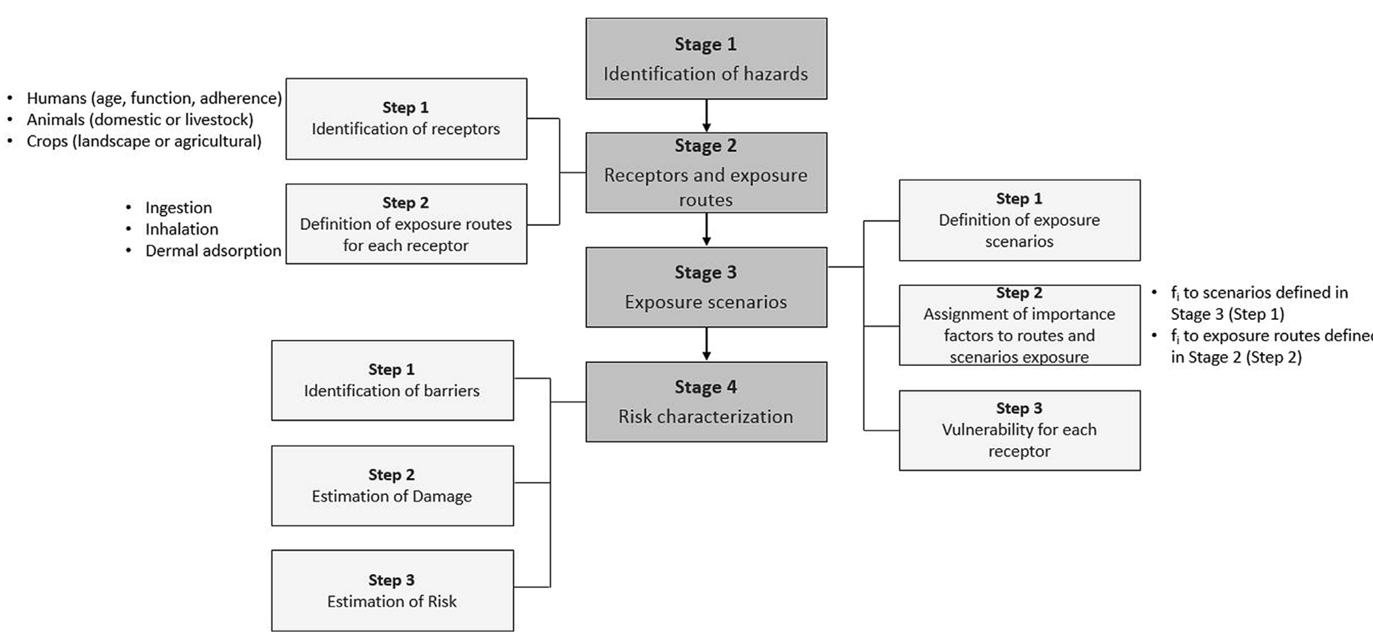

Fig. 1. Semiquantitative microbiological risk assessment methodology application flowchart.
Source: Adapted from Ref. [31].

Table 2
Importance factor applicable to each exposure scenario ($f_{i\ Scen}$).

exposure scenario		exposure routes		
Importance level	$f_{i\ Scen}$	route	$f_{i\ path}$	Importance level
Absolute (very high evidence of occurrence)	9	ingestion	9	Absolute
Demonstrated (high evidence of occurrence)	7	inhalation	9	Absolute in irrigation system by aspersion
Eventual (medium evidence of occurrence)	5	inhalation	5	Possible to other irrigation systems
Weak (low evidence of occurrence)	3	dermal adsorption	3	Weak due to no evidence of the occurrence
Low (with no evidence of occurrence)	1			

Source: Adapted from Ref. [34]. Source: Adapted from Ref. [4].

either directly or indirectly [4].

The highest risk exposure routes about RW are ingestion and inhalation, especially in situations where aerosols are produced, as in the case of sprinkler irrigation [33]. Regarding dermal adsorption, less evidence of infection is known, although a few cases have been identified in some studies, in Southeast Asia, of dermatitis, urticaria, and fungal infections of the fingers or nails in workers of untreated or just partially treated wastewater systems [11].

Stage 3 - Exposure scenarios

Step 1 - Definition of exposure scenarios

The definition of exposure scenarios is identified as one of the stages that demands higher attention due to the complexity of the analysis and the high level of uncertainty, especially in areas of unrestricted access with a high circulation of people [4]. The identification of exposure scenarios should be as exhaustive as possible, regardless of the probability of their occurrence [15].

Step 2 – Assignment of importance factors (f_i) to routes and scenarios exposure

For each exposure scenario, it is important to take into account the specific characteristics of the location and regional habits, as well as the operational criteria for applying the RW. For each type of receptor, the value assigned should vary depending on the understanding of greater or lesser exposure in each situation and the evidence described in the literature, related to the infection associated with the scenarios [4]. This step may involve a certain degree of uncertainty due to the absence of data demonstrating infections related to non-potable use [4,13].

Important factors (f_i), related to the probability of infection, are attributed to the different receptors, for each established scenario, with values ranging from 1 to 9 [34], due to an empirical qualitative approach to judgment. The use of this scale allows dealing with the complexity of the problem through its decomposition into clear and scalable factors, facilitating the establishment of comparative relationships for the construction of hierarchies and the definition of priorities [23].

To reduce uncertainties, the analysis should always consider the worst-case perspective; scenarios that present exposure routes with high importance of infection should initially be considered with the highest f_i [4]. For the attributions of f_i, justifications that are consistent and adequate for each situation must be pointed out. This justification, based on constructed hierarchies and defined priorities, provides the minimization of uncertainties, besides intensifying the risk assessment, ensuring a higher confidence on the process [4].

Table 2 shows the f_i related to exposure scenarios ($f_{i\ Scen}$) and exposure routes ($f_{i\ path}$). In the first case, for intermediate levels between two judgments, values of 2, 4, 6, or 8 can be assigned according to the need. In the second, the following variations are allowed [4]: for the route of ingestion, the value 9 is always assigned; for inhalation, 5 or 9; and for dermal adsorption, the value 3.

Step 3 – Vulnerability for each receptor

Vulnerability estimation is performed for each receptor by applying the equations presented in Table 3. Equation 1 characterizes a sum of the individual relationships between the exposure route and the number of scenarios for each situation. In Equation 2 the sum of the product of the f_i of the exposure route with the f_i of the exposure scenario is performed. In Equation 3, there is the calculation of the normalization factor, where the maximum importance factor is equal to 9 since it is considered the highest importance value. The use of normalization factors in hierarchical analytical method allows the reduction and adequacy of the work scale [35]. Through Equation 4, the vulnerability of each receptor is estimated.

Stage 4 - Risk Characterization

Step 1 – Barriers identification

To minimize the contact of receptors with RW, through exposure routes (direct and indirect) of ingestion, inhalation and dermal adsorption, the concept of physical or chemical barriers is introduced [27]. In this way, a barrier can be defined as the means of reducing and preventing risks associated with health and the environment, avoiding contact with RW and/or improving its quality [17].

Thus, water quality is not the only parameter to guarantee health protection in reuse projects. Other options, such as irrigation type and schedule, crop characteristics or harvesting options may limit contact between receptors and pathogenic organisms present in RW [4]. Some barriers, called accredited barriers, play a role of equivalence to the pathogenicity of RW, even if it still presents values higher than the maximum acceptable for the standard indicator of fecal contamination

Table 3
Equations adopted in the estimation of Damage.

Sum of factors of importance for exposure routes ($f_{i\ path}$)	Sum of the product ($f_{i\ path}$) x ($f_{i\ Scen}$)	Calculation of the normalization factor	Calculating the vulnerability of each receptor
$\sum(f_{i_{path}}\ x\ n_{Scen})$	$\sum(f_{i_{path}}\ x\ f_{i_{Scen}})$	$f_{i_{max}}\ x\ \sum(f_{i_{path}} x\ n_{Scen})$	$V_{Rec} = \frac{\sum(f_{i\ path}\ x\ f_{i\ Scen})}{f_{normal}}$
Equation 1	Equation 2	Equation 3	Equation 4

$f_{i\ path}$ = importance factors linked with the exposure route
n_{Scen} = number of scenarios considered by exposure route
$f_{i\ Scen}$ = importance factors linked with the exposure scenario
$f_{i\ max}$ = the higher value of importance (9)
f_{normal} = normalization factor

Source: Adapted from [4,36].

for the end-use [27].

When considering these options, lower quality RW can be used for different purposes in the context of multiple barriers [4]. In this case, the risk is minimized, as the probability of failure of multiple barriers is lower than the probability of failure of a single barrier [15]. The basic principle of multiple barriers is that the failure of one barrier can be compensated for by the effective operation of the remaining barriers in place, to make the project more reliable.

Table 4
Barriers and number of accredited barriers associated with the reduction of pathogenic organisms for irrigation of food crops with RW.

Barrier type	Application	Reduction of Pathogens (Log)	Number of accredited barriers
Drip irrigation	Drip irrigation growing close to the ground (25 cm), growing away from the ground (50 cm) or underground[1]	2–6	1–3
Spray and sprinkler irrigation	Sprinkler and micro-sprinkler irrigation of growing crops, close to the ground (25 cm) or fruit trees distant from the ground (50 cm)[1]	2–4	1–2
Additional disinfection in the field	Disinfection that guarantees a residual concentration less than <1 mg L^{-1} (low level) or that guarantees a residual concentration less than >1 mg L^{-1} (high level)[2]	2–4	1–2
Pathogen die-off	Interruption of irrigation before harvest	0.5 to 2 a day	1–2
Produce washing before selling to the customers	Washing of vegetable, vegetable and fruit crops with drinking water	1	1
Produce disinfection before selling to the customers	Washing of vegetable, vegetable and fruit crops with disinfectant solution and rinsing with drinking water	2	1
Produce peeling	Peeling of fruits and roots	2	1
Produce cooking	Immersion in boiling water or at high temperatures until the product is cooked	6–7	3
Access control	Restriction of entry to the irrigated site for 1 day or more after irrigation or 5 days or more after irrigation[3]	0.5 to 2 - 2 to 4	1–2
Sun drying of fodder crops	Forage or other crops that are exposed to sun drying and harvested before consumption	2 to 4	2

Note: 1 – Crops growing closer to the ground have lower values of pathogen reduction and equivalent barriers; the opposite is true. 2 – Low-level disinfection is associated with lower values of pathogen reduction from equivalent barriers; the opposite is true. 3 – Includes workers and animals; the more days of access restriction, the higher the reduction of pathogens and the number of equivalent barriers can be considered.
Source: Adapted from Refs. [27,33,37].

Table 4 shows the types of accredited barriers, their corresponding reductions in logarithmic units of pathogens and the associated number of accredited barriers.

Step 2 – Estimation of Damage

At this point, the damage severity *versus* the failure probability of each barrier associated with the project, defined in Step 1, is analyzed. The generalized application model for this type of analysis, called a prioritization matrix, whose cells, grouped in a certain number of classes, represent values, relating the probability (frequency) of the occurrence of the events with the consequence (severity) of the respective impacts [38]. Similarly, the damage matrix was adapted [36] and presented in Fig. 2, from the ISO 20462:2018 [26].

Damage estimation is performed by applying the equations presented in Table 5. Firstly, the sum of partial damages (Equation 5), referring to each barrier associated with the project, must be performed. Subsequently, we proceed with the calculation of the normalization factor (Equation 6). And, finally, the damage is calculated (Equation 7)) from the two previous ones.

Step 3 - Risk characterization

In this step, the estimation of risk for each receptor is calculated according to Equation 8. The Global Risk (R_{Global}) is an arithmetic mean between the individual risks associated with each receptor, as shown in Equation 9. Both equations are presented in Table 6.

Table 5
Equations adopted in the estimation of Damage.

Sum of partial damages (d_i)	Calculation of the normalization factor	Damage calculation
$\sum (d_i * n_i)$	$f_{normal} = (f_{i_{max}} \ x \ n_t)$	$Damage = \frac{\sum (d_i * n_i)}{f_{normal}}$
Equation 5	Equation 6	Equation 7

d_i = partial damage x number of barriers
n_i = number of barriers according with Table 4*
n_t = total number of barriers in place
$f_{i\ max}$ = the higher value of importance (9)
f_{normal} = normalization factor

Source: Adapted from Refs. [4,36].
Note: * it can be equal to one (1) when the mean in situ is not listed as an equivalent barrier.

Severity of damage ↓	Likelihood of occurrence				
	Rare	Unlikely	Possible	Likely	Almost certain
Insignificant	1	1	2	2	3
Minor	1	2	4	4	5
Moderate	2	4	4	6	7
Major	2	4	6	8	9
Catastrophic	3	5	7	9	9

Fig. 2. Partial Damage Determination Matrix for each barrier.
Source: Adapted from Ref. [36].

Table 6
Equations adopted in the estimation of risk.

Risk for each receptor	Global risk
$R_{receptor} = Hazard^{*}\ Damage\ ^{*}\ V_{receptor}$ Equation 8 $R_{receptor}$ = Risk for each respective receptor category $V_{receptor}$ = Vulnerability of receptors	$R_{Global} = \frac{\sum R_{Receptor}}{N_{Receptors}}$ Equation 9

Source: Adapted from Refs. [4,36].

Table 7
Global risk level in quantitative and qualitative scale.

Global Risk Level	
Quantitative Scale	Qualitative Scale
$0 <$ Global Risk <3	Despicable risk
$3 \leq$ Global Risk <7	Acceptable risk
$7 \leq$ Global Risk <9	Unacceptable risk

Source: [36].

The Hazard was previously established in Table 1 (Stage 1), the Damage was calculated using Equation 5 (Stage 4 – Step 2), and the Vulnerability of each receptor using Equation 4 (Stage 3 – Step 3).

The Global Risk presents values that vary between a value above zero to nine, depending on the characteristics involved in each project (scenarios, assigned importance factors, barriers, etc.). Prioritization is achieved by converting the R_{Global} into a three-level qualitative scale, as shown in Table 7 and adopted by other authors [4].

In case of an unacceptable Global Risk, it is necessary to repeat the entire process, to reassess the stages, with new actions such as changing the level of the hazard (by increasing the effluent treatment level) and/or application of new barriers to achieving an acceptable or despicable risk. If is not possible to obtain a minimal acceptable level, the project implementation is considered unfeasible [4].

Once the appropriate risk level for a specific project is reached, the previously established hazard (in this case a certain concentration value of *E. coli*) used in the risk characterization can be validated as the quality standard be applied to the RW [4].

4. Data adopted for the study

The SqMRA was applied to rice farming, considering that rice production occupies 25% of the total irrigated area in Brazil (1298 Mha) and demands 40% of the entire volume of water abstracted in the national territory [39]. It is also noteworthy that other low and middle-income countries such as China, India, Indonesia, and the Philippines are also major rice producers, contributing to the consumption of water for irrigation worldwide [40].

The management of this crop by flooding requires more water per unit area than in other irrigation systems [39]. In Brazil, the Federal States that produce rice in greater quantities are Rio Grande do Sul, Santa Catarina, and Tocantins, responsible for, respectively, 73%, 8%, and 11% of national production [39].

In general, the rice crop is produced from irrigation by furrows or flooding. Although the levels of exposure of receptors to hazard may differ among the irrigation methods, the similar approach was adopted in the application of the methodology, as both take into account the flooding of the area.

It is also worth noting that the SqMRA methodology must be applied in each project, individually, considering that the exposure levels may vary depending on the local characteristics and operational conditions of irrigation, harvesting, and storage. Thus, this generalized approach, adopted in the present study, is configured only for scientific studies, since the action can lead to a high degree of uncertainty.

Table 8
Data adopted in the paper carried out.

Stage/Step	Adopted data	observation
Hazard (**Stage 1**)	7 and 9[1]	Secondary disinfected effluent
Identification of Receptors (**Stage 2**/Step 1)	farmer consumer neighborhood	Grater hazard exposure Less hazard exposure Medium hazard exposure
Definition of exposure routes (**Stage 2**/Step 2)	Ingestion, Inhalation[2], and Dermal adsorption	All routes were adopted for all receptors
Definition of exposure scenarios (**Stage 3**/Step 1)	1. Inadvertent ingestion during irrigation 2. Intentional ingestion from the irrigation system 3. Crop ingestion 4. Soil ingestion 5. Dermal adsorption by contact with the irrigated crop, leaves, and roots 6. Dermal adsorption by contact with irrigation system 7. Dermal adsorption by contact with other surfaces	–
Assignment of f_i to routes and scenarios exposure (**Stage 3**/Step 2)	Adopted data according to values established in Table 2	
Vulnerability receptors (**Stage 3**/Step 3)	Calculated based on equations 1 to 4	
Identification and number of accredited barriers (**Stage 4**/Step 1)	Produce cooking (3 barriers) and peeling (1 barrier), as shown in Table 4[3]	
Estimation of damage (**Stage 4**/Step 2)	Calculated based on equations 5 to 7	
Estimation of risk (**Stage 4**/ Step 3)	The risk for each receptor was estimated based on Equation 8; The global risk was estimated based on Equation 9	

The data adopted for the application of the SqMRA methodology in rice cultivation in Brazil are presented in Table 8, according to the model previously described its stages and steps.

Notes: 1 The SqMRA was applied in two scenarios, in which the first considers the effluent to be disinfected (Hazard 7), and the second considers the reality of sewage treatment conditions in Brazil (Hazard 9). 2 Inhalation is attributed to aerosols, generally produced in a sprinkler irrigation system. Although intense winds can also produce these types of microdroplets in flooded systems, inhalation was not scenarioized in the present paper, for simplification purposes. However, in cases of application of the methodology in places with the possibility of high winds, it should be adopted for farmers and neighborhoods. 3 The barriers adopted, defined as actions after the harvest, relate only to consumers since the farmer harvests the rice in natura.

5. Results and discussion

Given the perspectives and the Brazilian reality, in terms of the quality of treated wastewater, the SqRMA was applied in two different scenarios. In the first one, we chose to adopt Hazard equal to 7, due to the prerogative that a disinfected effluent guarantees more safety to the practice. However, the reality about wastewater treatment in Brazil shows that most of the effluent is treated at a secondary level, without disinfection [41]. Thus, the second scenario relies on the application of the methodology, considering Hazard equal to 9.

5.1. Scenario 1 – Hazard equal to 7

Table 9 presents the main results of the application of the SqMRA

Table 9
SqMRA methodology application for rice farming - Hazard 7 (10^3 CFU/100 mL < *E. coli* <10^4 CFU/100 mL).

Item	Value
Hazard	7
Vulnerability for each receptor	Farmer: 0.87 Neighborhood: 0.50 Consumer: 0.43
Damage	Farmer and Neighborhood: 1.00 Consumer: 0.39
Risk receptors	Farmer: 6.09 Neighborhood: 3.50 Consumer: 1.17
Global Risk	3.58 (Acceptable risk) [1] 4.79 (Acceptable risk) [2]

Observation.
[1] Global risk considering the 3 receptors adopted in the study.
[2] Global risks considering only the 2 main receptors (farmer and neighborhood) since the possibility of several receptors involved after harvest could change the value end of the global risk.

Table 10
SqMRA methodology Reiteration for rice farming - Hazard 9 (*E. coli* >10^4 CFU/100 mL).

Item	Value
Hazard	9
Vulnerability for each receptor	Farmer: 0.96 Neighborhood: 0.53 Consumer: 0.43
Damage	Farmer and Neighborhood: 1.00 Consumer: 0.39
Risk Receptors	Farmer: 8.60 Neighborhood: 4.75 Consumer: 1.50
Global Risk	4.95 (Acceptable risk) [1] 6.67 (Acceptable risk) [2]

Notes.
[1] Global risk considering the 3 receptors adopted in the study.
[2] Global risks considering only the 2 main receptors involved (farmer and neighborhood) since the possibility of several receptors involved after harvest could change the value end of the overall risk.

methodology, considering all stages and steps, in addition to the data presented in Table 5. The complete spreadsheet is available as Supplementary Material. This spreadsheet was developed to facilitate the use of the methodology in other applications and regions, but care must be taken, each case is a case and this methodology represents a real portrait of this case. However, it is important to pay attention to the indiscriminate use of the available spreadsheet, since the user must always apply it with great care, considering the real local characteristics of each irrigation water reuse project.

The results presented in Table 6 demonstrate the feasibility of applying water reuse for rice cultivation in Brazil, about aspects of epidemiological risk. As expected, and in accordance with previous observations from other authors, there is an estimate of a higher risk of microbiological contamination for the farmer than for other receptors [11]. Despite the high possibility of contact between the farmer and the RW, the estimated global risk is still in the acceptable level.

In the case of the neighborhood, the risk is greatly reduced because the irrigation method is different from sprinkling and presents a lower possibility of producing microdroplets that could be inhaled, as already mentioned. But still, it is in the acceptable category.

For the consumer, low risk was also expected, due to the processing (with peeling) and cooking of the rice before consumption. However, it should be noted that these risk values may vary depending on the specifics of the configuration of each reuse system, since there may be situations that enhance (or minimize) certain types of contact. For this reason, to calculate the global risk, two procedures were adopted: i) considering the three receptors adopted in the study; and ii) considering only the 2 main receptors involved (farmer and neighborhood) since the possibility of several receptors, with multiple handling criteria, involved after harvest could change the final value of the global risk. Thus, should be emphasized that for the application of the methodology in a real project, all possible receptors, from irrigation to the final consumer, (professionals related to peeling, processing, handling, packaging, and marketing) must be taken into account in conjunction with the food safety procedures needs according to respective regulations, when in place.

It should also be noted that when considering all workers involved in the production process of rice irrigated with RW, is possible to minimize risks by introducing capacity building and systematic use of equipment and safety habits.

5.2. Scenario 2 – Hazard equal to 9

The States of Rio Grande do Sul and Santa Catarina, identified in the present study as responsible for 80% of the Brazilian production of rice, are comprised, almost entirely, in the River Basin (RB) of Uruguai and

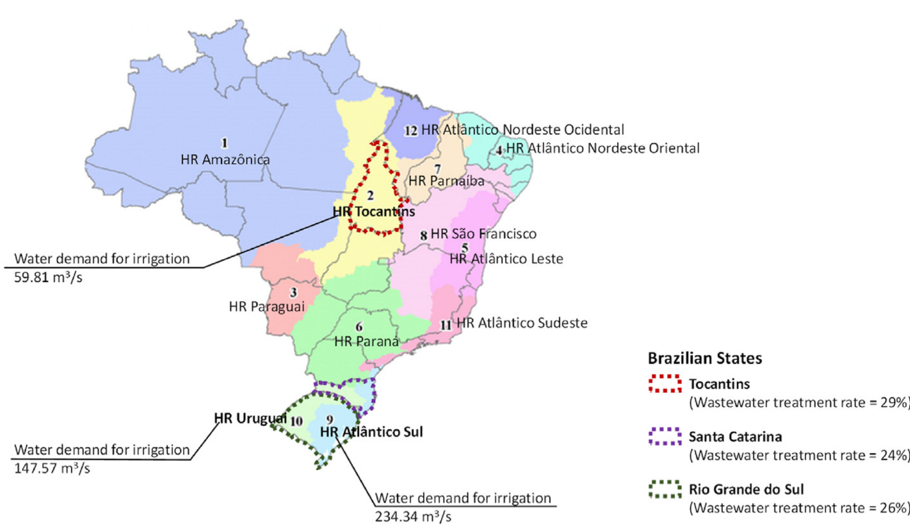

Fig. 3. Schematic map with Brazilian states and River Basin.

Atlântico Sul and require, in general, approximately 382 m^3/s of water for irrigation [41]. However, the two RBs present a service rate with domestic wastewater treatment at 30%. Similarly, the RB Tocantins-Araguaia, which involves practically the entire State of Tocantins, has a demand of approximately 60 m^3/s for irrigation but also has a low rate of wastewater treatment (less than 30%) [41,42].

The relationship between the Brazilian states highlighted in the study (Rio Grande do Sul, Santa Catarina, and Tocantins) and the River Basin Districts also highlighted (Uruguai, Atlântico Sul, and Tocantins-Araguaia) can be seen in the schematic map in Fig. 3.

The scenario of high demand for water for irrigation and low production of treated effluent shows the difficulty of structuring water reuse, although the water demand for rice crop production in these regions is high and the risk of contamination of human beings is moderate, as demonstrated by the application of methodology.

The RW was defined in two categories to assess the potential for reuse in Brazilian RB, as a function of water quality: Category 1 - RW from wastewater treatment plants (WWTP) that have an organic matter removal higher than 80%; and Category 2 – RW from wastewater treatment plants which, in addition to having an organic matter removal of more than 80%, have disinfection [41].

In this sense, considering the three RB (Uruguai, Atlântico Sul, and Tocantins-Araguaia), the potential for supply of reclaimed water in Category 1 (secondary effluent) is 2.53 m^3/s and in Categories 2 (disinfected secondary effluent), of 1.12 m^3/s [41].

Since Category 2 (disinfected secondary effluent), equivalent to Hazard equal to 7 (*E. coli* $\leq 10^{4}$ CFU/100 mL), represents the lowest available water potential for reuse, it was decided to repeat the process of applying the SqRMA methodology, considering hazard equal *to* 9, which represents Category 1 (secondary effluent). The results for this reiteration can be seen in Table 10.

This reiteration in the application of the methodology presents a very relevant result, in which when offering water corresponding to a secondary effluent (without disinfection), even the estimation of risk for the farmer changing from acceptable to unacceptable, the overall risk remains in the acceptable level, although quite close to the limit of the maximum value. Furthermore, the risk for the farmer can be reduced with equivalent barriers, such as rubber gloves and boots, consequently reducing overall risk.

In this sense, it can be highlighted that Uruguai, Atlântico Sul, and Tocantins-Araguaia River Basin have a high potential for the application of water reuse in the irrigation of rice crops by furrows or by flooding, with an acceptable risk of microbiological contamination of human beings involved in the practice [41]. However, it should be noted that the study deals with a generalized scientific approach and, in the case of a real application, all those involved must be carefully evaluated and the scenarios must be exhaustively studied, also considering the use of additional risk minimization means, such as equipment and safety habits among the workers in each sector, to provide more safety for the practice.

It is also noteworthy that in Asia, the largest producer of irrigated rice in the world, the crop represents 40–46% of the irrigated area among all other crops [43]. The water reuse in China has become the main objective of WWTP in the new era of wastewater treatment in the country [44].

In this sense, a good way to solve the problem of water scarcity is to increase water productivity, corroborates the results of the present research [45]. In the case of irrigated rice, it is important to determine the economic and energy implications when considering water reuse options to improve water productivity at the system level [40].

6. Conclusions

The present research presented the application of the semi-quantitative methodology of microbiological risk assessment for irrigation of rice crop in Brazil, with reclaimed water. This irrigated crop is the most demanding in terms of water for irrigation, not only in the Brazilian territory but also in other rice-producing countries.

Given the study presented, it is possible to conclude that the water reuse can be applied in rice farming, considering irrigation methods such as furrows and flooding, with an acceptable global risk of contamination of the receptors involved (farmer, consumer, and neighborhood), which can contribute to a considerable reduction of freshwater water consumption in the world.

Both for the secondary effluent and the disinfected secondary effluent, it was possible to reach an acceptable global risk (3.58 and 4.95, respectively), although the relevance of disinfection to minimize the risk in any water reuse application is highlighted. Furthermore, should be emphasized that is essential to adopt safety equipment and habits for all workers involved, in addition to capacity building, since reclaimed water is product that may present hazards to humans.

Should always be noted that the most appropriate application of this risk assessment methodology must take into account the characteristics and specificities of each project, with exhaustive scenarios, and all potential receptors involved in the project. In this case, it is possible to include, in addition to those adopted in the present study, all workers involved in rice processing, before arrival at the final consumer's table. A tool was made available in the supplementary material that allows the application of the methodology for different scenarios in a user-friendly interface.

Finally, both in Brazil and in regions with lower socioeconomic development, is needed to plan for advances in wastewater treatment service rates, considering the technical, economic, and logistical possibility of providing irrigation for the most appropriate crops, with reclaimed water.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watcyc.2022.04.003.

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