Reclaimed wastewater reuse impacts: from literature data gaps to integrated risk modelling

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Abstract
The complexity and the inherent interconnection of the reclaimed wastewater reuse (RWW) system requires the proper quantification of its advantages and drawbacks. In this context, water utilities and decision makers would benefit from a comprehensive risk-based framework of models aimed at the assessment of its associated impacts.
In this work, a critical literature review on the models available for the assessment of RWW reuse impacts is performed to highlight which gaps need to be filled and indicate the future research directions. A simplified approach for evaluating and integrating different type of risks was proposed to address the prioritization of critical endpoints and contaminants within regulations.

Keywords (maximum 6 in alphabetical order)
Antibiotic resistant bacteria; Impacts modelling; Literature Gaps; ONE-health approach; Risk assessment; Reclaimed wastewater reuse

INTRODUCTION

Given the interest on water as a renewable resource, the reuse of reclaimed wastewater (RWW) has been recognized as a fundamental alternative source for irrigation and is increasingly applied (de Santiago-Martín et al., 2020). Based on where the wastewater treatment plant (WWTP) effluent is discharged, the reuse can be (i) indirect, when the effluent is discharged into the surface water and irrigation water is derived downstream the point of discharge, or (ii) direct, when the effluent is directly used for crops irrigation, through a dedicated distribution network.
In both cases, it emerges that RWW reuse practices inherently connect water in numerous environmental compartments (e.g. surface water, groundwater, soil), leading to a series of impacts, either positive or negative, which need to be evaluated. As for positive impacts, besides alleviating the water stress, the reuse of RWW provides a reliable source of nutrients. On the other hand, the cross-contamination of the different environmental matrices is favored, due to the unavoidable presence of contaminants in the effluent, even after extensive treatment. RWW might be loaded with contaminants such as organic matter, suspended solids, salts, heavy metals, contaminants of emerging concern (CECs), disinfection by-products (DBPs), pathogenic microorganisms and antibiotic resistant bacteria (ARB). Besides, all these contaminants could have different effects depending on the compartment in which they occur. In fact, they can accumulate in soil, causing salinization and changes to the soils properties. From soil, contaminants can either be uptaken and accumulated by plants, negatively affecting their growth, or contaminate groundwater, where aquifers are present. Finally, the consumption of crops contaminated with, above all, pathogens, heavy metals and CECs implies a not negligible risk for human health (Delli Compagni et al., 2020). Given this system complexity, it emerges the need for a framework of models that allows a comprehensive assessment of the RWW reuse impacts, capable of quantitatively accounting and comparing all the related advantages and drawbacks, to support decision-makers and water utilities in planning, design and prioritizing the different alternatives to determine the optimum solution that minimize risks and costs.
Regarding the regulation, RWW quality aimed at direct reuse for irrigation is regulated in the European Union, and the common practice to establish minimum quality requirements is shifting towards preventive risk analysis aimed at minimizing risks (EU Commission, 2020). In this context, it becomes fundamental to define an integrated risk assessment approach, which considers all the impacts throughout all the steps of the RWW reuse chain in terms of quantitative risk for both human health and environment.
In this work, an overview of the models available for the evaluation of RWW reuse impacts is presented and a simplified approach to estimate and compare different risk assessment procedures applied to RWW reuse case studies is proposed.

MATERIALS AND METHODS

A comprehensive literature review was conducted in the field of municipal RWW reuse in agriculture, focusing on the related impacts and the models available to evaluate them. Scopus was used as database for the period 2017–2022 (documents published in 2023 were not included considering only complete annual periods). A sample of 252 articles was selected for a detailed analysis.

The RWW reuse framework was conceptualised based on four characteristics: (i) the type of RWW reuse, (ii) the analysed compartments, (iii) the models applied to evaluate the impacts, and (iv) the targeted variables in the models. For each characteristic, several categories were identified, and one or more of them were assigned to every article. Studies without at least one category from each characteristic were discarded. Ultimately, 139 articles were selected, to review the current state of the art on the available models for the evaluation of RWW reuse impacts, highlighting the gaps to be filled.

Finally, a simplified approach for comparing and prioritizing the available risk assessment procedures is proposed, focusing here on human health risk assessment due to CECs presence in crops irrigated through indirect RWW reuse. In detail, CECs concentration data in the WWTP effluent, in the receiving water body used for crops irrigation and in the irrigated crops were collected. Then, environmental risk quotient (RQ_E) and antibiotic resistance risk (RQ_R) were calculated comparing the Measured Environmental Concentrations (MEC) in rivers with the Predicted No-Effect Concentration, respectively for environmental ($PNEC_E$) and antibiotic resistance ($PNEC_R$), according to the following equations (Zhang et al., 2019):

$$RQ_E = MEC/PNEC_E \qquad RQ_R = MEC/PNEC_R$$

Details on the only 4 articles available for the comparison of human health, environmental and antimicrobial resistance risk in indirect RWW reuse practices are reported in Table 1.

Table 1. Summary of the studies used for the comparison of human health, environmental and antimicrobial risk: number of analysed CECs and antibiotics, concentration in WWTP, river and crops, indicated as average and range in brackets.

Study	# of CECs	# of antibiotics	WWTP effluent concentration [μg/L]	River concentration [μg/L]	Crop concentration [μg/g]
De Santiago-Martin et al., 2020	57	10	0.21 (<LOQ-1.5)	0.34 (<LOQ-6.5)	0.04 (<LOQ-0.25)
Delli Compagni et al., 2020	13	2	Not available	0.21 (<LOQ-0.8)	0.009 (<LOQ-0.08)
Liu et al., 2020	11	3	Not available	0.007 (<LOQ-0.025)	0.005 (<LOQ-0.03)
Meffe et al., 2021	25	3	Not available	0.25 (<LOQ-12.9)	0.001 (<LOQ-0.01)

RESULTS AND DISCUSSION

The selected studies were classified based on their characteristics and categories as shown in Figure 1, differentiated per type of RWW reuse, being (i) direct and (ii) indirect. The compartments correspond to the boundaries within which the impact is modelled and they were differentiated in (i) WWTP, (ii) environment (intended as the groundwater or surface water receiving the WWTP effluent), (iii) irrigation system, (iv) soil, (v) crops and (vi) humans. The models were differentiated between quantity- and quality-based models. Quantity-based models evaluate the impacts in terms of volumes of water available for irrigation; model as (i) water mass balances, (ii) Life Cycle Assessment (LCA), (iii) economic, (iv) energy, (v) sustainability and (vi) social assessments belong to this category. While quality-based models evaluate the impacts in terms of RWW quality, thus, concentrations or risks, and are usually specific for single compartments; here there are models assessing (vii) treatment removal, (viii) crop uptake, (ix) environmental risk and the (x) human health risk. Finally, the variables targeted by the applied models were divided again in quantity-based variables, affecting the volume of water, namely (i) water itself, and quality-based variables, affecting the water quality, such as (ii) nutrients, (iii) conventional contaminants (i.e., organic matter and suspended solids), (iv) salts, (v) heavy metals, (vi) CECs, (vii) DBPs, (viii) microbials and ARBs (ix).

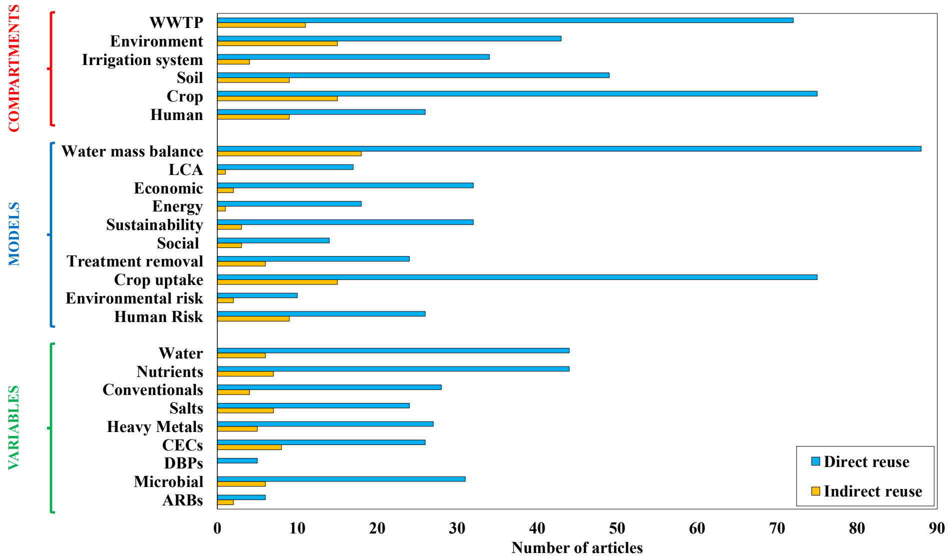

Figure 1. Number of articles mentioning the analyzed categories, differentiated per direct or indirect reuse.

Analysing Figure 1, it emerges that, on average for all the considered categories, the 85% of the studies deals with direct reuse, being the only type of reuse which is regulated so far, and being a process easier to replicate even in pilot-scale conditions, compared to indirect RWW reuse. However, there are a lot of RWW streams that are used *de facto* for indirect irrigation. Thus, studies in this field are a gap which need to be filled. Moreover, among articles addressing indirect RWW reuse practice, there are no studies considering how the dilution factor between the WWTP effluent and the receiving surface water affects the environmental impact, although the growing concern on the consequneces on the natural aquatic environment of climate change stress the importance of this evaluation.

(a)

	WWTP	Environment	Irrigation technique	Soil	Crop	Human
WWTP	81					
Environment	44	58				
Irrigation technique	19	9	37			
Soil	17	7	16	55		
Crop	45	28	30	45	89	
Human	20	16	6	13	20	34
Water mass balance	59	54	27	54	71	25
LCA	18	16	4	0	6	12
Economic	31	27	3	0	16	7
Energy	18	15	4	0	6	11
Sustainability	31	32	6	2	16	11
Social	15	11	3	0	7	1
Treatment removal	30	9	6	8	17	8
Crop uptake	23	11	22	43	66	17
Environmental risk	9	10	3	1	4	9
Human Risk	20	18	6	15	24	34
Water	43	39	10	2	20	10
Nutrients	28	22	21	18	39	13
Conventionals	24	13	12	12	18	7
Salts	16	10	12	19	27	6
Heavy Metals	16	12	8	17	24	12
CECs	15	11	7	21	26	15
DBPs	3	0	3	4	5	1
Microbial	22	9	13	16	26	14
ARBs	4	2	4	6	4	0

(b)

	Water mass balance	LCA	Economic	Energy	Sustainabilit y	Social	Treatment removal	Crop uptake	Environmental risk	Human Risk
Water mass balance	107									
LCA	14	18								
Economic	27	13	34							
Energy	15	14	13	18						
Sustainability	33	16	24	15	35					
Social	9	4	10	3	9	16				
Treatment removal	17	6	7	5	5	0	30			
Crop uptake	51	1	2	0	1	1	17	66		
Environmental risk	10	9	6	9	9	0	3	0	10	
Human Risk	26	12	7	11	11	1	8	18	9	34
Water	42	14	28	16	30	12	5	1	9	10
Nutrients	40	12	13	11	14	3	9	29	9	13
Conventionals	24	9	8	7	9	3	11	14	5	7
Salts	31	4	4	4	4	1	4	20	3	6
Heavy Metals	25	7	5	6	7	2	5	21	6	12
CECs	27	7	5	7	8	0	7	21	7	16
DBPs	4	0	0	0	0	0	3	5	0	1
Microbial	26	3	4	4	4	0	16	24	2	14
ARBs	7	0	0	0	0	0	4	4	0	0

(c)

	Water	Nutrients	Conventionals	Salts	Heavy Metals	Microbial	ARBs	CECs	DBPs
Water	47								
Nutrients	16	50							
Conventionals	11	25	32						
Salts	11	27	16	34					
Heavy Metals	7	22	16	14	32				
Microbial	4	15	13	9	10	37			
ARBs	0	0	0	0	1	1	8		
CECs	7	9	5	5	10	3	3	33	
DBPs	0	4	3	3	2	3	0	1	5

Figure 2. Heatmap reporting the paired correlations between the considered categories, differentiated per (a) compartments, (b) models and (c) variables.

Three heatmaps are reported in Figure 2 visualluy showing the paired correlations between all the considered categories, differentiated per compartments, models and variables. This visualization supports in analysing how the different characteristics (i.e., compartments, models and variables) are combined together to model the RWW reuse practice, and also permits to assess which fields are more consolidated and which ones need further research.

In particular, it is pointed out a lack of model application on ARBs, which are microrganisms of emerging concern inherently related to WWTP discharges. Regarding risk assessment models, LCA assesses human health and environmental risks through generalized standard values; if LCA studies

are not considered, it emerges that only a single study applied an environmental risk assessment to a RWW reuse practice, while no studies consider both environmental and human health risk together.
In this context, given the importance of risk-based approaches to assess the impacts of RWW reuse practices, as stressed by the revision of the WW reuse Directive, the absence of studies simultaneously evaluating the environmental, antibiotic resistance and human health risks when indirect RWW reuse is applied is an important literature gap.
The analysis performed on studies dealing with human health risk assessment highlighted that environmental and antibiotic resistance risks have significant contribution to the overall risk, being higher than the human health risk for some of the CECs. This evidence stresses the importance of an holistic risk assessment, with a ONE-Health approach, to evaluate the most critical endpoint for each CEC, useful to prioritize their regulation.
To conclude, this work gave an overview of the models currently available for the evaluation of the impacts of RWW reuse practices, highlighting which are the associated literature gaps, and it might be useful in indicating future research directions, as well as to suggest which impact need to be prioritized when a comprehensive assessment is performed.

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