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Review

Societal values, tensions and uncertainties in resource recovery from wastewaters

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ABSTRACT

The recovery of resources, including water reuse, has been presented as a solution to overcome scarcity, and improve the economic and environmental performance of water provision and treatment. However, its implementation faces non-technical challenges, including the need to collaborate with new stakeholders and face societal acceptance issues. Looking at the prominence of the circular economy in current policy developments and the challenges to resource recovery, exploring these issues is urgently needed. In this work, we reviewed a broad range of literature to identify societal values relevant to the recovery of water and other resources from wastewaters, particularly urban and industrial wastewater and desalination brines. We discuss tensions and uncertainties around these values, such as the tension between socio-economic expectations of resource recovery and potential long-term sustainability impacts, as well as uncertainties regarding safety and regulations. For addressing these tensions and uncertainties, we suggest aligning common methods in engineering and the natural sciences with Responsible Innovation approaches, such as Value Sensitive Design and Safe-by-Design. To complement Responsible Innovation, social learning with a Sustainability Transitions or Adaptive Governance perspective is suggested.

1. Introduction

Water scarcity is an important issue to face given the prominent role of water in society, and even more now with the additional challenge of climate change (Tzanakakis et al., 2020). Water recovery and reuse has been recognized as a means to face water scarcity, which is manifested in the Sustainable Development Goal 6 (SDG 6) of the United Nations promoting clean water and sanitation for all (WHO, 2017). Recovering resources from water streams has also been discussed as a way to face scarcity or improve the supply of resources like nutrients and energy (Kehrein et al., 2020c). Ensuring the availability of these resources is important, as they are necessary for the systems that support human basic needs, such as agriculture and health. An example is the list of critical raw materials of the European Union (EU), for which resource recovery and reuse is being promoted (Gislev and Milan Groho, 2018). Even more, the recovery of water and other resources is often referred to as part of a circular economy, intended to secure a supply of valuable materials while reducing waste and its environmental impact (e.g. (Belhout et al., 2018; Morseletto et al., 2022)). Considering this interest in circular approaches for wastewaters, as well as the large availability of wastewaters in urban areas and increasing seawater desalination rates (Goh et al., 2021; Puyol et al., 2017)), in this work we focus on the recovery of water and other resources from wastewaters, particularly urban and industrial wastewater and desalination brines (Fig. 1).

Despite the diversity of technologies for resource recovery, their implementation faces non-technical challenges that emphasize the need to consider their broader socio-technical context (Ampe et al., 2021; Rao and Otoo, 2017). Prominently, competitiveness and the need to develop specific markets for recovered resources, as well as suitable policy and legal frameworks, have been identified as bottleneck for the implementation of resource recovery (Kehrein et al., 2020a). Societal acceptance and public perceptions of risk are also important to consider (Paneque et al., 2018), and especially when talking about changing water systems with important roles in society, like sanitation and water provision. Even more, the definition of waste itself is an issue in the establishment of resource recovery, as recovered products need to reach an end-of-waste status for being marketable. In Europe the end-of-waste criteria was developed to facilitate and regulate this process, but it

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remains limited to a few resources only (Ragossnig and Schneider, 2019). As result, the end-of-waste status and the lack of regulations remains a barrier to the implementation of resource recovery (Kehrein et al., 2020a). All of these challenges indicate a strong need to engage and collaborate with stakeholders who can support the alignment of resource recovery innovations with their socio-technical context, including policies, markets, and responding to societal values and concerns, such as safety and sustainability. Even more, the participation of stakeholders can be a way of democratizing the decision-making and implementation of resource recovery, especially relevant when dealing with public services and resources.

Responsible Innovation has emerged as a research field and approach that seeks to align innovations with societal values since the early stages of development of an innovation (Asveld and van Dam-Mieras, 2017). For this, the engagement of stakeholders becomes a central part of the innovation process, allowing to anticipate and respond to emerging ethical and societal concerns. That is, in Responsible Innovation stakeholders are to be included in the innovation process, from agenda-setting to design, implementation and evaluation (Marques Postal et al., 2020). Considering the challenges to the implementation of resource recovery technologies mentioned above, a Responsible Innovation perspective could not only support the development and implementation of resource recovery from wastewaters, but also do so with and for society.

Therefore, here we provide an overall analysis of societal implications relevant to resource recovery from wastewaters, and propose approaches for addressing them in its development. Although there is previous work on the societal implications of sanitation (e.g. (Stefanovic and Adeel, 2021; Vliet et al., 2011)), water reuse and desalination in specific contexts (e.g. (Fielding et al., 2015; Voulvoulis, 2018; Zetland, 2017)), to the authors' knowledge there is no dedicated work looking at overall societal implications of resource recovery from wastewaters. Considering the non-technical challenges mentioned above, this knowledge is urgently needed. Therefore, in this work we provide a broad and interpreted understanding of societal values, tensions, and uncertainties relevant for the recovery of resources from wastewater and desalination brines. For that, we first identify societal values from a broad range of literature, and we then identified potential tensions and uncertainties emerging from this analysis. Then, taking Responsible Innovation as starting point, we propose paths forwards to address these issues during the development of resource recovery technologies. Overall, with this work we hope to contribute to the development of sustainable and societally acceptable resource recovery innovations. To situate the reader in our analysis, in Table 1 we present the main resource or product types to recover and some examples discussed in the reviewed literature.

2. Material and methods

In this work, we provide an interpreted understanding of societal values, tensions, and uncertainties relevant for the recovery of resources from wastewaters, including desalination brines. Considering this broad scope, with no specific location or target application, we based our analysis on a broad review of the literature that crossed disciplines and geographies. The methods for the literature search and data analysis are described in the following subsections.

2.1. Literature search

The review of the literature was focused on the recovery of resources from wastewaters, including urban and industrial contexts, and seawater desalination. For that, we conducted an initial literature search based on specified search terms in Google Scholar. The search started with the terms "wastewater", "resource recovery" and "zero liquid discharge" (ZLD), which is an approach to minimize waste streams while recovering water and other resources (Yaqub and Lee, 2019). The search also included "wastewater treatment" and "seawater desalination" as sources of wastewaters with potential for resource recovery, and as more established foci of study with ample real-life applications from which societal values could be identified. That is, if there are societal concerns related to seawater desalination (without resource recovery), these would most likely be relevant for the recovery of resources from desalination brines too. The search was extended to specific articles or topics identified in the reviewed literature after an initial analysis, as described in the next section. To include different perspectives and avoid a discipline bias, we searched for publications from diverse fields of knowledge, instead of trying to make an in depth review within a single field. That is, we do not present a review of the economic performance of technologies nor of water as a human right, but we do bring these concerns into discussion. Consequently, the reviewed documents included technical and sustainability analyses, as well as historical, governance and socio-cultural analyses around wastewaters, as mentioned above. In addition, the search process led to non-academic publications, such as policy, research and workshop reports, which are also included in the review. Given the large quantity of search results (>150 articles), review articles were prioritized. The search stopped when no new societal values and concerns were identified.

2.2. Analysis

A qualitative analysis of the reviewed documents was conducted following an open coding approach (Bryman and Burgess, 1994). Societal values were identified from normative statements or assumptions in the reviewed literature (arguments, assessments, optimizations, etc.) that indicate desirable aspects of the water systems around wastewaters or resource recovery, i.e. what is valued. The identified values were

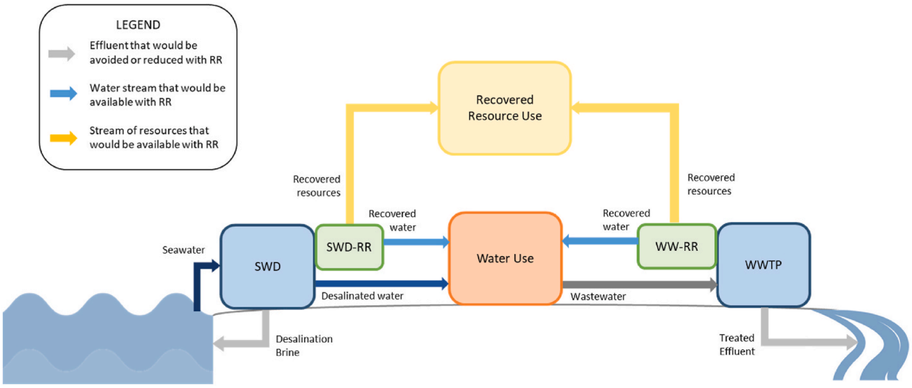

Fig. 1. Scheme of resource recovery from wastewaters investigated in this work, which can be integrated to WWTP and SWD. The wastewater stream in the scheme includes urban and industrial wastewaters, some of which may be saline like desalination brines. Desalination brines are indicated separately to other wastewaters as they are obtained from the production of desalinated water (not from water use) and they are usually discarded to the sea without treatment. RR: Resource recovery, SWD: seawater desalination, SWD-RR: Resource recovery from desalination brines, WW-RR: Resource recovery from wastewater, WWTP: Wastewater treatment plant.

Table 1

Main recovered resource types and some examples identified from the literature. This is not an exhaustive list, and recoverable resources depend on specific wastewater composition.

Resource type	Urban Wastewater Examples	Industrial Wastewater Examples	Seawater Desalination Brine Examples
Water	Water for various uses	Water for various uses	Water for various uses
Energy	Heat, biogas and other biofuels, H_2 and converted to electricity	Heat, biogas and other biofuels, dry sludge fuel, H_2 and converted to electricity	Heat and recovered energy from pressurized streams
Nutrients	Soluble P in sludge, struvite, sludge incineration ash	Soluble P in sludge, struvite, sludge incineration ash	
Polymers	Including alginate-like polymers, cellulose, EPS and PHA.	Including alginate-like polymers, cellulose, lignin, EPS and PHA.	
Other products	SCP, VFAs, soil conditioner	SCP, VFAs, soil conditioner, pigments, and various salts.	Salts of Na, Mg, Ca, and K, and other chemicals like HCl.

EPS: extra-polymeric substances, P: phosphorus, SCP: single-cell protein, VFA: volatile fatty-acids.

contrasted to each other to form value categories. This was done iteratively as new documents were retrieved and analyzed. From this analysis, it was possible to identify overarching values and the different ways in which they were discussed in the reviewed literature. In Section 3, we present these values and understandings, being reflective about the different perspectives encountered in the literature. We also identify potential value tensions (i.e. when resource recovery or a way to implement it could benefit and oppose one or more values at the same time), as well as uncertainties around resource recovery. In section 4, we gather these tensions and uncertainties, and discuss how they can be addressed from a Responsible Innovation perspective.

3. Societal values in water and resource recovery

In this section, the identified values are presented. Tensions and uncertainties are brought forward while describing these values and drawing examples from the literature.

3.1. *Water and resource security*

Water and resource security is a central value that drives the recovery of water and other resources. In the reviewed literature, water and resource security emerged as having reliable access at desirable qualities. In the next sub-sections, we present the different ways in which access and quality emerged in the reviewed documents, identifying tensions between water access and distributive justice, and quality and cost. In addition, uncertainties around the implications of resource recovery on the reliability and flexibility of the systems surrounding the investigated wastewaters are identified. Note that we make an explicit distinction between water and other resources, such as phosphorus, given the prominence of water and because, in contrast to other resources, water is not as easily transported (i.e. requiring large-volume transport to reach locations of demand).

3.1.1. *Water access and affordability*

Water access refers to the physical access to water and as being able to afford it. In some cases, a physical water access is the most prominent issue, and discussions center on water efficiency, technologies and their feasibility. Both water reuse from urban and industrial wastewater, and desalination with or without recovery from brines, have been presented as solutions in contexts of water scarcity and increasing water demands (e.g. (Colla et al., 2017; March et al., 2014; Xevgenos et al., 2015; Zetland, 2017)). However, in the reviewed literature water access is usually addressed through seawater desalination. For example, for some Mediterranean islands with limited freshwater sources, as well as for locations where water reuse is not enough to satisfy water demands, seawater desalination is discussed as water scarcity solution (Gómez-Gotor et al., 2018; Martínez-Granados and Calatrava, 2014; Trapanese and Frazitta, 2018; Xevgenos et al., 2015).

In some of cases, aspects of supply and affordability are so entangled that they raise questions about fairness in the distribution of benefits and costs related to water security. This tension can be illustrated by the development of seawater desalination in the Southeast region of Spain (While seawater desalination does not imply resource recovery per se, societal issues around it are relevant for resource recovery from desalination brines, as discussed below). This region has limited surface freshwater, and for long, it relied on groundwater extraction for agriculture. However, aquifer over-draft became a problem that until today threatens the availability of water in the region (Luis Caparrós-Martínez et al., 2020). Seawater desalination (SWD) was considered a reliable alternative to groundwater extraction that avoided controversial water transfers (March et al., 2014; Martínez-Granados and Calatrava, 2014). However, due to its large energy requirements, it became more costly than anticipated, being affordable only to some stakeholders (Luis Caparrós-Martínez et al., 2020). As consequence, some farmers did not sign agreements with SWD operators, putting pressure on the government for subsidies (Martínez-Alvarez et al., 2019). Public funding made desalinated water more affordable to farmers, although some question the policy when it benefits a limited section of the population at a cost for all (Zetland, 2017).

This tension between water access and distributive justice is relevant for resource recovery too. In a context where water is scarce and costly, new investments on resource recovery – even when talking about recovering additional water from brine – would need a negotiation of benefits and costs. That is, who would be benefited by the recovered water, and who should pay for the costs? What about the upfront investment for resource recovery plants? How would resource recovery affect water prices? Are subsidies to resources or other incentives desirable? Under which conditions? Looking at associated costs, especially energy, water reuse has been pointed as more interesting than desalination and recovery from brines (Swyngedouw and Williams, 2016). Nevertheless, water reuse also comes at a cost, which can affect affordability and willingness to pay at the household level (Lee and Jepson, 2020), requiring a careful consideration of distributive justice as pointed for seawater desalination. Additionally, a circular system with water reuse would still need additional water resources due to losses in the system and considering demand increases. For example, in Singapore, which is typically discussed in the literature as a water reuse success, water reuse provides about 30% of the total water use, the rest being provided by a combination of desalinated water, water imports and catchment (Lefebvre, 2018; Sanlath and Masila, 2020). Resource recovery would then need to be implemented facing these questions and concerns related to water security and distributive justice.

3.1.2. *Resource access*

Resource access emerged as having a reliable supply of non-renewable materials or for which there is interest in self-sufficiency. Resource access is associated to industrial production, and fertilizers are a prominent target in the wastewater context (Saliu and Oladoja, 2021). Phosphate fertilizers is of particular interest as they are typically produced from mined phosphate rock only available in a few places in the planet. Thus, its distribution and availability yields strong geopolitical and economic consequences (Ohtake and Tsuneda, 2019), making it a Critical Raw Material (CRM) in the EU (Magnus Gislev and Milan Groho, 2018). Other CRMs, such as magnesium and rare metals with industrial applications, can be present in desalination brines and industrial wastewaters. These materials can be recovered from wastewaters with various technologies, often discussed in the context of ZLD (e.g. (Mavukkandy et al., 2019; Tsalidis et al., 2020; Zhang et al., 2021).

In contrast, energy recovery is often proposed for covering the large energy requirements of wastewater treatment and desalination. In desalination, energy is sometimes recovered through turbines and isobaric devices (e.g. (Ameen et al., 2018; Martínez-Alvarez et al., 2019)). In wastewater treatment, energy is usually recovered as biogas and further processed for power and heat generation in-house (Kehrein et al., 2020b). Recovered energy is used in-house as it is barely enough to meet the energy demand of wastewater treatment plants (WWTP) (Coats and Wilson, 2017; Hao et al., 2019b). Recently, attention has been paid to the large potential for heat recovery from WWTP effluent, which is typically discharged into rivers and could be used for low temperature heating beyond WWTPs (Kehrein et al., 2020a; P. Wilson et al., 2021). This recovery would make it possible to integrate WWTP heat with near-by users, such as cities, opening the range of stakeholders and issues to consider.

Regardless, resource self-sufficiency emerges amongst other societal concerns around resource recovery from wastewates. That is, resource recovery is presented as a way to deal with stringent effluent quality requirements, with environmental and cost aspects coming into play (further discussed in section 3.2). Therefore, along with the potential towards self-sufficiency and higher quality, resource recovery brings questions similar to those about water access: who should pay for the costs and who would be benefited by the recovery? If recovered resources enter industrial production, what public-private arrangements are necessary?

3.1.3. Water and resource quality

Recovered water and other resources need to satisfy specific quality requirements depending on target uses. Official regulations set quality requirements to protect the environment and human health (Dereszewska and Cytawa, 2016). For example, in Europe, a new regulation was recently approved, which harmonises minimum quality and monitoring requirements that treated wastewaters should meet for their use in agriculture (European Commission, 2020). Besides safety legal requirements, discussed in more detail in Section 3.3, quality requirements vary depending on applications. For example, water recovered from wastewater and desalination brines could need polishing or the addition of certain salts to match required qualities. For example, for potable water, a remineralisation step would be needed if water has been recovered with thermal processing as in some ZLD approaches, or with reverse osmosis as in the case of Singapor's NEWater (Ghernaout, 2019). In industrial contexts, water can be reused for heat exchangers and as process water. However, requirements across industrial applications vary greatly: preventing corrosion, scaling and fouling are concerns in the reuse of water for heat exchange, whereas safety and the presence of contaminants is a concern for process water in the food industry (Colla et al., 2017; Meese et al., 2021). Besides the quality requirements that different applications may have, industrial contexts pose diverse challenges in the treatment of water and can thus require different technologies. For example, in the food industry wastewater usually contains organic matter, whereas water from the processing of primary metals can contain heavy metals that pose environmental concerns (Meese et al., 2021). An example from urban wastewater is phosphorus recovery, and different recovery strategies can yield phosphate fertilizer products at different qualities and costs (Kehrein et al., 2020a).

Resource recovery may face a quality-cost trade-off because improving the quality of water or other resources often means adding extra processing steps. Extra processing implies higher capital costs, which affect the decision-making around the recovery of resources or their affordability. For example, Kehrein et al. (2021) shows that capital expenditures for recovering water for irrigation increase from 0.03 EUR/m3 to 0.07 EUR/m3 when reverse osmosis is included for agricultural applications that demand higher-quality, and for industrial water it can increase to 0.1 EUR/m3. However, capital cost could be compensated by operational costs reductions related to extra processing steps, or even the potential for higher profits from higher-quality recovered resources (Kehrein et al., 2021). Nevertheless, a quality-cost trade-off has been observed in the implementation of resource recovery from municipal waste, where bulk applications are predominant over higher-quality products typically aimed with the circular economy (Gregson et al., 2015). This observation puts a contrast between the circular economy in theory and in practice, and is something to explore during the development of resource recovery innovations. Especially, involving relevant stakeholders can help to determine a desirable point in the quality-cost trade-off for a specific context, i.e. what quality or applications for recovered resources are desirable at the given costs.

3.1.4. Flexibility and reliability

Reliability emerged as an aspect of water security, with flexibility as a desirable feature to face contextual changes around water infrastructures. Reliability in the water and sanitation industry has been part of legal requirements and operation standards, making the industry 'risk-averse' (Coats and Wilson, 2017). It is therefore not surprising to find accounts of WWTP operators and designers showing a lack of confidence in resource recovery innovations (Energetics Incorporated, 2015). Comparisons of energy recovery alternatives from wastewater illustrate this point too. While energy can be recovered in many forms (as, e.g., biofuels, syn-gas, and even higher-value chemicals), simplicity and proven status of technologies are discussed as reasons to favor biogas production ((Oladejo et al., 2019), capital requirements are further discussed in Section 3). Additionally, while providing a reliable service, there has been a struggle to adapt water services to fluctuating demands (March et al., 2014; Seguido et al., 2017): Tourism, long-term migration trends, crises such as the COVID-19 pandemic affect the demands of water systems.

In this context, SWD and decentralized systems in general have been discussed as relatively flexible alternatives to large water infrastructures that can better respond to demand changes (i.e., they can be constructed and de-commissioned more easily than, e.g., water transfers and dams (Diaz-Elsayed et al., 2019)). However, the implications of resource recovery for a reliable and flexible provision of water and sanitation seem uncertain. Currently, water infrastructures are built with water quality and supply in mind, but resource recovery could imply a change of priorities. If so, what impacts could it have on the reliability of the water systems to intervene? How would resource recovery affect the capacity to respond to demand fluctuations? Could resource recovery make already existing large-scale centralized systems more flexible? How? This is something to take into account in the design and planning of resource recovery processes from wastewaters.

3.2. Environmental and socio-economic sustainability

Sustainability has been defined as care for the environment, society and economics, and balancing these aspects between and within generations (World Commission On Environment and Development, 1987). However, specific understandings of the concept, and how it is used can vary greatly. The differences in how sustainability can be understood are a result of different worldviews, or systems of meaning and meaning-making that inform how people interpret, enact and co-create reality (Hedlund-de Witt, 2014). Recognizing this flexibility of interpretation, in this work we present the diversity of sustainability understandings found in the reviewed literature structured around two main tensions: environmental sustainability trade-offs and long-term sustainability.

3.2.1. Environmental sustainability trade-offs

Environmental sustainability emerges as driver and critique of existing water systems in the scope of this work and of resource recovery. In the wastewater treatment and desalination context, resource recovery is presented as a solution to negative environmental impacts of effluent discharge on water bodies (Chrispim et al., 2019; Xevgenos et al., 2021). Even more, recovered water has been used for aquifer recharge and conservation (Martínez-Granados and Calatrava, 2014; Van Houtte and Verbauwhede, 2013).

Along these drivers, climate change emerged as a prominent sustainability concern often discussed in terms of the water-energy nexus. This nexus refers to the interdependency of water and energy resources, and the associated greenhouse gas (GHG) emissions. Energy requirements along water systems are vast, with the withdrawal and disposal of water taking about 2–3% of the total global energy (Meng et al., 2019). SWD is particularly energy-intensive, with requirements per m^3 that can be 10 times those of surface-water extraction and treatment (March et al., 2014; Nair et al., 2014; Panagopoulos et al., 2019). Wastewater treatment has prominent energy requirements too, especially considering the large volumes involved. Typically, WWTPs tend to be more energy efficient at larger scales and have higher energy requirements to reach lower nutrient concentrations in the effluent (Foley et al., 2010; Gallego-Schmid and Tarpani, 2019; Plappally and Lienhard V, 2012). This effect adds an energy component to the quality-cost trade-off mentioned above. Furthermore, direct GHG emissions from WWTP can be significant, and even a few times higher than those related to energy use (Gallego-Schmid and Tarpani, 2019; Zang et al., 2015). While the majority of direct emissions is biogenic and could be excluded in GHG emission accounting following the International Panel on Climate Change, non-biogenic fractions of direct emissions can have similar global warming impacts as those associated to electricity ((Gallego-Schmid and Tarpani, 2019), for more on direct emissions of WWTPs see (Corominas et al., 2020; Rodriguez-Garcia et al., 2012)).

These energy use and GHG emissions concerns in existing water systems are also relevant for the recovery of resources from them, and signal a sustainability trade-off. That is, on the one hand, recovering resources from wastewaters could lead to higher energy requirements and GHG emissions. On the other hand, it could bring higher effluent or product qualities, higher water reuse rates, as well as the avoidance of impacts of brine and nutrient discharge on the environment. To address this tension, it would be necessary to compare environmental impacts along the life cycle of recycled products vis-à-vis conventional products as discussed by (Bello et al., 2021) for brine management. A prominent exception to the trade-off is if recovered fertilizers from wastewater sludge substitute fossil-based fertilizers, reducing overall emissions (Lam et al., 2019). Nevertheless, considering potential trade-offs, any additional processing should be analyzed in perspective of available (renewable) energy resources and local environmental targets.

Some technical innovations emerge as solutions to this trade-off, coupling water and resource recovery with waste-heat and renewable energy resources (RES), improving energy efficiency, and integrating water reuse in water-intensive applications (Goh et al., 2021). Examples include the use of solar energy for desalination and ZLD to minimize GHG emissions (Kettani and Bandelier, 2020). Other examples include the recovery of energy from wastewater, which can significantly lower the carbon footprint of WWTP (Hao et al., 2019a), and integrated novel process schemes that could even yield energy positive facilities (Solon et al., 2019). These approaches have been advancing in development, moving to pilot and demonstration scales as shown in the recent EU Water-Mining project (Water-mining).

Despite the potential of technological innovations, their sustainability impacts depend on their implementation. For example, it has been found that circular flows within a local geographical scope is favorable to avoid transportation related costs and emissions (Iacovidou et al., 2017). This effect is more prominent for certain resources, like reclaimed water due to its large volume. Another concern is that coupling resource recovery with RES may cause a direct tension with the preservation of nature, landscape and spaces for recreation. This is the case of land use competition, as in small islands with protected environmental areas or with landscape preservation as societal priority (Beccali et al., 2020; Curto et al., 2020). Likewise, seawater desalination has faced Not-in-My-Backyard (NIMBY) reactions, being perceived as an industrial disruption of coastal space and landscape (Haddad et al., 2018). Resource recovery, which would add industrial activities to existing infrastructures could face the same issue (Energetics Incorporated, 2015). Overall, these sustainability trade-offs indicate a need to investigate how resource recovery technologies would be implemented in specific cases, considering its life cycle impacts and in their specific socio-ecological context.

3.2.2. Socio-economic and long-term sustainability tension

Water innovations have been presented as opportunities for economic development and re-industrialization. Examples include the development of agricultural production, urbanization and tourism following the availability of desalinated water in water-scarce regions (March et al., 2014; Martínez-Alvarez et al., 2019; Meerganz von Medeazza and Moreau, 2007). Like water desalination, resource recovery fits this paradigm as part of the circular economy. In a circular economy, materials are reused in a “closed-loop”, seeking to decouple industrial production and environmental impacts and costs (Puyol et al., 2017; Sgroi et al., 2018; Velenturf and Purnell, 2017). Even more, resource recovery is also presented as an opportunity to valorize waste streams, generating revenues, and potentially reducing costs of water services. Examples are the valorization of nutrients from wastewater as high-purity premium fertilizers (Otoo et al., 2015), the valorization of seawater desalination brine into salts, and even trace metals and CRM (Cipolletta et al., 2021; Xevgenos et al., 2015).

However, these technical solutions can lead to other sustainability concerns. The improvement of energy efficiency through the integration with the fossil sector, even if based on waste heat, could be questioned for its long-term sustainability. Particularly, potential lock-in effects can take place when an existing regime, such as the fossil sector, adjusts itself (e.g. through more efficiency or integration with another sector) instead of changing towards more sustainable paths (Grin et al., 2010). Already for the Dutch wastewater sector, a transition to a circular economy based on optimization and existing policies is discussed to lead to a lock-in of large-scale centralized systems, possibly undermining a transition towards a circular economy (Ampe et al., 2020). Even more, integration with existing fossil infrastructures could lead to a dependency and slow the uptake of renewable energies, as identified for the chemical sector (Janipour et al., 2020).

Another long-term sustainability concern is identified from seawater desalination discussions: increasing the availability of water (or other resources) in regions of scarcity can result in unsustainable resource consumption. Such a ‘rebound effect’ is a version of Jevon’s paradox, which states that contrary to common intuition, an increase in energy efficiency increases energy consumption (Freire-González, 2021). Examples include the expansion of water-intensive agriculture and tourism activities in water-scarce regions (Juntti and Downward, 2017; March et al., 2014; Meerganz von Medeazza, 2004). Swyngedouw and Williams (2016) refer to this phenomenon as a ‘growth contradiction’, bringing forth questions about a growth paradigm associated by some to seawater desalination. While this concern has not been explicitly discussed in the context of resource recovery in the reviewed literature, it calls for a reasonable utilization principle in the planning and implementation of recovered resources, as approached in the management of transnational water resources (Doorn, 2014).

3.3. Environmental and human safety

Safety emerged in the literature as an aspect of quality of recovered resources. However, we discuss safety as a separate value given its prominence in the literature. In the next sub-sections, we present a brief overview of safety concerns, technical responses and uncertainties, regulatory advances and limitations, and questions of societal acceptance.

3.3.1. Safety concerns

Safety concerns are about the presence of contaminants associated to the recovered products along their life cycle. Safety is more prominent in the case of urban wastewater, as pathogens, compounds like heavy metals, and more recently 'emerging contaminants' like pharmaceuticals, antibiotic resistant bacteria and their genes, have been found in the effluents from which resources can be recovered (Christou et al., 2017; Diaz-Elsayed et al., 2019; Oladejo et al., 2019). The presence of contaminants is a safety concern for the reuse of water, the processing of sludge, and for precipitation and extraction products, such as struvite and extracellular polymeric substances (Chrispim et al., 2019; STOWA, 2019; Van Der Grinten and Spijker, 2018). Human health concerns emerge when recovered resources are intended for direct contact with end-users or for agricultural applications (e.g. struvite, fertilizers) that bring them to the food chain (Christou et al., 2017). Safety is also an issue if contaminants present in recovered products can spread to the environment and accumulate, as in the case of per- and polyfluoroalkyl substances (PFAS). The health of sanitation system workers who may be exposed to pollutants during the handling of waste streams is another concern for which preventive measure are being investigated (Bischel et al., 2019).

3.3.2. Technical responses and uncertainties

It has been reported that microorganisms that pose a health risk can be eliminated during the processing for the recovery of some resources (STOWA, 2019), and that emerging contaminants can be removed or reduced with advanced water treatment technologies like membrane bioreactors and super critical water oxidation (Pazda et al., 2019; Qian et al., 2016). Some phosphate recovery technologies are also effective in the removal of some organic micropollutants and heavy metals. However, the extent of removal depends on the specific technologies and comes with an energy and cost trade-off (Amann et al., 2018). Additionally, uncertainties around emerging contaminants remain. Particularly, guidelines and methods for the detection and monitoring of some of these pollutants are not yet established or agreed upon (Hong et al., 2018; Rathi et al., 2021). Even more, the list of emerging pollutants continues to grow, especially with the rapid emergence of compounds that substitute un-desired chemicals (e.g. PFAS substitutes (Richardson and Kimura, 2020). Also, the health impacts for many of these compounds are not understood, although attention to this topic is increasing (Richardson and Kimura, 2020; Verlicchi and Ghirardini, 2019). These uncertainties make it difficult to identify the presence of emerging contaminants or derive recommendations for their control, especially if they increase costs significantly. As result, the implementation of advanced technologies for their removal is not wide-spread in the wastewater sector, leaving emerging pollutants as a concern (Diaz-Elsayed et al., 2019; Pazda et al., 2019).

3.3.3. Regulatory advances and limitations, and societal acceptance

Safety requirements for some recovered resources are set in official regulations (Dereszewska and Cytawa, 2016), such as the end-of-waste criteria specified within the Waste Framework Directive (Directive, 2008/98/EC). Regulations consider the processing and transport of recovered resources, and their placement in markets (Hukari et al., 2016). In many cases, however, regulations are limited at the national level, or even at regions of federal countries like Brazil and Germany. The EU end-of-waste criteria are applicable to the whole region but remain limited to a few resources, leaving the responsibility of many resources to regional administrations (Ragossnig and Schneider, 2019). This situation complicates the implementation of resource recovery. For example, if bio-based polymers are to be produced from wastewater, there are no EU-wide end-of-waste criteria for them, and the producer would have to turn to national legislation. The producer may then find that there is no regulation in place, that regulations are not recognized across borders, or that they have different requirements. Thus, some technologies and recovered resources may be acceptable in some places and not in others. Nevertheless, regulatory developments across countries like the treated wastewater for irrigation regulation mentioned above, and the Fertilising Product Regulation of the EU (European Commission, 2020) are interesting advances in this domain.

Still, many emerging contaminants are not controlled, not even within national or regional legislation. For example, while coliform presence is a common indicator of fecal pathogens in recovered water guidelines, antibiotic resistant bacteria and their genes are not part of these guidelines (Hong et al., 2018). The lack of regulatory frameworks relates to the rapid emergence of contaminants and the uncertainties mentioned above, as with PFAS substitutes. Another issue is that, in some cases, safety regulations and guidelines are not followed (Hanjra et al., 2015). The estimation that the area illegally irrigated with untreated or diluted wastewater is about 10 times the area irrigated with treated wastewater illustrates this problem (Otoo et al., 2015). Indicating that industrial practices are another aspect to consider in risk management.

Safety concerns and perceptions by the public have been investigated. As with sustainability, different perceptions of safety and acceptable risk emerge. For example, some studies found that some people respond negatively to the use of recovered water for drinking purposes (Diaz-Elsayed et al., 2019; Fielding et al., 2015). Others studies indicate that the acceptance of recovered resources increases in contexts of scarcity (Hanjra et al., 2015), and some even suggest a recent increase in public acceptance of nutrients recovered from wastewater (Saliu and Oladoja, 2021). Identified reasons for different public responses includes trust in science and the government (Fielding et al., 2015), which may be even more relevant with the COVID-19 pandemic.

Therefore, in a context with technical uncertainties, regulatory limitations and possible issues of societal acceptance, there is a need to investigate acceptable safety risks. For doing this, a negotiation between relevant stakeholders is needed for developing safety regulations and risk management strategies. In such a process, the uncertainties around safety will have to be weighed against the significant cost that monitoring and control imply. For that, not only the presence, concentration and risks of contaminants should be considered, but also the broader socio-technical context around them, including legislation (and its limits), industrial practice and societal acceptance.

3.4. Water and resource ownership

In this section, we briefly summarize water management discussions, concluding that this topic is relevant too for the recovery of resources from wastewaters. Additionally, we identify uncertainties about responsibilities in resource recovery.

Different formal and informal institutions that lead the way people see and use water have developed in diverse societal contexts (Babidge, 2016). Water in nature can be regarded as a common-pool good (Ostrom and Ostrom, 1977). Nevertheless, different rights and property regimes, as well as technical and physical barriers, make it possible to treat water as private good to different extents (Doorn, 2014). For example, in Spain the responsibility of water supply and tariffs usually falls on municipalities, who decide whether to manage the service, or to leave it to private or mixed public-private entities (López-Ruiz et al., 2020). With seawater desalination, it can be said that water becomes commodified. That is, water is processed and sold at a surplus value in public-private partnerships, leaving water supply under public control with significant privatized elements (Swyngedouw and Williams, 2016).

Water privatization has been promoted and it has led to opposition movements around the world (Mirosa and Harris, 2012). Exclusion mechanisms are justified in terms of inefficiencies (Karunananthan, 2019) or by evoking a 'tragedy of the commons', in which common-pool goods become over-exploited and unavailable to the public (Doorn, 2014). Water privatization has been advocated to fix these problems, and it has also been discussed as a mechanism focused on returns on investments and at a high social cost (Karunananthan, 2019). Some see public water management as an alternative to protect water access (López-Ruiz et al., 2020), leading to a re-municipalisation of water supply management (Bieler, 2017).

Water commodification brings questions about the ownership and legal rights over water resources (Campero and Harris, 2019; Swyngedouw and Williams, 2016), and could easily extend to wastewaters for resource recovery. Currently WWTP operators are paid for a service and not for the treated effluent. If WWTP become resource recovery factories, it means that wastewater could be commodified just like seawater in desalination. Debates about privatization and the distribution of costs and benefits around, e.g., access to water and sanitation services, and environmental protection, are relevant then for the implementation of resource recovery. For example, who should own and manage resource recovery factories? How should their benefits be distributed over water users who pay for water and its treatment? As part of the management of resource recovery, questions about responsibility would need to be addressed too. This is especially the case for maintaining a reliable water supply and sanitation service, and at required qualities. It is also about the supply and quality of recovered resources. Establishing clear responsibilities is important too considering that new actors, in new roles (e.g. resource recovery operators, technology developers) are likely to be involved.

4. Towards responsible resource recovery

Some of the identified values relevant for the recovery of resources from wastewaters imply tensions and bring forth uncertainties that need to be explored. In the next subsections we gather these tensions and uncertainties and suggest approaches to investigate them, making a distinction between tensions within the resource recovery technical systems (trade-offs) and in the broader sociotechnical context (broader tensions), see Table 2. We acknowledge that the values, tensions and uncertainties presented here may not be relevant for all cases or may not cover all societal concerns in a given context. For that, societal implications of resource recovery should be investigated in specific contexts. Additionally, identifying and facing these issues requires the inclusion of the public, and the social sciences and humanities in the development of technologies. For that, transdisciplinary approaches and researchers that can reconcile different ways to formulate and investigate scientific questions are needed.

4.1. Facing trade-offs

Here we refer to trade-offs as the tension between values that fall within the scope of the technical innovations, and include the tensions of quality-cost-energy and environmental sustainability. These tensions have a quantifiable relationship and have usually been explored in the engineering and natural sciences domain. It is common to learn about specific impacts (e.g., how much an improvement in quality would affect cost?) through methods and tools like techno-economic analysis (TEA) and life cycle assessment (LCA), as shown for example in (Meneses et al., 2015). However, the relative importance of expected benefits vis-à-vis potential negative impacts depends on specific contexts, including available technologies and opportunities for improvement but also stakeholder values and priorities. Therefore, learning about impacts is not enough to resolve these tensions. For example, if a resource recovery system avoids impacts on marine life but comes at a given amount of

Table 2
Identified tensions and uncertainties relevant for the implementation of resource recovery. Tensions are presented as trade-offs and broader tensions.

Issue	Examples (references)	Recommendations
Trade-offs		
Quality, Cost and Energy	Bringing recovered water to required qualities for some target uses can lead to additional costs and emissions. Depending on target applications, these costs could be compensated by price (Kehrein et al., 2021).	Coupling stakeholder engagement with common engineering methods (through, e.g. VSD) to find acceptable trade-offs like identifying locally desirable water uses at given costs.
Environmental sustainability trade-offs	Zero liquid discharge avoids impacts on marine ecosystems but may cause additional GHG. In some areas, RES for may be in tension with the use of land. (Goh et al., 2021).	
Broader tensions		
Water Access, Affordability and Distributive Justice	Seawater desalination (and resource recovery from brines), can be too costly for irrigation, leading to demands for subsidies and raising controversy over its societal acceptance (Martínez-Alvarez et al., 2019).	Social learning as a way to explore societal goals and acceptable conditions associated to resource recovery. Building on the complementarities between responsible innovation, sustainability transitions and adaptive governance is suggested.
Socio-economic and long-term sustainability	Integration with waste heat from fossil sources increases energy efficiency, but it may slow-down the update of RES (Janipour et al., 2020). Expected socio-economic benefits in tension with potential rebound effects, such as increased agricultural production in water-scarce regions (March et al., 2014).	
Water management arrangements	Resource recovery adds to current debates about the management of water and sanitation services (Campero and Harris, 2019; Karunananthan, 2019; Swyngedouw and Williams, 2016).	
Uncertainties		
Impacts of resource recovery	The presence, monitoring, and control of contaminants in wastewater is a safety concern for the reuse of water and the recovery of resources (Richardson and Kimura, 2020; Tyagi and Lo, 2013). There are concerns about the ability to cope with influent quality and quantity variations for the implementations of water and/or resource recovery (Energetics Incorporated, 2015).	An experimental approach aimed to learn about impacts, norms and institutions, values and worldviews is suggested. For example, SbD and VSD can be applied to identify specific concerns and guide, not only the research, design and development of resource recovery technologies, but also relevant policy, market and social innovations.
Norms and institutions	Regulations for recovered resources fall to different administrations, and they can differ or not be recognized across borders (	

(continued on next page)

Table 2 (*continued*)

Issue	Examples (references)	Recommendations
	Kehrein et al., 2020a; Ragossnig and Schneider, 2019). The entry of new actors to water systems and the emergence of new products that fall outside the scope of current legislation calls for an explicit attribution of responsibilities.	
Values and worldviews	Differences in perceptions about safety, and the acceptability of risk management measures (Diaz-Elsayed et al., 2019; Pazda et al., 2019).	

GHG: Greenhouse gas emissions, RES: Renewable energy resources, SbD: Safe-by-Design; SWD: Seawater desalination, VSD: Value sensitive design.

GHG emissions, knowing specific quantities does not say if or how the technology is socially acceptable.

From a responsible innovation perspective, there is a need to include stakeholders to identify and reflect about the values and impacts behind these tensions, and to make a participatory decision-making. Learning about, e.g., how sustainability is understood by actors in specific projects can indicate how it should be evaluated (Asveld, 2016). An open discussion about the technologies and the identified values could also lead to finding acceptable trade-offs in specific contexts. For example, in the case of a quality-cost trade-off in water scarce regions, local water priorities and acceptable costs can be discussed with stakeholders and facilitate the identification of desirable innovations. This identification would set the application, quality requirements and price a recovered product should meet to be acceptable by stakeholders, and considering conventional alternatives.

Therefore, coupling stakeholder engagement with common methods in engineering and project development (e.g. TEA and LCA), could support the exploration of these trade-offs for specific resource recovery projects or technologies (see, e.g., (Kehrein et al., 2020c; Matthews et al., 2019; Palmeros Parada et al., 2021). Another approach to consider is social LCA, which has been applied for a few resource recovery innovations already. Particularly, social risks surrounding resource recovery technologies for wastewaters have been identified through social LCA, allowing to recognize technologies or aspects of a technology to minimize such risk (Foglia et al., 2021; Shemfe et al., 2018; Tsalidis et al., 2020). Even more, these approaches could support a Value Sensitive Design (VSD) approach to innovation. VSD is a design framework to proactively accommodate values in technological designs (Friedman et al., 2017). In VSD stakeholder values are investigated and put into the context of a technology to identify the desirable technical features (or undesirable ones). Through it, value tensions can be investigated, possibly finding acceptable resolutions within design alternatives or through innovation (Palmeros Parada et al., 2020).

4.2. Facing broader tensions

The tensions between affordability and distributive justice, and socio-economic and long-term sustainability, and water management arrangements have a scope that goes beyond the technological domain. These tensions are about the outcomes of the technology, about how it should be managed, but also about defining the problem to solve in the first place and what types of solutions are envisioned. For example, addressing the tension of affordability and distributive justice will probably require looking at policies and bundles of rights, and finding out which instruments in these and other domains are socially acceptable. Depending on the context, this process could bring forth a struggle between the different values and priorities around the governance of resource recovery innovations (see, e.g. (Ampe et al., 2021),). In these cases, social learning can be a way to approach these tensions. Social learning is the learning that emerges from interactions between actors that exchange knowledge, and who through interaction create new knowledge (Sol et al., 2017). Through social learning, a shared understanding could be reached over the societal goals to which resource recovery could contribute and identify desirable paths for its implementation, as shown in other innovation cases (Sol et al., 2013; van de Poel and Zwart, 2010). For example, ensuring water access for all or aquifer restoration may be agreed as goals of water recovery in some contexts, and may lead to discussions about the desirability of, e.g., ZLD subsidies or tariffs on groundwater extraction.

Although Responsible Innovation can enable social learning (Stilgoe et al., 2011), it has an important limitation to face the tensions above. That is, while Responsible Innovation promotes participation, its focus remains on technical innovations, possibly leading to a limited vision of how to address societal problem, which some call a kind of naive optimism (Genus and Iskandarova, 2018; Saille and Medvecky, 2016; Sovacool et al., 2021). Another limitation is that it does not explicitly consider power asymmetries between stakeholders, which can influence the shape and direction of innovations (Loorbach et al., 2017). A sustainability transitions perspective can serve to address these limitations though, e.g., transition management and social innovations that consider the politics and power dynamics around transformative innovations (Köhler et al., 2019). Recently, mission-oriented innovation policies have gained prominence, aiming to translate systemic challenges to concrete missions with defined goals, setting actions and coordinating innovation efforts (Janssen et al., 2021). Considering this aim, approaching resource recovery innovations as part of missions surrounding (waste-) water and resource use, and in perspective of broader transitions or societal changes, could support a negotiation of interests and values in specific contexts and set concrete innovation actions. We also suggest looking at the Adaptive Governance domain, which seek to develop governance structures for natural resources to promote resilience (Hurlbert, 2018). While focusing on socio-ecological systems, Adaptive Governance brings evidence from case studies about the collaboration and coordination between stakeholders at different scales, capacity development, community empowerment and engagement, and more (Sharma-Wallace et al., 2018). All of these theoretical perspectives imply participation, learning and experimentation in the management of socio-technical and socio-ecological systems (Foxon et al., 2009; Marques Postal et al., 2020; Voβ and Bornemann, 2011). Therefore, it is suggested to approach these broader resource recovery tensions with social learning, building on the complementarities between Responsible Innovation, Sustainability Transitions and Adaptive Governance.

4.3. Exploring uncertainties

In this section, we discuss some of the uncertainties related to resource recovery identified throughout Section 3 that fall outside of the scope of the tensions discussed above. These are uncertainties on impacts of resource recovery (i.e. on the reliability and flexibility of water systems, on the presence of pollutants, and how to monitor and control them), on norms and institutions (i.e. quality and safety regulations, responsibility ascriptions in resource recovery), and on values and worldviews that impact what acceptable risk is. For that, we refer back to Responsible Innovation, and take up on the experimental approach discussed by Asveld (2016). That is, acknowledging that the development of innovative technologies implies uncertainty, technologies can be introduced to society as an experiment aimed to learn about impacts, norms and institutions, and values and worldviews, with the possibility to stop or change the direction of innovations.

Safe-by-Design (SbD) and VSD could be applied in such an experimental set-up. SbD is a risk management framework that introduces considerations of safety during the development and design of new technologies (van de Poel and Robaey, 2017). SbD, like VSD, aims to open the design process to the participation of stakeholders for the co-design of technologies, taking into account their values, perceptions and expectations with a focus on safety (Bouchaut and Asveld, 2020). Because these approaches can be applied openly and iteratively, they are suitable for an experimental setting to learn about uncertainties associated to resource recovery technologies. That is, these approaches could be applied to identify specific concerns to guide the development of resource recovery technologies and their governance, with consideration of safety and other societal concerns.

5. Conclusions

This work indicates that while the recovery of resources seems desirable, its implementation entails societal concerns around water and resource security, sustainability, safety, and water and resource ownership. Tensions and uncertainties around these four main societal values call for a closer look at the interaction between resource recovery technologies and the socio-technical and socio-ecological context of implementation. A few of the concerns identified here already emerge from existing water systems, (i.e. without resource recovery), and the recovery of resources accentuates or brings new aspects to them. For example, while seawater desalination raises questions about the distribution of costs and its desirability (Swyngedouw and Williams, 2016; Zetland, 2017), resource recovery expands them with other potential impacts. These impacts include avoiding effluent discharge, obtaining resources, as well as additional costs and potential environmental impacts (e.g. land use), and which are relevant too in other contexts beyond desalination. Other questions emerge specifically for the recovery of water and other resources, like which resources should be recovered from a waste stream and for what uses (e.g. water for irrigation or water for re-filling aquifers?), and what cost is acceptable? Could resource recovery lead to rebound effects? How to prevent them? What arrangements and responsibilities should be defined, especially towards safety and regulations? These questions should be addressed for the implementation of resource recovery in specific contexts.

Looking at the prominence of the circular economy in current policy developments (e.g. in the EU Green Deal (Trincado et al., 2021)) and the non-technical barriers to resource recovery (Kehrein et al., 2020a), exploring these concerns is urgently needed. To address tensions and uncertainties around resource recovery in future developments, we suggest exploring the application of Responsible Innovation approaches, such as VSD and SbD, coupled with common methods in engineering and the natural sciences. Additionally, Sustainability Transitions and Adaptive Governance are suggested as theoretical perspectives to complement Responsible Innovation in the development of resource recovery. Overall, by having identified relevant values, tensions and uncertainties, we hope to contribute the development of sustainable and socially acceptable resource recovery innovations.

Author contributions

MPP: Conceptualization, Formal analysis, Investigation, Writing – original draft. PK: Investigation, Writing – review & editing. DX: Writing – review & editing, Funding acquisition. LA: Conceptualization, Writing – review & editing, Funding acquisition. PO: Writing – review & editing, Funding acquisition

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.

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