Water Reuse from wastewater treatment: The transition towards Circular Economy in the water sector

Giorgio Mannina[1*], Hazal Gulhan[1, 2], Bing-Jie Ni[3]

[1] Engineering Department – Palermo University, Viale delle Scienze, Ed. 8, 90128 Palermo, Italy

[2] Environmental Engineering Department, Civil Engineering Faculty, Istanbul Technical University, Ayazaga Campus, Maslak, 34469 Istanbul, Turkey

[3] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia

*Corresponding author:

Prof. Giorgio Mannina: giorgio.mannina@unipa.it

Abstract

Water is crucial for economic development since it interacts with the agricultural, production, and energy sectors. However, the increasing demand and climate change put pressure on water sources. This paper argued the necessity of using reclaimed water for irrigation within the scope of a circular economy. The barriers (i.e., technological and economic, institutional/regulatory, and social) to water reuse practices were revealed. Lessons on how to overcome the barriers were learned from good practices. The roadmaps adopted in the European Union for the transition towards the circular economy were reviewed. It has been observed that these roadmaps are generally on the circularity of solid wastes. However, water is too important for the economy to be ignored in the transition towards circular economy. Research needs and perspective for a comprehensive roadmap to widen water-smart solutions such as water reuse were drawn.

Keywords: *Agriculture, barriers, circular economy, roadmap, water reuse.*

1. Introduction

The water withdrawal for agriculture, industrial, and domestic activities has increased from 0.67 trillion m^3/year in the 1900s to 3.79 trillion m^3/year in 2000 (Ritchie and Roser, 2017), and it is estimated to increase 55% by 2050 due to anthropogenic activities (OECD, 2012). The available freshwater reserves on earth are not sufficient to meet the water demand of increasing human activities. Moreover, it is estimated that extreme climatic events, decreasing rainfall amount and regularity as a result of climate change will make it difficult to access usable water (WEF, 2020). In fact, in the Mediterranean Region of Europe (Cyprus, Spain, France, Greece, Italy, Malta, Portugal), 11% reduction in water resources is expected by 2060 (IPCC, 2022). Therefore, it is necessary to manage water consumption for anthropogenic activities.

The availability of water is crucial for economic development since sectors like agriculture, tourism, and all kind of production consume water. The agricultural sector takes the lead as it is responsible for 70% of the world's water consumption (UN-Water, 2021). This rate varies according to the intensity of agricultural activities in the region. In Europe, agricultural activities are concentrated in the southern region. Therefore, while the agricultural sector to gross domestic product (GDP) in the Mediterranean Region is higher than in European Union (EU) (The World Bank, 2022). Accordingly, 85% of the water used for irrigation in Europe originates from the south (EEA, 2021). The difficulty with accessing irrigation water caused by climate change will adversely affect agriculture. Since Southern Europe is more dependent on agriculture, it is more vulnerable to climate change than the north (IPCC, 2022). In addition, when there is a shortage of water, water is supplied for domestic and industrial consumption instead of agriculture, which adversely affects the agricultural sector (Cirelli et al., 2012). Alternatives to conventional sources (rainfall, surface or ground water) for irrigation should be applied because water shortages are expected to continue in Southern Europe (La Jeunesse et al., 2016).

Agricultural drainage, rain and stormwater runoff, and seawater can be given as examples of non-conventional water resources specific to the agricultural sector (Chen et al., 2021). As the stress caused by climate change on water resources accelerates the transition towards a circular economy, the reuse of treated water, which ensures the circularity of water, in agriculture is becoming increasingly common. Nowadays, wastewater is seen as a resource rather than a waste (Yadav et al., 2021). Because, in addition to the need for water in production for agriculture and industrial processes, water has a carrier role for other sources (nutrients, chemicals, minerals, organics). The environmental burden of anthropological activities can be minimized by closing the loop by recovering the energy, water, and nutrients in the wastewater. Reusing treated wastewater in agriculture achieves both water, organic matter, and nutrient (nitrogen, phosphorus, potassium (Ricart and Rico, 2019)) recovery. Furthermore, Ofori et al. (2021) stated that using reclaimed water for irrigation increases quality of arable soils and it has a potential to decrease greenhouse gas (GHG) emissions release compared to water import or high energy-consuming treatment technologies such as desalination (Alcon et al., 2012; Kirhensteine et al., 2016).

The benefits of using reclaimed water in irrigation listed above help to ensure sustainability in agriculture and water sector by creating a synergy between these two sectors (Smol et a., 2020). The circular use of resources, thus creating minimum waste, is vital for sustainable development.

Chen et al. (2021) defined the circular water economy as a business model that provides sustainable production and consumption with the reuse of water, and resource recovery. This transformation is expected to mitigate climate change effects as well as increase economic gains such as reducing transportation cost and trade of materials (Qtaishat et al., 2021). For these reasons, reclaimed water as an alternative source of irrigation water is crucial for both agricultural and water sectors. The use of treated wastewater for irrigation purposes will become a widespread activity, especially in countries where water crisis is experienced or expected (Pedrero et al., 2010).

However, there are organizational, economic, social, and technical barriers to overcome for widespread application of reusing water for irrigation purposes. A broader application of water reuse practice and the shift from a linear to a circular economy can only be achieved by a systematic change.

Roadmap is an important tool used in the realization of systemic transitions such as the shift from a linear to a circular economy. Roadmaps are strategic instruments to achieve these transitions that private companies and governments use. They reveal the current status of the technology/management approach, goal to achieve, barriers to overcome, and strategy to realize the transition. They consist of sets of steps, and identify the actors, determine research and development needs, specify the required changes for the market and related regulation, and create projections for the future (McDowall, 2012). Because of its importance in achieving systematical transitions, roadmaps are necessary for achieving a circular economy. Since water is a resource and a carrier of other resources (nutrients and energy), the inclusion of water circularity in roadmaps toward a circular economy is necessary. Water reuse practices are useful for providing water circularity. However, current roadmaps aiming circular economy adopted by some EU countries (Germany, Republic of Serbia, Belgium, Poland) overlook the significance of water reuse.

In this paper, the current state of reclaimed water use for irrigation, the barriers in front of wider applications of water reuse in agriculture, and the good practices in water reuse in agriculture were reviewed. The roadmaps adopted in the EU for the transition from linear to circular economy and their relations with the water sector were evaluated. Finally, an updated roadmap created within the framework of the Horizon 2020 European Project “Achieving wider uptake of water-smart solutions — Wider-Uptake” to widen water-smart solution such as water reuse in agriculture is innovatively proposed.

2. The current state of reclaimed water use for irrigation

Reusing treated wastewater as irrigation water has the highest rate with 52% among other reuse alternatives in the world (industrial, fire protection, toilet flushing, wetlands, recreation, groundwater recharge, potable) (Yang et al., 2020). Especially in regions where access to water is difficult, it is preferred to reuse treated wastewater because it is more feasible than other alternatives (such as seawater). In Israel, the rate of recovered domestic wastewater is 85%, and most of it is used in agriculture, with negligible industrial reuse rate. Moreover, 54% of the recovered water in Israel is treated to the best quality required for irrigation (Avgar, 2018).

In northern Europe, 51% of the recovered water is used for environmental applications (augmentation of existing water sources, wetland creation etc.), while in southern Europe, it is mainly (44%) used for irrigation (Sato et al., 2013). Spain, Italy, Cyprus, and Greece are pioneers in reclaimed water use in agriculture (Voulvoulis, 2018). Cyprus uses 76% (in 2013) of treated wastewater as irrigation water (Kirhensteine et al., 2016). In Spain, %10 of the wastewater is recovered and 61% of it was used in agriculture in 2016 (SUWANU, 2019). Hristov et al. (2021) stated that with the current water reuse applications in EU, water stress reduction is predicted as only 1% by 2030, although the potential was estimated as 14%. The EC adopted for the regulation that for minimum reclaimed water quality for the European Union, however, regulatory framework differs for every nation, and stringent regulations reduce reuse application. For example, Israel, water reuse covers the 50% of irrigation water need (Tal, 2016), monitors less than a dozen parameters but defines required treatment level and crop/produce type, and irrigation technique. On the other hand, Italy defines limits for parameters that some of them are not considered for drinking water analysis (Ait-Mouheb et al., 2020).

3. Reclaimed water use for irrigation in the circular economy model

Protecting the environment and public health without compromising economic development is the driving force for the transition from a linear to circular economy in water sector (Smol et al., 2020). In the linear economy model, there is no connection between waste management and resource use. The main approach in the linear economy is extract-produce-use-dispose (Korhonen et al., 2018). On the other hand, there is a strong link between waste management and resource use in the circular economy model. In circular economy, resources and products are kept in used for as long as possible thanks to the reuse and recycling of materials and recovery of resources. Thus, it minimizes waste generation and regenerates natural systems (Fitch-Roy et al., 2021). The goal of circular economy is to protect the environment and ensure social equity while accomplishing economic growth (Kirchher et al., 2017).

The European Commission (EC) adapted the first circular economy action plan in 2015, and “A new Circular Economy Action Plan” plan was adopted in 2020 (EC, 2020). Water connects agricultural, industrial, and municipal systems. The ubiquity of water makes it very important in realizing the circular economy model. Water reclamation practices are used to produce or recirculate water for agricultural, industrial, and urban (landscape irrigation, street cleaning, fire protection, toilet flushing etc.) activities (Lazarova, 2022). Water reuse in agriculture was included in “Food, water and nutrient” product value chain of the new plan. The EC highlighted the potential to minimize industrialized fertilizers by recycling nutrients via water reuse (EC, 2015). Extending water life cycle and preserving fresh water sources are the other contribution factors of achieving circular economy in water sector by using reclaimed water for irrigation (Smol et al., 2020). Although the EC's action plan secures reclaimed water quality for safe food production, there is still barriers in front of transition from linear and circular economic model.

4. The barriers in front of wider applications of water use for irrigation

With the existing technologies used in domestic wastewater treatment, it is possible to obtain irrigation water suitable for agricultural use. However, the wide use of reclaimed water in agriculture is limited by (i) technical and economic, (ii) institutional/regulatory, and (iii) social barriers.

4.1. Technical and economic barriers

Pathogens, particulate matter, organic matter, heavy metals, salinity, and emerging pollutants in domestic wastewater are undesirable parameters in irrigation water. Secondary wastewater treatment plants remove organics and nutrients from wastewater but do not produce effluent water applicable for irrigation. Thanks to the advanced treatment technologies following secondary treatment even potable water can be produced from domestic wastewater (Rubiano et al., 2012). Some of the advance treatment technologies used for irrigation water production are membrane filtration, advanced oxidation processes, and adsorption.

Membrane filtration technology is based on the physical retention of pollutants in the filtered stream, depending on the gap size on the filtration material (Davis and Cornwell, 2019). Membrane process has low footprint and high treatment performance. Ultrafiltration (UF) membranes can retain the particulate and colloid material, bacteria, and even some viruses. For this reason, UF membranes are preferred after secondary treatment in most water reuse projects (Kehrein et al., 2021). In membrane bioreactors (MBR), which are the integration of the membrane process and the activated sludge process, membranes are used instead of conventional settling tanks to separate the treated water from biomass. Sludge retention time and hydraulic retention time are separated from each other in MBR systems and higher removal efficiencies can be obtained with higher biomass concentrations (Judd and Judd, 2006). However, the disadvantage of membrane processes is the high investment and operating costs (Yang et al., 2020).

Advanced oxidation processes (AOP) stand out, especially in the removal of emerging pollutants. In this technology, highly reactive oxidant agents ensure the destruction of non-biodegradable organic pollutants (Silva et al., 2017). The appropriate AOP is decided according to the emerging pollutant to be eliminated. Chlorination is an oxidation process used in disinfection of WWTP effluents. When organic matter found in the effluent, disinfection by-products which are harmful to human health are formed. For this reason, in reuse applications, the organic matter removal efficiency from the wastewater must be high. Another AOP is ozonation. It is possible to remove organic matter, emerging pollutants, and pathogens from wastewater by ozonation process, but if bromide is present in wastewater, there is a risk of formation of carcinogenic bromated organic compounds (Kehrein et al., 2020). The high energy requirement of AOP systems is another disadvantage of this technology (Li et al., 2022).

The raw carbonaceous materials have a very high adsorption capacity after being activated. Activated carbon in granular form can be used as filter medium to adsorb emerging pollutants from wastewater and can be reactivated after use (Alvarino et al., 2018). However, dissolved organic matter (DOM) in the treated wastewater can create a competition with targeted emerging pollutants in granular activated carbon reactors. On the other hand, since pollutants are not degraded by adsorption, biomass growth due to adsorbed DOM in the granular activated carbon (GAC) reactor may increase emerging pollutants degradation and decrease the need for further processes (Gutiérrez et al., 2021).

For the treated wastewater to be reused safely in agriculture, the pathogens in its content must be removed according to the intended use. Chlorination is the most widely used disinfection method. Despite its effectiveness in eliminating pathogens, high doses of chlorine can react with organic substances in treated wastewater and form potentially carcinogenic chlorination byproducts (Furst et al., 2018). Disinfection can be performed quickly and cost-effectively with ultraviolet (UV) rays (Banach et al., 2022). However, it has been observed that the total amount of bacteria in the water can rise to the same level as the wastewater that has not been disinfected in a short time as five days after UV disinfection (Guo et al., 2009).

Despite the scientific evidence for effective wastewater treatment, there are still deficiencies in technical knowledge, skills, and training in the transition from existing wastewater treatment plants to water recovery plants (Yadav et al., 2021). Moreover, after using advanced technologies for production of irrigation water from wastewater, supplying the reclaimed water to the users required a separate distribution network (Guo et al., 2014). In conventional water systems, the water taken from the source is delivered to the users via the distribution network, while wastewater is collected via the collection network and transferred to the wastewater treatment plants. To bring the collected wastewater to the WWTP by gravity and to lower the energy costs associated with pumping, treatment plants are usually located at a lower altitude from the wastewater basin. However, the low altitude of the treatment plant may increase the cost of reclaimed water distribution, as it requires pumping (Kehrein et al., 2020). In addition, the delivery of reclaimed water produced to the farms located separately from each other requires a complex reclaimed water distribution network.

As the treatment performance increases, the costs of the processes increase. Moreover, the distribution of reclaimed water increases the reclamation project costs. For this reason, the feasibility of irrigation water production from domestic wastewater is low in areas where water suitable for irrigation is easily accessible. However, in places where access to water is difficult, producing irrigation water from wastewater is cheaper and causes lower carbon footprint compared to other alternatives such as desalination or water import (Kirhensteine et al., 2016). To promote the circular water economy, the use of reclaimed water must be made economically profitable

(Salminen et al., 2022). Yet, it is difficult to achieve this with the natural market mechanism without government support (economic tools) (Qadir et al., 2010, Lyu et al., 2016).

4.2. Institutional/regulatory barriers

Lyu et al. (2016) stated that reclaimed water applications are mostly affected by policy rather than technical and economic reasons. Decision makers and politicians often do not have enough information about the reuse of wastewater in agriculture, so they are reluctant to take steps to encourage water reclamation (Mannina et al., 2021a). Some institutional barriers in front of water reuse are not putting common regulations for water reuse, not encouraging water reuse by the economic tools (intensives, tax relaxation etc.), lack of healthy communication between farmers and decision-makers, and not informing public about water reuse (Saliba et al., 2018).

The quality of reclaimed water used in agriculture is very important for the crop quality and therefore for human health. Hence, reclaimed water quality must be strict enough minimize health related risks. On the other hand, it is also important to set reclaimed water quality standards in a way that does not limit water reuse applications (Mizyed, 2013). Indeed, the stringency of reclaimed water quality standards hinders the wider application of water reuse practices. For example, in Israel, which is the leader in water reuse, technical practices (treatment technology, suitable crop type, appropriate irrigation technique, etc.) that should be applied for water reclamation are shown as a necessity, instead of aggressively limiting parameter concentrations in the reclaimed water. On the other hand, due to strict Italian regulations on water reuse, the number of water reclamation projects in Italy is limited (Ait-Mouheb et al., 2020). In addition, the standards should not lag behind the scientific developments (Yang, 2020). Another issue about water reuse standards is the fragmented legislations among different administrations (such as water treatment and agricultural administrations). Not having a common regulation for water reuse in agriculture creates uncertainties for water reuse projects and makes decision-makers avoid investing on these projects (Kehrein et al., 2020). Furthermore, having a common circular market between many reclamation applications increases the success of reclamation processes. Indeed, unification of European members aims to promote common economic and social progress. The current water reuse policies of the EU are in the evolution phase from a linear economy to a circular economy model (Mannina et al., 2021). One of the most important developments regarding water reuse in the EU is Regulation 2020/741 on minimum reclaimed water quality requirements, which limits total suspended solids, turbidity, biological oxygen demand, and *Escherichia coli* in reclaimed water. The purpose of this regulation is to spread water reuse practices by providing public confidence that the use of treated water in agriculture is safe for public and environmental health. In Regulation 2020/741, apart from reclaimed water quality safety, the potential of saving commercial fertilizer costs is also highlighted by not restricting nitrogen and phosphorus in treated wastewater. Thus, it aims to pave the way for the circularity of resources (water, nitrogen, and phosphorus). Despite these progressive steps taken by the EU, members may still decide that water reuse is inappropriate for irrigation. This situation hinders the creation of a common market of circular economy and the unification of European law (Mannina et al. 2021).

4.3. Social barriers

Water reclamation projects cannot be successful without public acceptance (Kehrein et al., 2020). In a study examining the psychological and social barriers to the reuse of wastewater, it was revealed that a high sense of pathogen disgust is correlated to the refusal of reclaimed water use in agriculture. This is caused by the public not being sufficiently informed about reclaimed water quality and its benefits (Stenekes et al., 2006; Saliba et al., 2018). In addition, the lack of trust in the authorities by the public is another reason of not achieving public acceptance (Beveridge et al., 2017). However, increasing water scarcity and water consumption restrictions were found to be directly proportional to the acceptance of treated water use in agriculture (Wester et al., 2015). The concerns of the farmers about the use of reclaimed water are the continuity of the water quality, risks related with crop and soil quality, and the market value of the crops. Frijns et al. (2016) stated that farmers believe that products irrigated with reclaimed water will not be preferred by the public. However, as crop contact with reclaimed water decreases, the hesitations of farmers also decrease (Ricart and Rico, 2019). In addition, the nitrogen and phosphorus content of reclaimed water reduces the cost of commercial fertilizers, increasing the willingness of farmers to reuse water (Ricart and Rico, 2019).

5. Lessons learned from good practices in water use for irrigation

A good practice is a real-world example that consistently shows better results than other practices. This section examines good practices from two Mediterranean countries. Therefore, the method and approach they used in water reuse projects can be used as an exemplary benchmark for other applications.

Cyprus uses more than 75% of reclaimed water for direct and indirect irrigation in rural and urban areas in 2013 (Kirhensteine et al., 2016). The reasons for Cyprus to use reclaimed water in irrigation are that the freshwater resources on the island are under stress due to changing land-use activities, increasing groundwater abstraction due to increasing tourism activities, and climate change. In Cyprus, water reclamation is managed by the Ministry of Agriculture Natural Resources and Environment, which covers the agriculture and water sector. In this way, the uncertainty in water reclamation projects is reduced. Gaining public acceptance for reclaimed water irrigation is a common result of the exposed water scarcity, government-provided education, and applied pricing policies (Papaiacovou and Papatheodoulou, 2013). The government covers the costs of tertiary treatment and the delivery of reclaimed water to users. Users are charged for the volume of water they use, but to promote reclaimed water use, the price of reclaimed water is set to cover only 88% of the treatment cost (Republic of Cyprus Ministry of Agriculture Natural Resources and Environment, 2010).

Approximately 36% of the wastewater treated in Milan, Italy, is used for agricultural irrigation. Soil and crop quality produced in Milan decreased due to the wastewater production increase caused by the drastic population increase (Lazarova et al., 2013). The structure of the water basin in Milan is very suitable for using wastewater in agriculture because the farms are close to the city and there are irrigation channels. For this reason, treated wastewater has been used in agriculture since 2004 and an increase in soil and crop quality has been achieved. Regular meetings are held to ensure a healthy relationship between the farmers and the Municipality of Milan (the highest decision-making administrative). The cost of the treatment plants is covered by the Municipality of Milan and the farmer does not pay for the treated water. In addition, treatment plants are operated in a very transparent manner. Thanks to these steps, reclaimed water use in irrigation gained public acceptance in Milan.

Successful projects on irrigation water reclamation from Cyprus and Milan have three things in common: public acceptance, adequate pricing mechanisms, and the attitude of decision-makers.

In Cyprus, farmers are trained in the use of treated wastewater in agriculture; In Milan, a transparent collaboration was established with the events organized by non-profit organizations (such as universities) and stakeholders (Lazarova et al., 2013). In summary, training farmers to ensure crop quality, showing good practice results to stakeholder, and being transparent about treated wastewater quality helps to ensure public acceptance of reclaimed water use in agriculture. Pricing mechanisms are very important for reclaimed water to compete with conventional water sources. undertaking the construction and operation costs of tertiary treatment plants to promote water reclamation processes not getting full-recovery full-cost recovery of treatment costs from users are effective financing mechanisms. Decision-makers' attitude on involving the public at the beginning of the projects, finding users, making water supply systems suitable for reclaimed water use, being transparent have led the projects to success.

6. Current roadmaps to achieve circular economy

The transition from a linear to a circular economy needs multi-level policy packages (Fitch-Roy et al., 2021). Circular economy policy packages include multi-tool strategies, plans, framework legislations, and roadmaps (Benson and Monciardini, 2018). The European Circular Economy Stakeholder Platform (ECESP) gathers policies for the transition to a circular economy adopted at the national, regional, or local level by public authorities in the EU (ECESP, 2022). **Errore. L'origine riferimento non è stata trovata.** summarizes the current roadmaps adopted to achieve a circular economy model. The key areas that roadmaps focused on are assigned by ECESP. Since water is an important resource in all sectors, the use of circular water contributes to the overall resource circularity in all sectors. But the inclusion of water reuse in irrigation as a step forward to a circular economy is only mentioned in roadmaps prepared by Montenegro and Finland. Salminen et al. (2022) stated that the reasons for ignoring water and water-related ecosystems in circular economy policy tools are that water is seen as a risk that may undermine global peace and is invaluable compared to other resources (such as materials and energy). However, since water is necessary for all sectors and establishes a link between sectors, it should be included in circular economy roadmaps and managed according to this approach. As such, these current roadmaps are urgently required to be updated by considering water use, especially for agriculture sector.

7. Updated roadmap for circular economy in the water sector: In view of widening reclaimed water use in agriculture

Horizon 2020 European Project “Achieving wider uptake of water-smart solutions — Wider-Uptake” aims to overcome the existing barriers toward the transition from linear to circular economy approach in the wastewater sector (Mannina et al., 2021a). Production of irrigation water, fertilizer, soil conditioner, and bioplastic are included as water-smart solution alternatives and demonstrated in laboratory and pilot scale applications (**Errore. L'origine riferimento non è stata trovata.**).

Within the scope of the WIDER UPTAKE project, a roadmap is developed for water-smart solutions that include wastewater reuse and resource recovery according to the circular economy model. **Errore. L'origine riferimento non è stata trovata.** shows the key practices that followed in the roadmap developed to realize systematic transitions. Circular economy roadmaps need to be developed collaboratively because resource circularity occurs between different sectors. Therefore, networking and defining roles are crucial at the beginning of roadmap development. Then, the current situation should be thoroughly examined to show possible future of the transition, barriers and ways to overcome these barriers. Next, the roadmap should be created where the milestones are indicated clearly in this transition process. A plan should be developed to implement the created roadmap into practice. While progressing on the roadmap during the transition, the outputs of the process should be constantly monitored and the roadmap should be reviewed and updated when necessary (Garcia and Bray, 1997; McDowall, 2012). The roadmap developed in WIDER UPTAKE project consists of scoping, forecasting, back casting, transfer, implementation of the roadmap, exploitation of results, and dissemination steps (**Errore. L'origine riferimento non è stata trovata.**). These steps cover perfectly the key practices shown in **Errore. L'origine riferimento non è stata trovata.** for developing a roadmap.

All partners in the WIDER UPTAKE project (universities, private and public sectors from different countries) contributed to the formation of the roadmap. The outputs obtained at each stage of the roadmap creation were shared with the partners and evaluated with the Communities of Practice (CoPs). Lessons learned from CoPs on water reuse opportunities, barriers, and ways to overcome them are:

- Policies, market availability, collaboration, transparency, constant learning, and innovations are decisive for water reclamation projects to be successful.
- Although multi-level policy instruments need to be harmonized across regions, they must have the flexibility to meet local needs. Because the success of the projects is highly dependent on the water availability, agricultural characteristics, and infrastructure of the region.
- Policymakers should be open to innovations and cooperate with water enterprises in this regard.
- Authorities and water utilities need to communicate transparently about their underlying assumptions, values, and goals in water management.
- Water managers are responsible actors in creating circular economy strategies with fit-for-purpose approach and finding potential users.

Lessons learned from good practices together with CoPs indicate that (i) educating the young generation and end-users to create awareness, (ii) demonstrating water-smart solutions to stakeholders to convince them to support projects financially, and (iii) updating and simplifying the regulations to eliminate the factors (too strict water quality limits and complex regulations) that create uncertainties are necessary to achieve successful water reuse projects. Moreover, to reduce the treatment cost and get the maximum benefit from the produced irrigation water, wastewater authorities should follow the circular economy approach from the planning stage of new projects and design the treatment technology according to reuse purpose (fit-for-purpose) (**Errore.**

L'origine riferimento non è stata trovata.). Recently, the state-of-the-art in water-smart solutions and roadmapping toward the circular economy has been published in a book called "Current Developments in Biotechnology and Bioengineering, Smart Solutions for Wastewater: Road-mapping the Transition to Circular Economy" (Mannina et al., 2022). The book covers the current situation and future research perspectives about resource recovery facilities and includes promising preliminary results on water reuse obtained from the WIDER UPTAKE project.

Sicily is an island in the south of Italy (in the Mediterranean region) and 69% of its land is used for agriculture. Irrigation water need in Sicily exceeds the available amount of freshwater sources and causes a water deficit (66×10^6 m^3/year). Ventura et al. (2019) calculated the treated water amount that can be used in irrigation as 163×10^6 m^3/year. Especially in dry periods, treated water reuse in Sicily has a great potential to support the various uses of water, particularly that of the agricultural sector. However, the complex and relatively strict Italian regulation on water reuse increases the treatment costs and makes water reclamation unfeasible. Yet, it is undeniable that the growth margins in the area are evident. Nevertheless, guidance on how to divide the costs of reclaiming, storage, and transport is up to the political decision-maker, and the improvement of the infrastructure serving the different uses remains fundamental.

In order to demonstrate the effectiveness of a resources recovery system from wastewater treatment, a pilot-scale resource recovery plant and irrigation system were established at Palermo University (Sicily, Italy). The pilot plant is fed by wastewater collected from the University Residence and canteen (Mannina et al., 2021b). In the view of water reuse for irrigation, reclaimed water is stored in storage tanks after disinfection. The reclaimed water is used for irrigation of the green areas of the university campus and the greenhouse (**Errore. L'origine riferimento non è stata trovata.**). As with other systematic transitions, demonstrating case studies are vital for transitions to sustainable water-smart solutions. Universities play a crucial role in highlighting the need for achieving a higher environmental sustainability level (Mannina et al., 2021). Particularly, involving students/young generations in educational programs about water-smart solutions helps to create public awareness. Additionally, stakeholders' concerns about health and product quality are resolved and thus hesitations about financing water reuse projects are decreased.

8. Future perspectives and challenges

Water reuse from treated wastewater contributes significantly to the goal of global carbon neutrality. Resources from wastewater treatment (i.e., carbon, nutrients, bioplastics etc.) can be also recovered applying a circular economy approach. Despite such potentialities literature shows that only few real case studies exist especially in the Mediterranean region, such as Sicily, where there is a clear need due to water shortage and a very high potential agriculture demand. Literature shows that main causes are barriers: technological, social, legislative, organizational. A possible solution to overcome such barriers are a robust and comprehensive roadmap which may lead to the transition from a linear to a circular economy model in the water sector. Despite some efforts have been already provided in the literature (e.g., wider-uptake EU project) still there is a need to robust such path spreading among involved multidisciplinary stakeholders (i.e., industry, legislation, researchers, administrative etc.). Policy makers play a central role but not only; indeed, for an effective transition there is the need of education of young generation about the importance of water reuse and resource recovery. With this respect some efforts have been recently provided within Wider-Uptake project building up the first WRRF within a university Campus (i.e., Palermo University, Italy). Such strategy is getting good results in terms of public engagement having the university a potential outstanding role. At present, no other case studies exist and research should go in that direction fostering the creation of such models to break the aforementioned barriers. It is also necessary to develop more targeted solutions (water smart) to allow a real transition to circular economy in the water sector.

9. Conclusions

In this paper, to enhance water circularity in Mediterranean Region, literature on water reuse was examined to reveal the barriers (technological and economic, institutional/regulatory, and social) and the ways (public participation, education, financial support via pricing policies, fit-for-purpose design, planning according to the circular economy concept, updating and simplifying regulations) to overcome these barriers. Current roadmaps on the transition towards a circular economy overlook the importance of water reuse. Thus, a comprehensive roadmap, including scoping, forecasting, back casting, transfer, implementation of the roadmap, exploitation of results, and dissemination steps, is needed as an effective solution.

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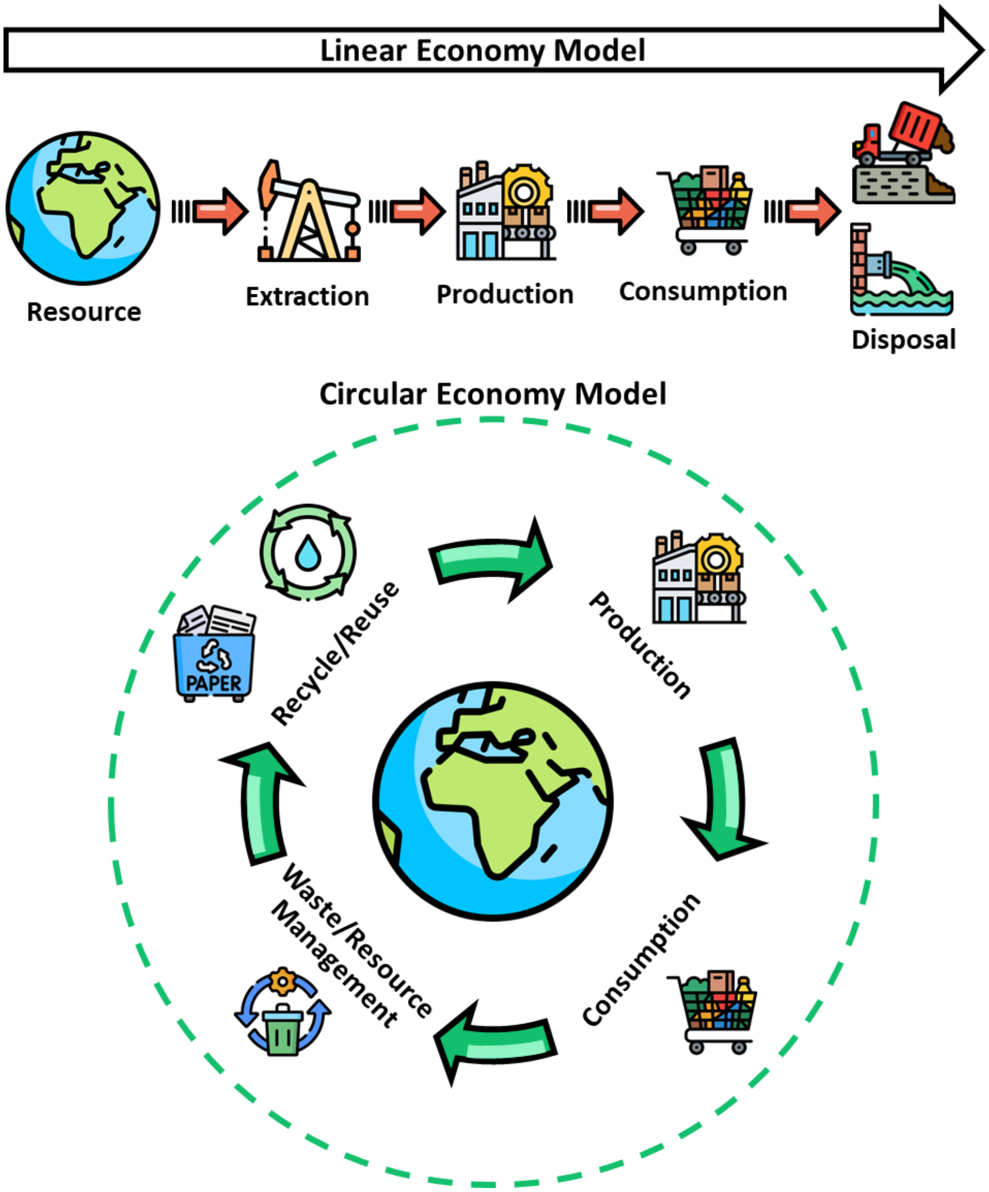

Figure 1. Comparison of linear and circular economy models

Table 1. Roadmaps to achieve circular economy in different parts of the European Union

City/Region/ Country	Document	Year	Key areas	Inclusion of water reuse in irrigation
Montenegro	Roadmap - Towards the Circular Economy in Montenegro	2022	Production Consumption Waste management Innovation and investments	Yes: "Water is an essential resource for the value chains of the food system; however, its sectors are water-intensive. This highlights the importance of transitioning from a linear use of water to sustainable water management practices, such as sustainable irrigation, management of rainwater and **wastewater treatment-to-reuse**."
Germany	Circular Economy Roadmap for Germany	2021	Production Consumption Waste management Secondary raw materials Innovation and investments	No
Finland	Circular Turku - A Roadmap Toward Resource Wisdom	2021	Production Consumption Waste management Innovation and investments	Yes: "The entry of pollutants into water is prevented as effectively as possible, **water is** used efficiently and **reused or recycled locally**."
Republic of Serbia	Roadmap for circular economy in Serbia	2020	Waste management	No
Belgium	Leuven Circulair - a detailed programme for circularity, in the context of Leuven 2030 Roadmap	2020	Production Consumption Waste management Secondary raw materials Innovation and investments	No
Poland	Poland's Circular Economy Roadmap	2019	Production Waste management Secondary raw materials Innovation and investments	No

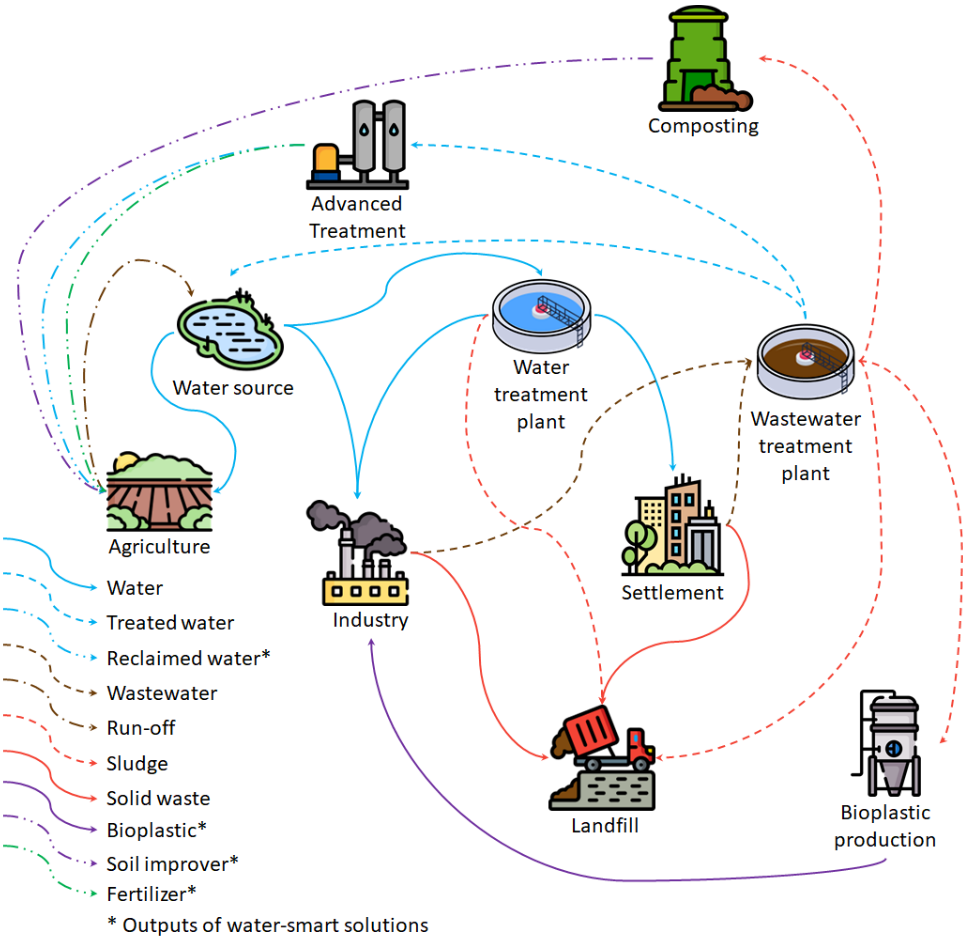

Figure 2. Water-smart solutions demonstrated by Wider-Uptake project for circular economy in wastewater sector

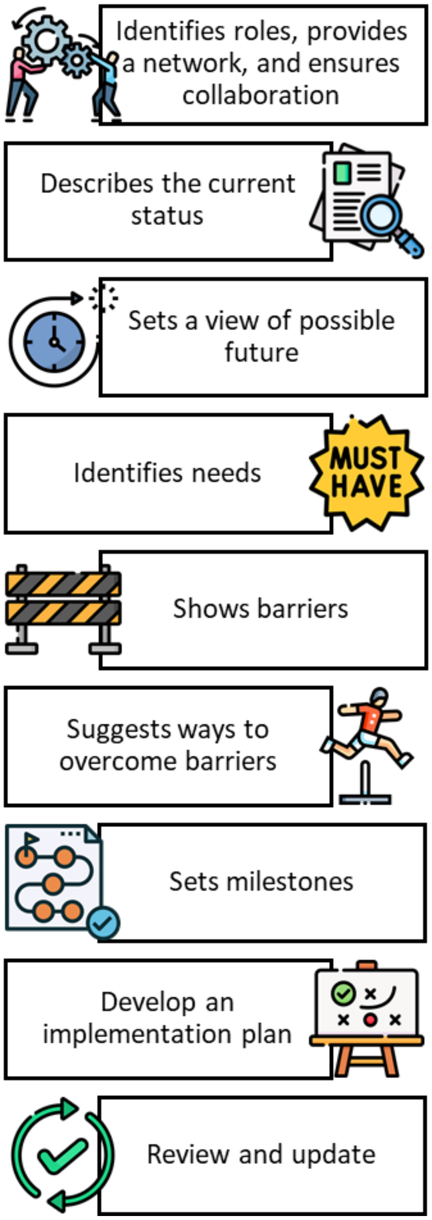

Figure 3. The key practices of roadmaps

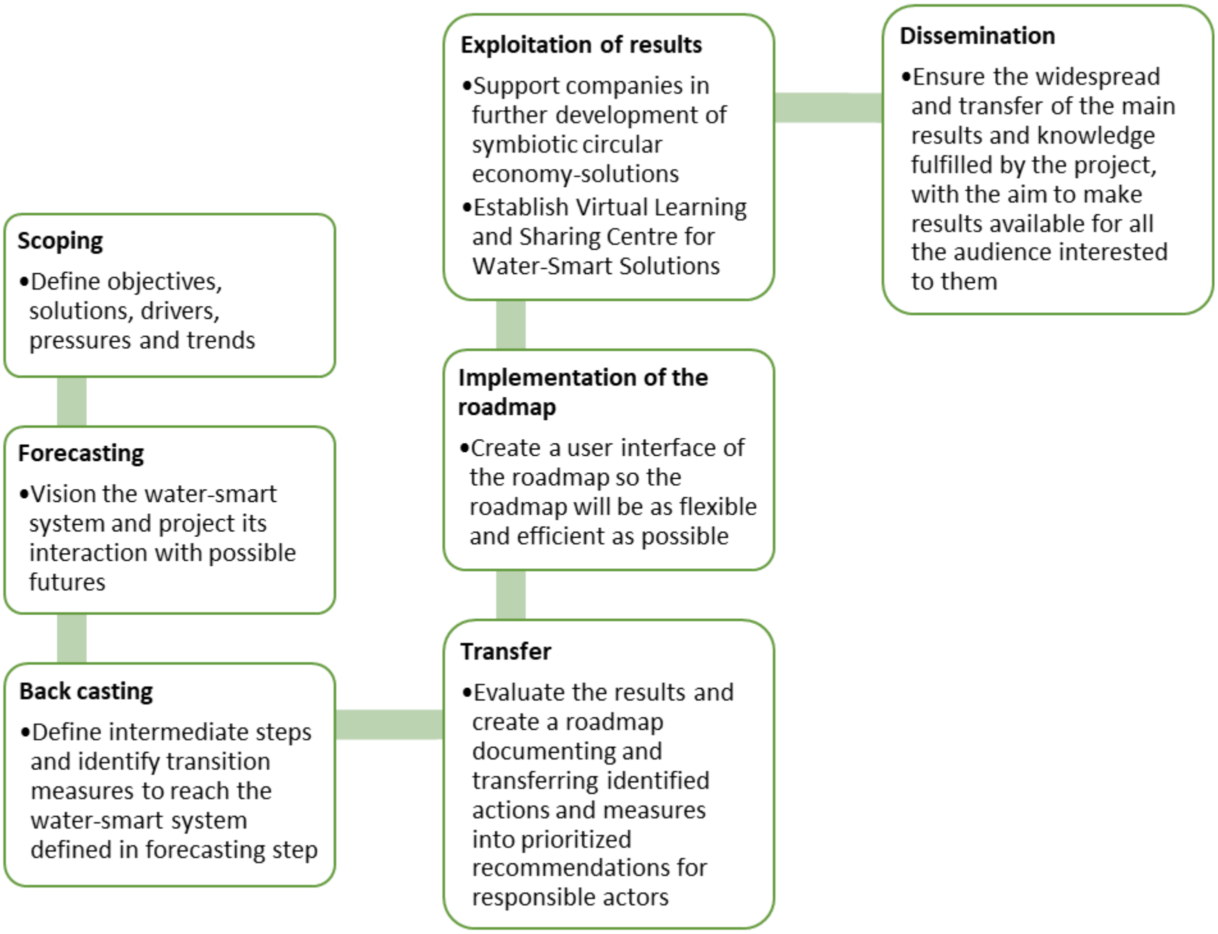

Figure 4. The roadmap towards wide spread use of water-smart solutions in circular economy

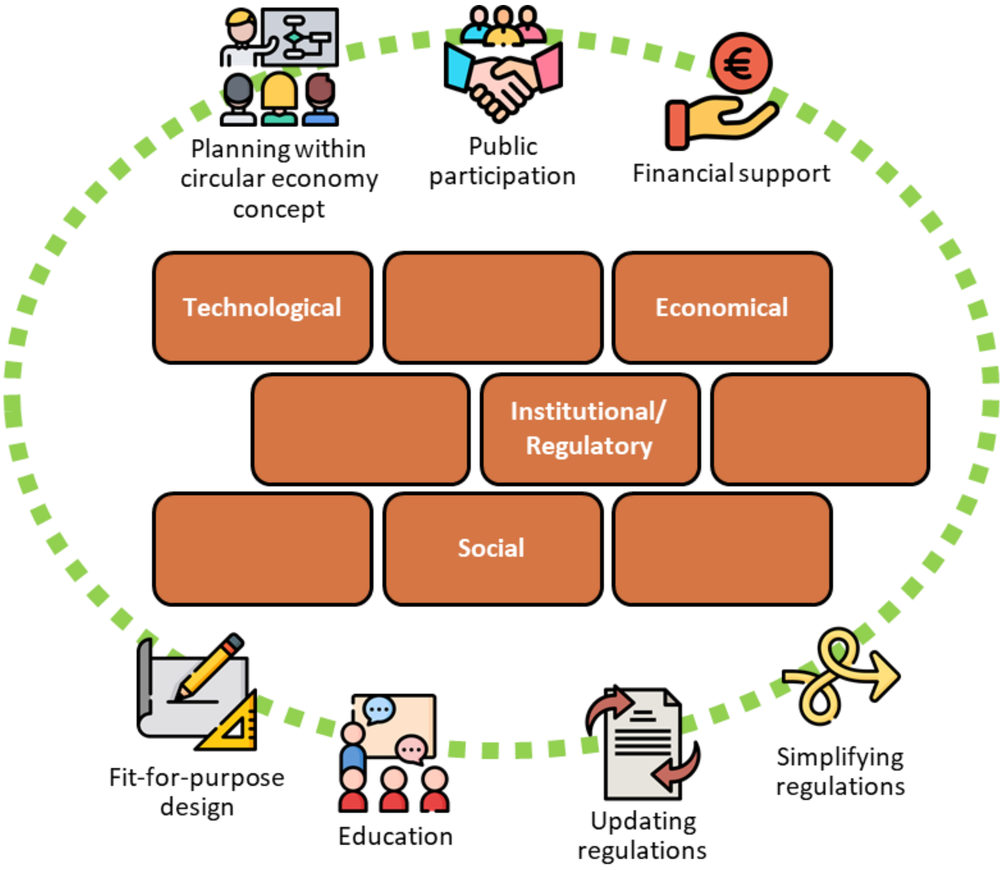

Figure 5. Barriers to the widespread use of reclaimed water in agriculture and what needs to be done to overcome these barriers

Figure 6. The pilot plant for wastewater treatment and water reuse system in Palermo University Campus