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Safe and sustainable solutions for the integrated use of non-conventional water resources in the Mediterranean agricultural sector

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EXECUTIVE SUMMARY

The Mediterranean region suffers from intense water scarcity which is exacerbated by climate change as well as by consumptions patterns which are more intensive in water consumption. In this context, reusing water from municipal wastewater is an effective strategy to increase the availability of water resources. This non-conventional resource is called reclaimed water which can be defined as treated wastewater that meets discharge parameters and subsequently undergoes additional treatment to meet the quality standards required for a specific use according to the legal framework of application. Water reuse is a common practice in countries like Israel, Singapore, Australia, Cyprus and the US States of California and Florida. However, its huge potential is underused in many other areas in the world such as the Mediterranean.

These guidelines are one of the outputs of FIT4REUSE project which aims to develop of innovative solutions for water reuse in with minimum costs and impacts to the environment and human health. However, the use of reclaimed water may pose serious risks to human health and the environment when it is not properly managed

The use of reclaimed water has many proven benefits but also risks associated to the presence of different pollutants. Good practices shall be adopted to minimise risks and these guidelines are intended to compile practical and applicable knowledge to respond to main challenges and risks associated to the use of reclaimed water

Appropriate technologies for water reclamation shall be adopted to ensure compliance with quality standards of the effluent. This document includes a summary of different reclamation technologies for different uses following the "fit for purpose" approach. This includes different disinfection technologies and their potential risks to produce disinfection by-products (DBPs).

Quality requirements of European Regulation 2020/741 on minimum requirements for water reuse are directly applicable to European Mediterranean countries such as Spain, France, Italy and Greece, but it is also reference legislation that influence non-EU Mediterranean countries. Regulation 2020/741 is focused on reuse for irrigation in agriculture, the agricultural sector presents a strong potential to extend the use of reclaimed water in the Mediterranean as agriculture is the economic with highest consumption of water resources.

There are several aspects to be taken into account when using reclaimed water for irrigation such as an adequate irrigation method and proper equipment. Drip irrigation is generally the most suitable technique for the application of reclaimed water due to the low contamination risk and the high efficiency of water application. It is also important to consider the nutrients included in the reclaimed water. Reclaimed water contains nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), which are commonly found in fertilizers. This is commonly ignored by reclaimed water users leading to surplus dosage of nutrients and the consequent pollution of water bodies. It also implies more costs in fertilisers for farmers. Examples on how to perform a nutrient balance and calculate the exact amount of fertiliser when using reclaimed water are also included in these guidelines. Storage and distribution is also crucial for the use of reclaimed water in irrigation as there is a potential risk of microbiological contamination during transport and storage.

Finally, aquifer recharge with reclaimed water is also another alternative for water reuse which was explored under FIT4REUSE. The deterioration in groundwater quality has become a major issue for many aquifers. In urban, industrial, and agricultural areas, a vast array of

contaminants may be found because they are introduced into aquifers through different recharge sources. Aquifer recharge (AR) and aquifer storage and recovery (ASR) are manmade processes or natural processes enhanced by humans that convey water underground. Where soil and groundwater conditions are favourable for artificial recharge of groundwater through infiltration basins, a high degree of improvement in water quality can be achieved by allowing partially treated sewage effluent to infiltrate into the soil and move down to the groundwater. Different solutions are discussed in these guidelines including several case studies such as the case of Soil Aquifer Treatment (SAT) in Shafdan, Israel, with a reclamation plant that treats approximately 135 million cubic meters per year. The secondary effluent from the Waste Water Treatment Plant (WWTP) flows into an operational reservoir and is then distributed to 70 infiltration basins with a total area of 1.1 km^2. The research conducted in FIT4REUSE presents a methodology of how real-time real-world SAT system data can be transformed into metadata, and how to use the data to feed ML models and predict the infiltration rate. Implementation of the Shafdan case study implies that it is theoretically possible to increase the infiltration potential of the basins significantly by optimizing the operational regime.

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ABBREVIATIONS

AR = Aquifer recharge
ASR = Aquifer storage and recovery
BOD = Biological Oxygen Demand
COD = Chemical Oxygen Demand
DBPs = Disinfection by-products
EU = European Union
HAAs = Haloacetic acids
MS = Member States
RW = Reclaimed Water
THMs = Trihalomethans
TSS = Total Suspended Solids
UNIBO = University Alma Mater of Bologna
WWTP = Wastewater Treatment Plants

INTRODUCTION

The Mediterranean region is one of the most water scarce regions of the world. Climate change is increasing the existing pressures on water resources, leading to higher global temperatures, less precipitation and increased evapotranspiration. The agricultural sector is being affected very intensively by climate change. Extreme heat events and reductions in precipitation and water availability affect crop productivity and jeopardise agricultural activity in many regions. Furthermore, most projections indicate significant and growing water demand during the coming decades is expected to increase due to the population growth and changes in dietary and consumption patterns. This situation will increase the demand for crops and agricultural products placing agriculture in a very delicate situation in terms of water security as most of the fresh water is used in irrigation in the Mediterranean.

To respond to this problem, water resources should be managed more efficiently. We need to adapt food-production systems to cope with climate change effects. Reusing water after treatment constitutes an effective and sustainable alternative water supply, and so can be a useful tool for managing water resources in a context of scarcity. The use of reclaimed water in agriculture is a measure for climate change adaptation, it provides circularity to water resources, and potentiality to the embedded valuable compounds such as crop nutrients, contributing to the preservation of ecosystems and the services they provide to humans.

Reclaimed water can be defined as treated wastewater that meets discharge parameters and subsequently undergoes additional treatment to meet the quality standards required for a specific use according to the legal framework of application. For example, this can involve a municipal treatment plant receiving wastewater from households and then sending the outlet for a separate treatment in a water reclamation plant and distributing the effluent (i.e., reclaimed water) by pipe to farmers.

Countries like Israel, Singapore, Australia, Cyprus and the US States of California and Florida are reusing water on a large scale. However, reclaimed water is still an untapped resource in many regions. For instance, in Europe, up to now only 3% of wastewater is reused. More than 40,000 million m^3 of wastewater are treated in EU every year but only 964 million m^3 of this treated wastewater is reused (Hochstrat et al., 2006).

Water Reuse in the Mediterranean

The degree of water scarcity is especially severe in the Mediterranean. The Mediterranean region accounts for 7 % of the world population with water resources per capita of less than 1000 m^3 water/inhabitant/year in South and East Mediterranean countries (Mandi, L., 2014).

The water resources are irregularly distributed in both time and place, and most of them (76% of precipitations and 85 % of renewable resources) correspond to the northern shore countries, and Turkey, while the southern basin of the Mediterranean is going through drought, and consequently, suffering from acute water scarcity. The arid and semi-arid regions of the Mediterranean combine a low rate of rainfall and a high rate of evapotranspiration and are subject to extreme recurrent droughts. Irrigated agriculture is the largest consumer of water in the Mediterranean and therefore sustainable water management is crucial for the sector.

In this context, only 75 % of the wastewater was treated and only 21 % of the treated volume was reused, although this varies considerably from country to country and in the different

regions in every country. These numbers indicate that there is a big potential of water reuse in the Mediterranean region.
Current water reuse is applied mostly in agriculture across the region, including planned projects and unplanned practices mostly in Jordan, France, Spain, Morocco, and Algeria. The volume of water used for irrigation is estimated at 2,100 million m^3, with an average per-hectare consumption of approximately 5,500 m^3/year. Consumption reaches 20,000 m^3/hectare/year in the oasis in the South and is on average about 4,000 m^3/hectare/year in the North, with most of the water being used for irrigation, 72 %, 10 % for drinking and 16 % for industry (Mandi, L., 2014). Water reuse is of utmost interest for agricultural application as irrigation is the highest water consuming sector in Southern European and Mediterranean countries.

Purpose of these guidelines

One of the aims of FIT4REUSE project is the development of innovative solutions for water treatment and reclamation in order to obtain a high-quality effluent with minimum costs and impacts to the environment and human health. However, the use of reclaimed water may pose serious risks to human health and the environment when it is not properly managed. These risks arise from the occurrence of a great variety of microbial pathogens and chemical pollutants in wastewater which are not completely removed in the reclaimed water used for irrigation. The use of adequate water treatment technologies is undoubtedly an important factor, but it is not the only one.
Reclaimed water usually presents higher load of dissolved organic matter (DOM), suspended solids, sodium adsorption ratio (SAR) and salinity compared with its conventional freshwater. When reclaimed water is not properly managed, undesired and adverse effects may occur in the soil, the crop or the irrigation system.
The use of reclaimed water for irrigation brings some challenges due to the need for its nutritional balance assessment, as well as its variation along the distribution network and how it may suffer changes along it and in the storage points. Its enriched composition must be taken into account for a good application in the agricultural sector, meeting the needs of the crops while not causing associated environmental problems such as soil salinity, overfertilization and contamination of soil and water, in case of lixiviation.
Simultaneously, when using this reclaimed water, public health is a concern, making it another important aspect that needs to be considered managing this resource. The diverse irrigation methods result in better or worse rates of water savings and efficiency but when dealing with reclaimed water also implies reduced or amplified exposure to contaminants for both farmers and consumers. The choice of the best irrigation method is, therefore, a priority in the overall situation.
Therefore, safe and sustainable use of reclaimed water require good practices that minimise risks and maximise benefits. When properly managed, reclaimed water used in irrigation does not result in adverse impacts and is safe for human health and the environment. The purpose of the present guidelines is to serve as an advisory document for farmers and water reuse practitioners to promote the improvement of adequate practices and disseminate existing knowledge on water reuse. There are many applications for reclaimed water such as agricultural, aquifer recharge, process water for different industrial processes, and even potable water. These guidelines will focus on the first two applications as they are the ones included in FIT4REUSE technological solutions. The guidelines are based on existing literature

and try to compile practical and applicable knowledge to respond to main challenges and risks associated to the use of reclaimed water.

Benefits and barriers of water reuse

Circular economy approaches have grown interest as response to the rising costs of raw materials and the associated environmental impacts of by-products and non-sustainable waste management. The use of reclaimed water has proven benefits. The main advantages can be summarised as follows:

- Availability of a constant source of water independent of climate events;
- Incentives to extend wastewater treatment in areas with deficient sanitation infrastructure;
- Supply of water and nutrients thus enabling irrigators to reduce costs by reducing fertilser consumption;
- Reduction of diffuse pollution as crops absorb the nutrients in the reclaimed so that they do not accumulate in water bodies (if properly managed);
- Net increase of water resources in coastal areas;
- Lower impacts and costs than other alternative water supply options (e.g., desalinated water or water transfers).

Nevertheless, there are still significant barriers for the implementation of water reuse in practice. Reuse water requires adequate treatment and reclamation facilities and this implies investment in infrastructures to upgrade existing ones when they are not able to meet reuse standards or to install new sanitation and reclamation facilities when non-exisiting. Even when benefits of reuse are clear, it is not easy to assess if those benefits will pay-off the necessary investments needed for reusing water. Moreover, operation and maintenance of such infrastructure and monitoring water quality also implies operational costs. Water pricing shall be adapted to cover those costs and this is always a difficult decisions for authorities.

Lavish bureaucratic procedures to obtain a license for water reuse also constitute a barrier, especially in countries or regions where there is not a clear and coherent regulatory framework. If there is not an institutional body responsible for water reuse management, this can be an even larger obstacle. This might happen due to lack of specialized people and knowledge or even due to political reasons when decision makers do not consider water related issues a priority.

Another barrier to water reuse is the negative perception associated to the use of a water resource which is coming from the sewage system. This is described by Ricart *et al.*, 2019 as the "yuck factor", which is translated into an irrational rejection of consuming agricultural products which have been irrigated with reclaimed water regardless the quality and monitoring of the resource. This fear might be sometimes linked to the potential presence of pathogens in fruits and vegetables, but also farmers might be reluctant to irrigate with reclaimed water when they fear of impact in crop productivity and quality.

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1 QUALITY STANDARDS IN THE EU REGULATION 2020/741

In 2020, it was approved the European Regulation 2020/741 on minimum requirements for water reuse. This is a regulatory framework that affects directly to EU Mediterranean countries such as Spain, France, Italy and Greece, but it is also reference legislation that probably influence other non-EU Mediterranean countries such as Morocco, Tunisia, Egypt, Lebanon or Jordan.

EU Regulation 2020/741 aims to guarantee the safety of agricultural irrigation with reclaimed providing high levels of protection for environmental, human and animal health. This is ensured by two type of requirements, namely i) monitoring and quality requirements and ii) water reuse risk management plans. Moreover, end-users of the reclaimed water are required to obtain a permit with the provisions applicable to their specific situation (e.g. applicable quality class, responsibilities of each actor, provisions of the risk management plan, etc.).

The European Regulation 2020/741 sets requirements which are, in some cases, stricter than those previously imposed by EU Member States (MS). Therefore, there is a need to adapt procedures and controls to the new scenario. Monitoring and quality requirements are to be met at the "point of compliance", i.e. the point where a reclamation facility operator delivers reclaimed water to the next actor in the chain. Therefore, sampling and analyses to monitor water quality shall be applied to the effluent of the reclamation facility. Annex I of the Regulation sets the different quality parameters for different categories which depend on the potential contact between water and crop, the final use of the crop (e.g. consumed raw, food processing, industrial uses, etc.) and the irrigation method as shown in table 1).

Table 1: Minimum requirements for water reuse

Minimum reclaimed water quality class	Crop category (*)	Irrigation method
A	All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw	All irrigation methods
B	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	All irrigation methods
C	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	Drip irrigation (**) or other irrigation method that avoids direct contact with the edible part of the crop
D	Industrial, energy and seeded crops	All irrigation methods (***)

(*) If the same type of irrigated crop falls under multiple categories of Table 1, the requirements of the most stringent category shall apply.

(**) Drip irrigation (also called trickle irrigation) is a micro-irrigation system capable of delivering water drops or tiny streams to the plants and involves dripping water onto the soil or directly under its surface at very low rates (2–20 liters/hour) from a system of small-diameter plastic pipes fitted with outlets called emitters or drippers.

(***) In the case of irrigation methods which imitate rain, special attention should be paid to the protection of the health of workers or bystanders. For this purpose, appropriate preventive measures shall be applied

For these four quality classes, the Regulation 2020/741 sets out quality requirements for several parameters, namely E. Coli, Biological Oxygen Demand (BOD_5), Total Suspended Solids (TSS), Turbidity and in specific cases, Legionella and intestinal nematodes. These requirements are additional to those requirements for the discharge of treated wastewater set out in the Urban Wastewater Treatment Directive or Directive 91/271/EEC.

Table 2: Quality requirements to irrigate with reclaimed water according to each quality class

Reclaimed water quality class	Indicative technology target	Quality requirements				
		E.coli (number/100 ml)	BOD_5 (mg/l)	TSS (mg/l)	Turbidity (NTU)	Other
A	Secondary treatment, filtration, and disinfection	≤ 10	≤ 10	≤ 10	≤ 5	Legionella spp.: < 1 000 cfu/l where there is a risk of aerosolisation Intestinal nematodes (helminth eggs): ≤ 1 egg/l for irrigation of pastures or forage
B	Secondary treatment, and disinfection	≤ 100	In accordance with Directive 91/271/EEC (Annex I, Table 1)	In accordance with Directive 91/271/EEC (Annex I, Table 1)	-	
C	Secondary treatment, and disinfection	≤ 1 000			-	
D	Secondary treatment, and disinfection	≤ 10 000			-	

Regulation 2020/741 also sets the obligation to validate any new reclamation facility which is put into operation. This is applicable for new reclamation plants and also when the current infrastructure is upgraded and new equipment or processes are added. With this purpose, Annex I of the Regulation sets out reduction performance targets for indicators associated with each group of pathogens, namely bacteria, viruses and protozoa.

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Table 3: Performance targets for pathogens indicators to validate new or upgraded reclamation facilities.

Reclaimed water quality class	Indicator microorganisms (*)	Performance targets for the treatment chain (log_{10} reduction)
A	E. coli	≥ 5,0
	Total coliphages/F-specific coliphages/somatic coliphages/coliphages (**)	≥ 6,0
	Clostridium perfringens spores/spore-forming sulfate-reducing bacteria (***)	≥ 4,0 (in case of Clostridium perfringens spores)
(*) The reference pathogens Campylobacter, Rotavirus and Cryptosporidium may also be used for validation monitoring purposes instead of the proposed indicator microorganisms. The following log10 reduction performance targets shall then apply: Campylobacter (≥ 5,0), Rotavirus (≥ 6,0) and Cryptosporidium (≥ 5,0). (**) Total coliphages is selected as the most appropriate viral indicator. However, if analysis of total coliphages is not feasible, at least one of them (F-specific or somatic coliphages) shall be analysed. (***) Clostridium perfringens spores is selected as the most appropriate protozoa indicator. However, spore-forming sulfate-reducing bacteria are an alternative if the concentration of Clostridium perfringens spores does not make it possible to validate the requested log10 removal.		

Finally, the Regulation includes general provisions to perform water reuse risk management plans in Annex II. In this sense, the regulation sets three sections within the plans:

A. Key elements of risk management: This section includes a description of the entire water reuse system, the roles and responsibilities of all the actors involved, the identification of hazards, environments and populations at risk, as well as the exposure routes. This information shall enable to perform an assessment of risks to the environment and to human and animal health.
B. Conditions relating to the additional requirements: The risk assessment may result that it is necessary to include stricter and/or additional requirements for water quality and monitoring than those specified in Annex I in order to ensure adequate protection of the environment and of human and animal health.
C. Identification of preventive measures: Measures that are already in place or that should be taken to limit risks so that all identified risks can be adequately managed. Special attention shall be paid to water bodies used for the abstraction of water intended for human consumption and relevant safeguard zones.

The EU Regulation 2020/741 was published in the Official Journal of the EU on the 5th of June 2020 and will apply from the 26th of June 2023.

2 TECHNOLOGIES FOR WATER RECLAMATION

2.1 Water reclamation technologies

During the treatment of municipal wastewater, WWTPs are placed to remove contaminants that are unhealthy or undesirable for the environment before discharging the effluent to a river or another water body. When we are dealing with reuse, and additional treatment is needed for water reclamation in order to achieve the quality standards needed for an intended use.
Considering today's technologies, water treatment and reclamation can be performed at a very high level and achieve adequate standards for reuse. The quality of reclaimed water needed for a specific use is defined by different parameters depending on the final purpose (e.g., agriculture, aquifer recharge, streets cleaning, etc.), ensuring that reclaimed water poses no risks to animal and human health and the environment. This approach is called "fit-for-purpose".
Once the wastewater is treated in urban WWTP and comply with the discharge standards, the effluent can be sent to the water reclamation plant where additional treatment technologies are applied for water reclamation in order to achieve the specific standards of the intended use. For instance, in EU countries, wastewater shall be treated for reuse in agriculture according to the standards defined by A, B, C and D classes which depend on the final use of the crop, type of irrigation method and level of contact between crop and reclaimed water. The technologies that can be used to reclaim the water coming out of the wastewater treatment plant in accordance with reuse are listed below.

Table 4: Water reclamation for each water quality class of EU 2020/741

Technology	Advantages	Disadvantages	Water Class
Membrane filtration	High bacterial, nutrient, BOD,TSS,EC, Na, and Cl removal efficiency. Simultaneously disinfection.	High investment and operation cost.	A
Ponds, constructed wetlands	Low maintenance costs and energy usage, no formation of by-products	Large footprint, efficiency depending on meteorological conditions	B-C
Medium filtration	Low investment costs, low operating costs	Low removal of fecal coliform	C-D
NaOCl	High bacterial action, Low operating costs	High operability, high formation of by products, moderate investment costs	A
Electrolysis	Effective in killing a wide spectrum of microorganisms with low current charges	Formation of significant amounts of perchlorates	A
TiO2	Likely use of renewable energy in the case of solar photocatalysis, no formation of by-products, use of inexpensive catalysts and facilities	Lack of residual bactericidal action and slow kinetic behaviour	A
Anaerobic Ponds, Facultative Ponds	Resistant to organic and hydraulic shock loads High reduction of solids, BOD and pathogens High nutrient removal if combined with aquaculture	Requires a large land area - High capital costs depending on the price of land - Requires expert design and construction	A-B

	Low operating costs No electrical energy is required No real problems with insects or odours	- Sludge requires proper removal and treatment	
Advanced Oxidation processes	Rapid response time, minimalist footprint, organic mineralization, disinfection	Capital/operating costs, residue peroxide	A
Activated Carbon Adsorption	High efficiency in VOC removal Simple and robust technology Suitable for discontinuous processes Easy to maintain Easy to place	Dust can lead to blockages Component mixes may lead to early malfunction Risk of spontaneous combustion in the bed Polymerisation risk for unsaturated hydrocarbons on the activated carbon	A

Upgrade alternatives

Great efforts need to be conducted to upgrade the existing WWTPs processes. Chemical coagulants have been applied successfully to enhance the performance of existing WWTPs and to improve the quality of the produced sludge . Moreover, cost-effective natural wastewater treatment processes such as constructed wetlands (CWs), oxidation ponds, maturation ponds, lagoons and anaerobic processes have been also implemented for the same purposes.
Therefore, the upgrading and optimizing of dated WWTPs is essential to meet the new effluent standards while considering the cost effectiveness within an economically responsible and environmentally sound framework.

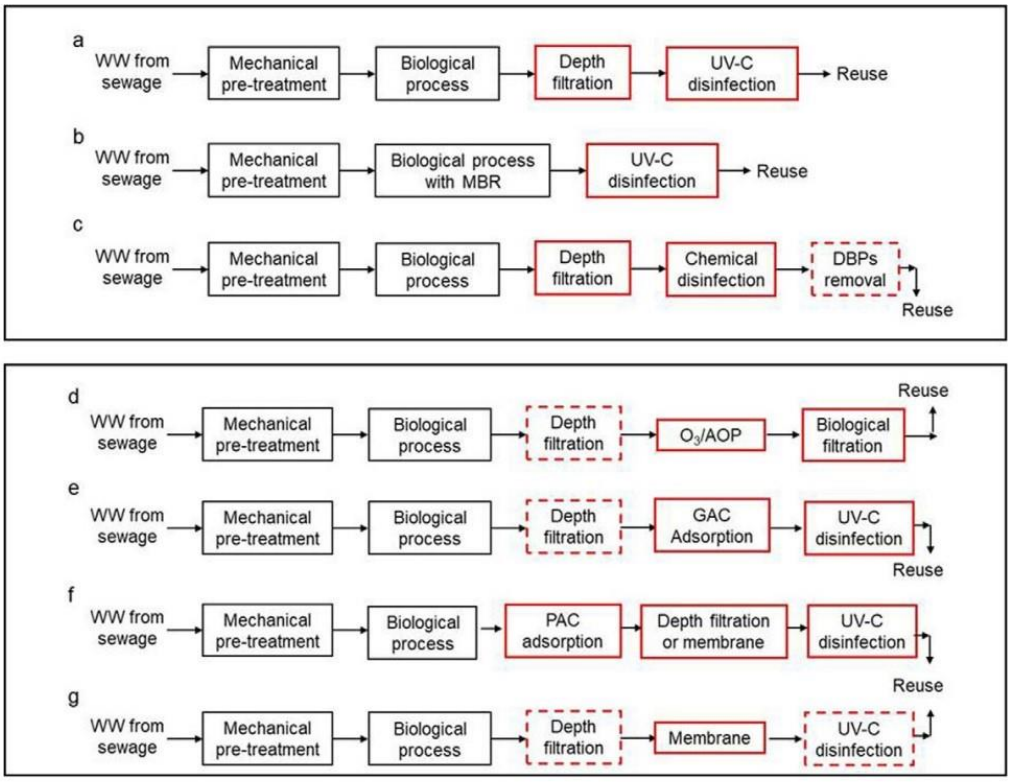

Figure 1: Upgrade alternatives for different treatment plants

2.2 Water disinfection

Disinfection is the inactivation or destruction of micro-organisms that cause disease. In irrigation, disinfectant agents are used to reduce pathogenic microbial loads on the water and comply with sanitary standards needed avoid negative impacts of health of consumers. The most commonly used disinfectants are the oxidizing disinfectants, and chlorine is the one used most universally. Ozone is highly effective disinfectant and its use is increasing. Highly acid or alkaline water can also be used to destroy pathogen bacteria, because water with a pH greater than 11 or less than 3 is relatively toxic to the bacteria.
When reclaimed water is used in irrigation, the potential of the microbiological contamination needs to be carefully considered. In recycled water, we have high initial microbial content but it changes to low risk with sufficient and appropriate treatment.
While treatment of irrigation water might be effective in reducing the incidence of pathogen contamination through direct transfer of pathogens from irrigation water to plant surfaces and soil, changes in agricultural management practices might also be required to reduce the potential for endophytic pathogen colonization from contaminated soil and/or manure-based fertilizers.
To reduce the potential for pathogen contamination of fresh produce, selection of an appropriate water source and/or pretreatment of irrigation water is critical. Irrigation practices and distribution networks must be maintained to the highest possible standards to ensure that the potential for contamination is minimized. As with drinking water treatment, a multiple barrier approach would be considered to ensure that irrigation water quality remains high even in the event of failure or suboptimal performance of individual treatment modules. On-site treatment of irrigation water could represent an important component of a multiple barrier approach, especially in the context of irrigation with recycled water.
However, a risk related to chemical disinfection of irrigation water is the possible accumulation of undesirable by-products in the crops. The occurrence of disinfection by-products (DBPs) as pollutants in irrigation water has been highlighted as a health risk of emerging concern since they can be uptaken by the plant and accumulated in the edible parts during crop production. Several reports showed the risks for the presence of DBPs in reclaimed water, including regulated trihalomethanes (THMs) and haloacetic acids (HAAs), and emerging nitrogenous DBPs (Garrido et al, 2020). Disinfection doses must be optimized to maximize pathogen inactivation while responsibly managing the formation of DBPs.

Chlorination
Chlorination is the most common disinfection treatment in use to date for wastewater to minimize the health risk caused by pathogenic microorganisms. Chlorination is generally done by adding gaseous chlorine (Cl_2) or liquid sodium hypochlorite (bleach, NaOCl) to form hypochlorous acid. In the presence of bromine, hypobromous acid is also formed. Both chlorine and bromine are in the "halogen" group of elements and have similar chemical characteristics. Hypochlorous and hypobromous acid form strong oxidizing agents in water and react with a wide variety of compounds, which is why they are such effective disinfectants. 600 water disinfection by-products, including haloacetic acids (HAAs). THMs, and to a lesser extent HAAs, are currently used as indicator chemicals for all potentially harmful compounds formed by the addition of chlorine to water. In many countries the levels of THMs and HAAs in chlorinated water supplies are regulated based on this assumption.

Chlorination is an acceptable method for disinfecting water and reuse it in agriculture. However, there is a limitation of 1 mg/l of chlorine at the point of application of reclaimed water (Ishak, 2018). These limits mostly do not harm the plant life. However, some sensitive crops may be damaged at a level of chlorine lower than 1 mg/l especially if there is direct contact between the reclaimed water and the edible part of the crop. Users should therefore consider the sensitivity of the crop and the potential contact with reclaimed water to decide the best disinfection method. Chlorine, no matter the form, is a toxic and corrosive substance. Safety precautions should be observed at all times when handling chlorine. Chlorine may react with some metal and plastic components of irrigation systems. Therefore, always check with the manufacturer or supplier of system components to identify any potential problems before beginning a chlorine injection program. Chlorine should be injected before (upstream of) the system filter(s) so that any precipitates that form can be trapped in the filters. Filters should be cleaned on a regular basis to maintain their operational capabilities.

Other disinfection technologies:

Selection criteria for disinfection technologies can generally be broken down into three categories—technological, managerial, and sustainability related. Disinfection processes can involve the application of chemicals, such as chlorine, ozone (O_3), peroxyacetic acid (PAA), or hydrogen peroxide (H_2O_2), or might be based on non-chemical disinfection methods like ultraviolet (UV) irradiation. As the scientific literature about on-site disinfection of irrigation water is rather limited and generally targeted toward plant pathogens rather than human pathogens.

Table 5: Comparison of disinfection technologies for using reclaimed water in agriculture

Process	Process	Advantages	Disadvantages
Chlorination	gaseous chlorine (Cl_2) or liquid sodium hypochlorite (bleach, NaOCl) is added to, and reacts with, water to form hypochlorous acid. In the presence of bromine, hypobromous acid is also formed.	Effective disinfectant Easily adaptable to change Easily measurable Chlorination is a cheaper source than UV or ozone disinfection methods used to treat water. It is very effective against a wide range of pathogenic microorganisms. Dosing rates are controlled easily as they are flexible. The chlorine residuals left in the wastewater effluent can make the disinfection process longer even after initial treatment. They can be further used to evaluate the effectiveness	Minimum 30 min detention time Effective mixing need Traces
Ozonation	Ozone is an allotropic (unstable) formula of oxygen in which three molecules are combined to produce a new molecule. It quickly decomposes to generate highly reactive free radicals. The ozone's oxidation potential (−2.7 V) is greater than that of the chlorine (−1.36 V) or hypochlorite ion (−1.49 V), substances widely used in wastewater treatment such as oxidants. Ozone is surpassed only by the hydroxyl radical (•OH) and fluoride in its oxidation capacity	Ozone possesses strong oxidizing power Short reaction time is needed so germs (including viruses) are killed in a few seconds No change in color and taste occurs. Requires no chemicals Oxygen is provided to water after disinfection Destroys and removes algae Oxidizes iron and manganese Reacts with and removes all organic matter	Min detention time varies No immediate measure of success Energy intensive Relatively expensive It is toxic in high concentrations as it is a greenhouse gas. It is unstable at atmospheric pressure.
Lagoon based		Economic	the excessive growth of undesirable organisms, such as blue-green algae.Land need
UV	UV light energy between 100 400 nm wavelength. treatment can be used for	Can be applied both high and low flow conditions	The major limitation is the energy requirement. In many systems, the electric power supply cannot be guaranteed.

	treating waste water, drinking water, and aquaculture. The UV light causes disinfection by changing the biological components of microorganisms specifically breaking the chemical bonds in DNA, RNA, and proteins	It limits the regrowth potential within the distribution system so no increase in the concentration of biodegradable or assimilable organic carbon (AOC) occurs. With respect to interactions with pipe material, there are no concerns. No by-products are formed (e.g., hemoglobin-associated acetaldehydes (HAA), trihalomethanes (THM), aldehydes, ketoacidosis, and bromate). By using UV light we can achieve the same log inactivation of Giardia and Cryptosporidium, less in cost either than chlorine dioxide and ozone techniques. When used in relation with chloramines, no formation of chlorinated disinfection by-product (DBP) is noticed	It is only effective as a primary disinfectant as it does not leave any residues. It does not act as a secondary disinfectant as it does not work against reinfection in water.
Photocatalytic Disinfection	In photogenerated catalysis, electron–hole pairs are created by the photocatalytic activity (PCA) generating free radicals (e.g., hydroxyl radicals: •OH) that have the ability to undergo secondary reactions.	Photocatalysis uses capacity for renewable and pollution-free solar energy, thus it is a good replacement for the energy-intensive conventional treatment methods. In comparison to the conventional treatment methods photocatalysis leads to the formation of harmless compounds. Waste water contains different hazardous compounds. Photocatalytic process causes destruction of a wide range of these hazardous compounds in various wastewater streams. These reactions are mild. Less chemical input is required and the reaction time is modest. It can be applied to hydrogen generation, gaseous phase, and aqueous treatments as well for solid (soil) phase treatments to some extent	For the effective TiO_2 application in water treatment, the mass transfer limitation has to be minimized since photocatalytic degradation mainly occurs on the surface of TiO_2. TiO_2 has poor affinity toward organic pollutants (more specifically the hydrophobic organic pollutants) so the adsorption of organic pollutants on the surface of TiO_2 is low that results in slow photocatalytic degradation rates. the slurry system, one main practical challenge to overcome is to recover the nanosized TiO_2 particles from the treated water in regards to both the economic concern and safety concern

3 RECOMMENDATIONS FOR IRRIGATION

3.1 IRRIGATION METHODS AND IRRIGATING WITH RECLAIMED WATER

In order to determine which irrigation method is more suitable for irrigating with reclaimed water, there is a need to understand which methods are available and which are the most efficient, as well as comprehending the limits and obstacles of reclaimed water use through the effect it has throughout the irrigation process, both in the system itself (and how it is affected) and for the workers exposed to it and finally the consumers of the yields.
Most irrigation methods used in agriculture divide in two main group: Gravity-driven or Surface irrigation and Pressure-driven irrigation (Fawibe *et al.*, 2022), further dividing into a palette of specific types with smaller variations between them.

3.1.1 Gravity-driven or Surface irrigation

Gravity-driven irrigation, as its own name indicates, is the most natural and simplest approach to irrigation without the use of tubing or complex accessories, relying on the water's mobility properties according to the topography and gravity. This type of irrigation is suitable for flat cultivated areas, allowing for a homogeneous distribution and it is divided in three stages: advance, storage and recession, according to the same author.
The first stage is the introduction of the water to the field, flooding it by gravity, while the second one corresponds to the time interval that the water takes to infiltrate the soil and the last one initiates when the eater supply is cut off. The efficiency of this type of irrigation is determined not only by the topography of the terrain, but also the soil's properties such as its water retainability and roughness among others. Evapotranspiration rates are also important, conditioning a part of the water's loss.
This irrigation method englobes at least two sub methods, which are Continuous flooding and Furrow irrigation.

3.1.2 Continuous flooding / Flood irrigation

This process consists in submerging a crop, artificially (figure 3). It is an irrigation method commonly used in Asia, for rice cultivation, which is an aquatic plant. The water sheet has to reach centimetric thickness, varying on the plant type and location properties, and must be continuous throughout the cropping season.
This is an extremely water consuming irrigation type, aggravated by its high percentage of water loss and also a generator of greenhouse gases, overall, not efficient neither recommended, being the least preferable method to be applied.

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Figure 2: Crop irrigated with Flood Irrigation

3.1.3 Furrow irrigation

In this process, the water supply is done through furrows, which are narrow parallel canals or water paths between the cultivated parts of the crops (figure 3). These canals have to be made, but are of simple construction, and then, alike the previous method, the irrigation is topographically and gravitationally driven. One of its down points is the possible negative effect on the plant's respiration if they're flooded, in addition to the considerable water volume used and lost, also resembling the Continuous Flooding.

Figure 3: Crop irrigated with furrow irrigation

3.1.4 Pressure-driven Irrigation

These types of irrigation systems use pressure systems instead of gravity for the water's distribution. They were developed in light of water scarcity phenomena happening globally, allowing for a more efficient water distribution and use. Although it is necessary to invest in the pipeline network and the consumption of energy for the irrigation itself, the control and precision it allows for in terms of quantity and location of the water distribution is compensatory.
The type of pressure-driven irrigation method should be chosen according to many criteria, such as the type of vegetation, soil, topography, required water volume and pressure and, in this case, cost also.
Two commonly used Pressure-driven irrigation methods are Drip irrigation and Sprinkler irrigation.

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3.1.5 Drip irrigation

This method of irrigation can be efficiently applied in row cropping. The irrigation tubes are installed on the soil surface or some centimetres inside the soil, directly reaching the plant's root region, (figure 4) making it very efficient due to the water savings achieved. Only 15 % to 60 % of the soil surface is wet using this system, and the drop application reduces runoff and percolation phenomena (figure 5).
Other advantages to this system are the higher control in the whole irrigation process, resulting in a better water management, as well as disease and salinity control, improving the yield's quality and optimizing the application of fertilizers or other additives.


Figures 4 and 5: Crops with installed drip irrigation and active irrigation in the second figure

3.1.6 Types of drippers

There are a variety of drippers available. The pipeline insertion differentiates the type of dripper: <u>in-line</u> drippers are an integral part of the dripping laterals while <u>on-line</u> drippers are mounted on top of the lateral pipes.
On-line drippers are more suitable for crops where plants are set out spacious and it offers the possibility to split outlets and make adjustments for individual plants. In-line, on the other hand, are used for denser crops and underground irrigation and they are commercialized with defined spacing intervals between the drippers. Furthermore, both types of drippers, on-line and in-line, can be pressure compensated, allowing for a constant water flow, (Baeza et al, 2020).
In "Evolution of Thirty-Eight Models of Drippers Using Reclaimed Water: Effect on Distribution Uniformity and Emitter Clogging" the authors concluded that on-line emitters had a higher percentage of flow reduction and showed less uniformity of flow distribution coefficient. In-line emitters performed better in terms of uniformity and clogging issues.
The greater reduction in uniformity of the on-line emitters was due to the pressure-compensating emitter models, because of a higher sensibility to clogging by biofilm formation compared to non-compensated emitters, (Gamri et al., 2013).
However, it is also obvious that some operations measures, such as intermittent irrigation, have an effect on the dripper performance because the biofilm dries, as well as resulting in a fluctuation of quality and flow rate.

3.1.7 Drip Irrigation with Reclaimed Water

Alike fertigation, which is the irrigation with a mix of water and soluble fertilizers previously added, reclaimed water provides dissolved nutrients to the crop, which have a much higher plant intake efficiency than the addition of solid fertilizers. According to Ashrafi et al., the absorption rate of fertilizer in a solid inorganic phase was between 10 % and 40 % while the estimation for an equivalent concentration but through fertigation was 90 %. This author also concluded that yields such as cotton and tomatoes were notably higher (from 20 % up to 52 % higher), when using fertigation, comparing to the same plantations but using furrow irrigation and direct fertilizer application.

3.1.8 Sprinkler Irrigation

In this method the crops are irrigated through sprinklers, the closest type of irrigation to the natural phenomenon of rainfall. There are different types of sprinklers, varying the infrastructure of irrigation, its' mobility and way of operating, but the water mechanism is common: the water comes out of the sprinklers in high pressure and spray form, into the air, falling in a droplet form on top of the plants (figures 6 and 7).
There is a need to install sprinklers close together, according to their pressure and reach, once that the water distribution is uneven, being more concentrated near the sprinklers and more spaced out with distance to them. There are different pressure sprinklers available, from the low-pressure extreme (which has the smallest nozzle diameter, the lesser pressure and discharge and the smallest diameter of coverage) up until the high pressure one, that can go up to 7 bars of pressure and 60 m diameter of coverage.
This method of irrigation can be used on different terrains, but its more commonly used in flat topography crops. It is also adaptable to most soils, but more efficient on permeable sandy soils.


Figures 6 and 7: Crops irrigated with different types of sprinklers

According to Phocaides *et al.*, 2007, pressurized irrigation techniques make the delivery of small quantities of water over big areas, regardless of the terrain, possible. The water losses that occur with this type of irrigation in a well-maintained network are negligible, its major drawback being the energy consumption and gear necessary for the functioning of the pumps and distribution networks.
There are also micro-spray devices that spray water in small areas close to the plants, commonly used for tree and vine crops with wider root zones. Their water application efficiency is slightly lower than drip systems (80 %), due to the fact that they have larger water

passages and higher flow rate, (Lazarova et al., 2004), and the small diameter of the devices' jets (< 1 mm) make them prone to partial and total plugging of emitters.

3.1.9 Clogging in the pressure-driven irrigation systems

A common disadvantage of both drip and sprinkler irrigation is the complications that might occur in the emitters – the piece of the irrigation system where the water comes out, often clogging. This directly affects the quality of irrigation because the water amount and quality might not reach the plant's roots as it should. The clogging can happen due to physical turbidity (caused by the presence of sediment particles in the water), biological turbidity (presence of bacteria) resulting in biofilm formation, which is a thin barrier that adheres to materials caused by the presence of microorganisms (Pachepsky *et al.*, 2012), and chemical turbidity (due to the presence of fertilizers or salts). The build-up caused by one or more of these types of turbidity can impede the water passage, decreasing the irrigation effectiveness.
However, there are different strategies to prevent clogging, such as:

- a filtration system;
- previous to irrigation sediments settlers;
- often cleaning the irrigation network through flushing;
- the addition of a chemical cleaner like chlorine.

In order to irrigate using reclaimed water with the most efficiency possible there are some aspects that should be taken into consideration:

- <u>Exposure of workers and / or consumer to the reclaimed water</u>

This is a conditional aspect of the irrigation process' choice, regulated by legislation of water reuse. Generally, the sprinkler irrigation methods, particularly the ones that produce aerosol, are the ones which present a higher health risk, and consequentially demand a higher protection of the field workers. On the opposite side, drip irrigation is the one which presents a lower health risk due to low human exposure, both the workers and consumers.

- <u>Irrigation efficiency</u>

The efficiency of an irrigation method is defined as the ratio between the water which is accessible (and up taken by the plant) and the total of water that is applied; the gap of water in this ratio is lost in its transport, run off, etc. In most cases, pressurized systems have a higher efficiency than gravity driven ones, although several factors such as the quality of the irrigation system, water quantity, soil characteristics, type of crop, etc. should be considered.

- <u>Clogging considerations</u>

The presence of high suspended solids, mineral precipitations and the possible biological growth can cause clogging in the irrigation systems network distribution. When using drip irrigation, the last two factors are of high relevance, possibly becoming problematic due to lengthy distribution tubes and a low water velocity.
In the following table (table 7) there is an overview of these characteristics and some others for the different irrigation methods:

Table 6: Resume table of Irrigation methods and some of their specifications

Irrigation method	Measures for irrigation with reclaimed water	Leveling	Cost	Irrigation Efficiency	Health protection
Continuous flooding / Flood irrigation	High protection of field workers, crop handlers and consumers necessary	Not required	Lowest	Low	Low
Furrow irrigation	Low level of wastewater treatment necessary Protection of field workers and possibly of crop handlers and consumers necessary Adecuate crop selection necessary	Some leveling might be necessary	Low to Medium	Low	Medium
Sprinkler irrigation	Minimum distance from potable water supply wells, houses and roads required Water quality restrictions	Not required	Medium to High	Medium	Low (aggravated due to aerosol generation)
Drip irrigation	No special protection measures necessary / Water quality restrictions necessary to prevent emmiter clogging	Not required	High	High	Highest

These different irrigation methods result in distinct nutritional uptake capacities according to the system's efficiency. Usually, the irrigation efficiency and the nutrient uptake efficiency increase in parallel, being the microirrigation (drip irrigation) the one with the highest NPK Fertilizers uptake, while the lowest is provided by Surface irrigation methods, happening due to leaching, extracted from FAO.

As concluded by Lazarova *et al.*, 2004, drip irrigation is the most suitable technique for the application of wastewater due to the low contamination risk and the high efficiency of water application.

3.2 CROP NUTRITION AND USE OF RECLAIMED WATER FOR IRRIGATION

Modern agricultural practices often require high levels of fertilisers and manure leading to high nutrient surpluses that are transferred to water bodies. When more quantity of fertilizers is applied, nutrient losses may take place through leaching and surface runoff and enter into nearby water bodies. Therefore, intensive use of chemical fertilisers in agriculture has resulted in the deterioration of environmental quality and soil systems by promoting eutrophication, with an associated loss of plant and animal species.

Controlling and managing nutrient transfers to water from excessive nutrient use on agricultural land is a significant challenge. Fertigation management is highly complex, especially when reclaimed water is used for irrigation. This problem can be exacerbated if reclaimed water is used since it already contains nutrients. For this reason, water quality must be considered in the fertilization plan. Farmers that use reclaimed water might use it as the unique source of water or mixed with other conventional resources such as well water. In any case, farmers and their advisory entities need to understand the necessary nutritional balance of a mix of reclaimed water, fresh water and fertilizers and how to fertigate with the exact amount of nutrients needed by the crop in an adequate and profitable way, while also being environmentally sustainable.

The nutrients necessary for efficient plant growth come from the soils in as well as from the application of fertilizers, when needed, and with the reclaimed water used for irrigation as another source of nutrients.

The major nutrients needed for plant growth are Nitrogen, Phosphorus and Potassium, although there are others with the same importance but in significantly smaller quantities. In the following table (table 5) these macronutrients are listed in their element form, with a brief description of their function or use by plants.

Table 7: Some of the essential Plant elements obtained by root uptake from the soil adapted from Stevens, D. *et al.*, 2006

Essential plant elements obtained by root uptake from the soil	
Nutrient	Principal roles in plant metabolism and in metabolites plant components
Nitrogen (N)	Major component of amino and nucleic acids, and chlorophyll
Phosporus (P)	Important component of ATP, used for energy storage and transfer, component of nucleic acids, lipids and cell membranes
Potassium (K)	Cation-anion balance, pH regulation, stomatal control, energy and water relations, osmotic adjustement
Magnesium (Mg)	Ionic balance, photosynthesis, pH regulation, protein synthesis, carbohydrate partitioning, chlorophyll component
Sodium (Na)	Ionic balance, C4 photosynthesis, enzyme activation
Chlorine (Cl)	Ionic balance, enzyme activation

The nutrient concentration in reclaimed wastewater depends on the degree of treatment it receives: higher levels of treatment originate waters with lower nutrient concentration

(Stevens, 2006) 1, especially Nitrogen (N), which can also be reduced in consequence of denitrification during storage (Schmidt *et al,* 2003), and Phosphorus (P).

Plants need both macro and micronutrients for their development. Furthermore, the more accurate are the quantities added to their crops, the more and better-quality yield will be collected. The most common macronutrients needed by plants are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) (Parsons, 2009).

Depending on the type of crop, the nutrients' quantities that are needed for the plant growth vary, not only in their concentrated sum, but also individually, i.e., according to the harvested part of the plants, its nutritional demand will be higher or lower in N, P or K, separately. "Leaf crops thus tend to have a relatively high N demand, root crops a relatively high P demand, and fruit crops a relatively high K demand." (Stevens *et al*, 2006)

In parallel, the nutrient contribution to the crops from using reclaimed water for irrigation is dependent on its quantity and concentration. When irrigating, there's a number of variables that have to be taken into account to calculate the quantity of water supply and to schedule the watering such as: evapotranspiration, soil storage capacity, precipitation and soils' permeability. These parameters are variable in time and location of the crops which condition its' climate, the soil composition and thus its' characteristics, among others.

An inadequate input of nutrients, whether it's in defect or in excess, will have a negative impact on the cultivations and could result in their unproductivity, appearance of diseases or even yields loss, so the aim is to manage the nutrients contribution in a way that maximizes the crops' productivity and efficiency whilst reducing costs and not negatively impacting environment.

Furthermore, for this to be put to good use there are two main points that should be positively fulfilled: a combined use of effective wastewater treatments and irrigation practices to prevent adverse consequences both to the environment where they will be applied and to public health regarding farmers' exposure and the consumption of the productions (Ait-Mouheb *et al.*, 2018).

3.2.1 Nitrogen

Nitrogen has a diverse cycle in the atmosphere, soil and live beings as seen in figure 8, bellow.

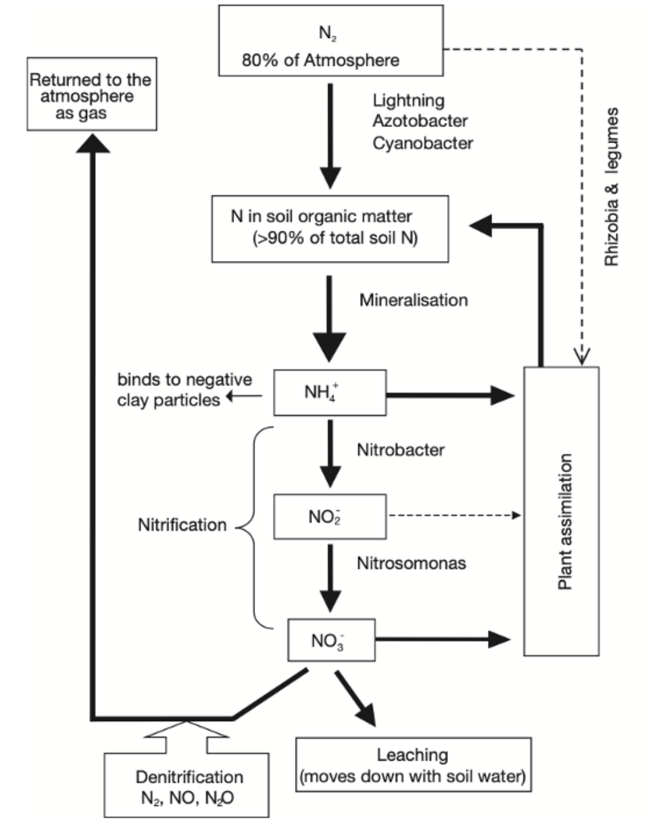

Figure 8: Nitrogen forms and interactions in the soil, from Growing Crops with Reclaimed Wastewater, 2006

Its diverse forms and constant transformation through the processes of nitrification, denitrification, mineralisation and volatilisation that occur both in soil and in water and the inertia in the atmosphere, for example, makes it have a low availability to plants. On the other hand, nitrate leaching and runoff is what causes this nutrient to be a contamination problem and, as studied by Polglase *et al.,* (1995), the total of N can be used as the measure for the risk of contamination by NO_3^- , because in reclaimed water there is a high potential for its full conversion from nitrogen to nitrate.

Nitrogen is the nutrient added to crops in the highest quantity but the amount applied through fertilizers vs the quantity provided by the irrigation with reclaimed water is hard to precise, because their demands might not coincide, which can cause the Nitrogen to be under or over the desired values, causing negative changes in the yields in both situations, resulting in its reduction, whether in deficiency or excess, and possible contamination of soil and/or water in case of excess. The results of any imbalance will depend on the type of cultivation, varying from important changes in yield to none at all.

The nitrogen present in the fertilizers added to crops is usually in the form of the element N, while the nitrogen content in reclaimed water can be quantified in different groups:

- Total Nitrogen (TN) represents the sum of the nitrogen present in nitrate, nitrite, ammonia and organically bonded nitrogen
- Total Kjeldahl Nitrogen (TKN) represents the sum of the nitrogen present in ammonia and the organically bound nitrogen

This is a crucial information when calculating the nutritional balance, because there is the need to know the full Nitrogen input through the reclaimed water and not only a part of it (as would happen with TKN), allowing for a correct estimation of the Nitrogen balance and reducing the probability of a contamination or deficiency problem.

3.2.2 Phosphorus

Phosphorus is the other most common nutrient added to soils through fertilizers. It is conventionally found in the form of Phosphorus Pentoxide, a soluble form, reacting with water and with other components present in the soil. Its properties make the processes of absorption to soil or precipitation in insoluble compounds its two major destinations, resulting in a small percentage available to plant uptake (Wild 1988), which constitutes the major issue of this fertilizer's component. P. 100

As resumed in the diagram bellow (figure 9), in a natural environment, most of it originates from living organic beings such as plant and animal residues, dividing through natural processes, in soluble P (available for plant intake) or in insoluble P (fixated in the soil), having a part of it being also lost by erosion or runoff.

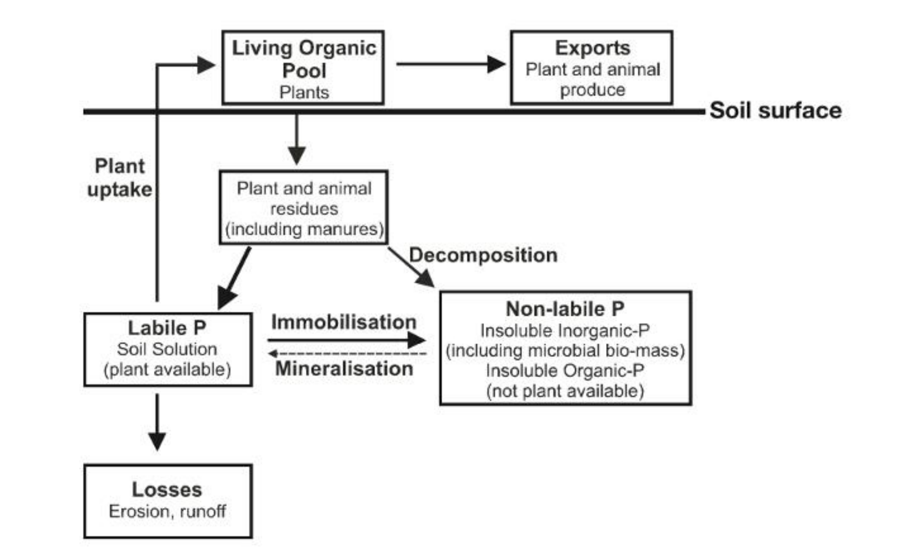

Figure 9: Diagram of pathways for phosphorus transfer in the plant-soil system from Brady and Well, 1999

In the image bellow, extracted from Pierzynski *et al.*, 2000, the different types of inputs, outputs and internal cycling reactions are represented, allowing for a better understanding of the reactions in which the P takes part in, and how they simultaneously happen in the system and interact, originating a fraction of P that is soluble and present in the soil solution, available for plant uptake.

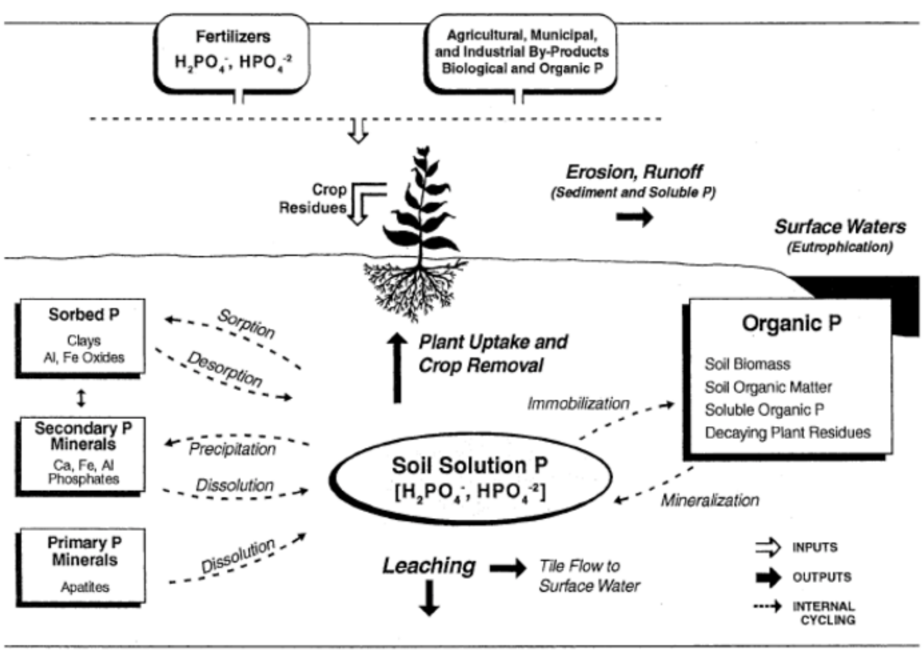

Figure 10: The soil P cycle from Pierzynski *et al.*, 2000

As represented in the following image, "Soil pH has a large influence on P fixation since it controls the presence of active forms of iron, aluminium and calcium (figure 11)". This means that the ideal pH window for an P availability is very reduced, often occurring fixation by other components present in the soil, resulting in non-soluble, unavailable for plant intake P forms.

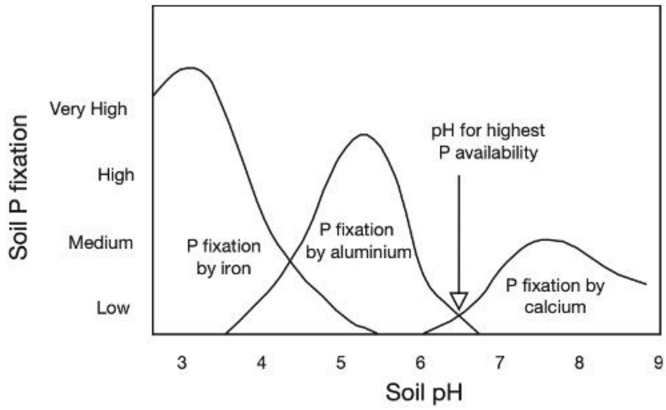

Figure 11: Relationships between soil pH and phosphorus fixation by iron, aluminum and calcium from Glendinning, 1999

However, there are some measures that can be adopted in order to minimize this, such as the addition of lime or other substances to adjust the soil's pH, regulating it to a more suitable value.

Phosphorus present in Wastewater vs. Plants' Phosphorus needs

The average quantities of Phosphorus found in reclaimed wastewater wouldn't be enough for the cultivation requirements, which is an advantage in the sense that it will not provoke overfertilization because most of this nutrient will not be available for plant uptake due to its absorption by the soil (Ryden and Pratt, 1980).

On the other hand, there is a case where this could be a problem: for some native plants adapted to nutrient poor soils, the combined use of reclaimed wastewater and fertilizers (with soluble P) could result in an increase of toxicity risk.

The phosphorus added to crops through fertilizers is usually in a molecule form of P_2O_5, which is the standard and most commonly used form to quantify the phosphorus in labels. This soluble oxide form reacts with others, available for plant uptake, while the phosphorus present in reclaimed water is usually given in a total P content value. Further along when calculating the balance between both, it is necessary to use the same nutritional unit, in this case the element of P to correctly estimate the remaining crops' needs.

3.2.3 Potassium

Potassium (K) is the third major macronutrient essential for plant growth. It's role in plant growth is extense, being associated with water movement in the plant, as well as with the nutrients and carbohydrates in plant tissue, among other processes (University of Minnesota, 2018).

It is involved in various processes in the soil, as represented in following figure (figure 12), a part of it being in solution, another forming secondary minerals and compunds and some other beinh weathered.

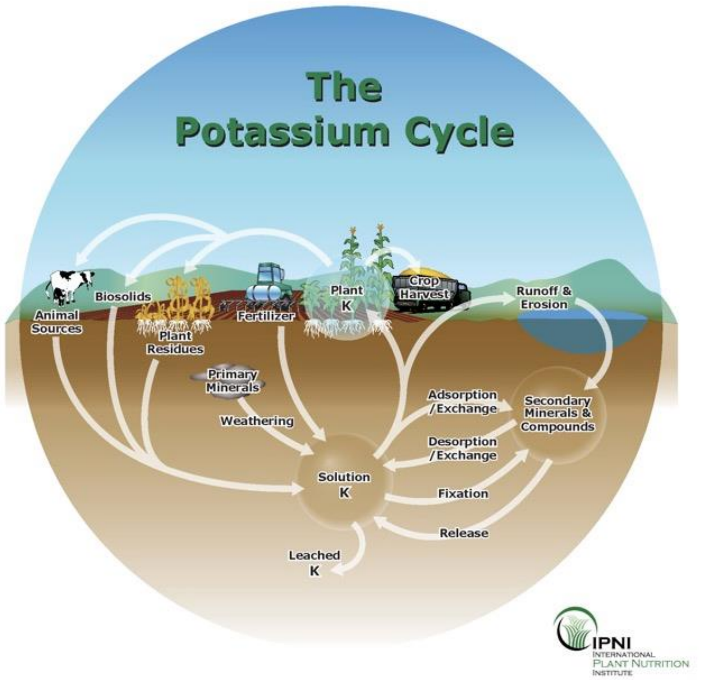

Figure 12: Potassium Cycle extracted from IPNI Canada

This nutrient's content in the soil is variable depending on the type of soil, some being mre susceptible to to forming comounds or to weathering. It is often high, however only a small quantity is available for plant growth because almost all the Potassium is usually fixed as soil minerals.

According to Alkhamisi, S. *et al.*, 2016, the Potassium content in reclaimed water was lower in reclaimed water than in groundwater, so the risk of having this nutrient in excess in the water is low due to this and the other reasons mentioned before.

On the other hand, potassium can be a problem to soil, if in excess because it can destabilize the soil's structural stability. An acumulation of K^+ in the soil goes hand in hand with a decline in Mg^{2+} due to the processes of cation exchange due to "a higher selectivity and exchange of K^+ relative to Na^+ and higher K/Na ratio in the wastewater" (Liang, X., *et al.,* 2021).

3.3 NUTRIENT CALCULATION

3.3.1 Calculation of the Nutritional Balance of RW and Fertilizers Mixture

When using Reclaimed Water for Irrigation, a part of the crops' nutrients needs are met. This implies that the quantity of fertilizers needed would be less than in the case of freshwater use. The calculation of the nutrients' fraction supplied by the Reclaimed Water is extremely important in order to add only the fertilizer that is lacking in the total crops' needed supply, preventing overfertilization and the contamination of soil and water through an excess of nutrients.
Since most of the commercialized and used fertilizers have an NPK (Nitrogen, Phosphorus and Potassium) formula, and these being the nutrients present in higher concentrations in reclaimed water, they are of the highest importance for the nutritional balance. In parallel, there is always the need to control less abundant elements that are also present in this mixture as to not overpass their limits for irrigation or to add them through supplements in case they are lacking.

<u>Example of Nutritional Balance Calculation</u>
A given crop with 4 ha has the following nutritional demand:

Crop's Nutrient Demand	
N	1 kg/ha
P	2,5 kg/ha
K	3 kg/ha

It is irrigated with 20 m^3 of 100 % Reclaimed Water with the following nutritional content:

Nutrient Content in RW	
N	10 mg/l
P	8 mg/l
K	25 mg/l

Dividing the 20 m^3 of water by the 4 hectares that need irrigation we obtain 5000 l/ha. By converting the units of the Nutritional Content in the Reclaimed Water to the same as the crops demand (mg to kg) and multiplying by 5000 l we are able to know how much of the crop's nutritional demand is met through Irrigating with the reclaimed water per hectare.

Nutrient Content in RW	
N	0,05 kg/ha
P	0,04 kg/ha
K	0,125 kg/ha

Then subtracting the Nutrients Content in the RW to the Crops' Nutritional Demand we obtain the quantity of Nutrients still lacking, which will be added through fertilizers.

Nutrient Content lacking	
N	0,95 kg/ha
P	2,46 kg/ha
K	2,875 kg/ha

Nitrogen

The Nitrogen content in reclaimed water and in fertilizers is usually given in the N element form, so it isn't necessary to do any element or molecule N content conversion. The quantity of N in deficit will be added through one or various fertilizers to the crop in the exact kilograms that is lacking.
In this example, it is needed the addition of 0,95 kg/ha of N.

Phosphorus

While the Phosphorus Content in Reclaimed Water is given in the element P total quantity, in fertilizers it's usually in the molecule form of P_2O_5.
Not all the Phosphorus present in the fertilizer is necessarily available for plant uptake; on the fertilizer's labels it is indicated the usable P (soluble, available for plant uptake) and the total P, so when calculating the nutritional balance this should be taken into account.
Additionally, before calculating the nutrients balance, there's a need to calculate the P quantity present in the P_2O_5 molecule present in fertilizers, otherwise the estimation would be wrong, similarly as making calculations with parcels in different units.
To make this conversion, in order to obtain the P quantity in P_2O_5, the P_2O_5, should be divided by 2,29. This is due to the following molecular weights and their relative proportions:
P Molecular weight = 31
O Molecular weight = 16
P_2O_5 Molecular weight = 2 x 31 + 5 x 16 = 142
P_2 Molecular weight = 2 x 31 = 62
P_2O_5 / P_2 Ratio = 142/62 = 2,29
This way, any given fertilizers P_2O_5 soluble content should be divided by 2,29 to know the real P quantity available for the cultivations.

Potassium

Potassium content in Reclaimed Water is given in total K element quantity while in fertilizers it's usually present in K_2O molecule form.

As it happens with the Phosphorus, there's a need to calculate the K quantity present in the K_2O molecule to accurately calculate the nutritional balance. This conversion is given by dividing the K_2O quantity by 1,21. This is due to the following molecular weights and their relative proportions:
K Molecular weight = 39,1
O Molecular weight = 16
K_2O Molecular weight = 2 x 39,1 + 16 = 94,2
K_2 Molecular weight = 2 x 39,1 = 78,2
K_2O / K_2 Ratio = 94,2 / 78,2 = 1,2046
So, any fertilizers given K_2O quantity should be divided by 1,21 so as to know the K quantity available for the cultivations.

Using a standard NPK 20-20-20 fertilizer as an example (figures 13 and 14), we can estimate what quantity is needed to fulfil the crop's requirements lacking from the RW contribution:

Figures 13 and 14: Label and composition of a standard 20 – 20 – 20 composition fertilizer by Symbio ethical

As read in the label, there's a 20 % of total Nitrogen, 20 % of soluble P_2O_5 and 20 % of soluble K_2O.
For a bag of 1 kg, this is equivalent to a 0,2 kg of N, 0,2 kg of P_2O_5 and 0,2 kg of K_2O. Converting these values to the element forms of P and K as explained before we obtain:
0,2 kg of P_2O_5 / 2,29 = 0,087 kg of P
and
0,2 kg of K_2O / 1,21 = 0,165 kg of K

Previously we calculated the nutrients still lacking:

Nutrient Content lacking	
N	0,95 kg/ha
P	2,46 kg/ha
K	2,875 kg/ha

To fulfil the Nitrogen demand it would be needed 0,95 kg N / 0,2 kg N = 4,75 bags of 1 kg of fertilizer.
Using the rule of three, or the inverse of the factor calculated before we can obtain the quantities of P_2O_5 and K_2O needed to obtain the P and K quantities missing:
As 0,087 kg of P are present in 0,2 kg of P_2O_5,
2,46 kg of P are present in X kg of P_2O_5
X = 2,46 x 0,2 / 0,087 = 5,66 kg of P_2O_5
So, to fulfil the Phosphorus demand it would be needed 5,66 kg of P_2O_5 / 0,2 kg of P_2O_5 = 28,3 bags of 1 kg of fertilizer.
And for the K:
As 0,165 kg of K are present in 0,2 kg of K_2O,
2,875 kg of K are present in X kg of K_2O
X = 2,875 x 0,2 / 0,165 = 3,48 kg of K_2O
So, to fulfil the Potassium demand it would be needed 3,48 kg of P_2O_5 / 0,2 kg of P_2O_5 = 17,4 bags of 1 kg of fertilizer.
As this is an aleatory example, the fertilizer quantities needed for the adequate input of each element are not viable, since the number of fertilizer's bags (with this composition) needed for the Phosphorus and for the Potassium are a lot more than needed for the Nitrogen.
In a real practical case, this is a setback that would be solved with the use of the calculation tool in development, since it gives the user the combination of different fertilizers and their respective quantities for the best approximation to the exact nutrient´s input values, i.e., closer to each element's crop demand, without considerate deficit or excess of any of them.

3.4 SALINITY

Crops' salinity control when using reclaimed water (Extracted from FAO, 2003)
The salinity of reclaimed wastewater, like in all types of water, varies according to its total content of salts, and the water's suitability for irrigation depends on it.
The salinity of reclaimed water is usually higher in reclaimed water than in conventional water due to the higher quantity of substances present; it generally has a low to medium salinity with electrical conductivity values between 0.6 and 1.7 dS/m.
A high salinity, especially caused by water scarcity and consequent concentration of salts may be a problem, causing osmotic pressure in the soil water and consequently leading to an increase in the energy plants need to extract water from the soil. This causes an increase in plant respiration, resulting in a decrease of the growth and yield of most plants progressively with the increasing osmotic pressure.
But there are some measures or ways to approach this situation to minimize it without conditioning the yield or its profit:

- Select crops tolerant to the wastewater salinity;
- Select salt tolerant crops with the ability to absorb high amounts of salts (without abnormal toxicity);

- Select an irrigation system that provides a uniform irrigation, that is efficient and allows for frequent irrigation;
- Scheduling of irrigation, permitting the control of the amount of water used and periodicity of irrigation;
- Drainage facilities combined with adequate scheduled irrigation allow for the leaching of excess salts.

3.5 FIT4REUSE Case study at Cesena site

The University Alma Mater of Bologna (UNIBO) in Italy has conducted several studies in the city of Cesena. The experimental test site had tomato and peach plantations irrigated with reclaimed water from the muncicipal treatment plant of Cesena.

Figure 15: Peach and tomate plantations at FIT4REUSE Cesena site

For the **irrigation** of **peach trees**, iDrop drippers (by Irritec company) were used. These drippers provide 2,1 litres per hour. Irrigation followed a plan calibrated on water needs of peach species, and modified in case of higher evapotranspirative requests.

For the **irrigation** of **tomato plants**, 1,1 l/h drippers have been chosen.

As for **plant nutrition** (for both tomato and peach crops), a fert-irrigation plan has been created based on macronutrient requirements during the different phenological phases. **Calcium nitrate**, **Monoammonium Phosphate**, **Potassium Sulphate** were used as an integration to the macronutrients already present in the secondary water coming from the treatment plant of Cesena. The mineral fertilizers have been chosen because of their high solubility.

The use of **secondary water** for irrigation on Peach (cultivar *Aliblanca*) allowed considerable savings of mineral fertilizers: **-32%** of Nitrogen, **-8%** of Phosphorus and **-98%** of Potassium.

At the end of August 2021, the Peach trees' **crop yield** was of:

- **3.34** kg/tree for plants irrigated only with secondary water;
- **4,11** kg/tree for plants irrigated with secondary water fortified with mineral fertilizers;
- **4,56** kg/tree for plants irrigated with fresh water fortified with mineral fertilizers.

The use of **tertiary water** for irrigation on Tomato (cultivar *Big Rio*) allowed considerable savings of mineral fertilizers, but lower than peach: **-24%** of Nitrogen, **-0,4%** of Phosphorus and **-74%** of Potassium.

At harvesting on July 2021, the Tomato plants' **crop yield** (expressed in terms of single fruit average weight) was of:

- **82 g** for plants irrigated only with tertiary water;
- **72,3 g** for plants irrigated with tertiary water fortified with mineral fertilizers;
- **85 g** for plants irrigated with fresh water fortified with mineral fertilizers.

Soil Analysis

At the end of 2021 productive season, there was an increase in EC and pH in the soil of secondary water irrigated plants, both between 0 and 20 cm and between 20 and 40 cm, compared with fresh water irrigated trees. Increase in EC with depth.

There was also a limited increase of some elements such as Na, Al, Ba, B, in the surface soil layers (except for Na).

For the tomato trial, continued use of tertiary effluent did not result in significant increases in either pH or electrical conductivity (EC) at the soil level and for both sampling depths (with the exception of the first 10 cm of soil for the tertiary treatment).

3.6 STORAGE AND DISTRIBUTION

3.6.1 Water distribution systems

It is of extreme importance to separate the piping tubes systems that transport reclaimed water from the ones with potable water, assuring there is no cross-connection between them. For this reason, the colouring of the tubes network is a common practice, usually reclaimed water ones being coloured in purple. Other options are to distinguish them by using different tube materials or to lower the pressure in reclaimed water tubes compared to potable water systems, minimizing the chance of the reclaimed water entering the drinking water network.

The material of the distribution tubes is also of high importance in order to not alter the water's quality while being resistance and durable. "CPVC, PEX, PE-RT and PP pipes and fitting systems are intended for reclaimed water systems", extracted from Plastics Pipe Institute.

Besides the correct choice of the tube material, there is also the need to maintain the distribution system against bacterial growth due to biodegradation of organic matter and odour emission. To prevent these issues, similarly to clogging prevention, the systems should be:

- Periodically purged;
- Chlorinated;

- Physically and periodically cleaning of the distribution's mains (ISO 16075-3:2015).

3.6.2 Storage reservoirs

The water storing reservoirs are a crucial part of any water distribution network, but especially for reclaimed water systems. The mix of reclaimed water with conventional water, if and when needed, is done in these infrastructures, as well as the control and management of the water demand for irrigation and the water inflow from wastewater treatment plants and from other reservoirs.

These reservoirs should be properly identified and closed to public access.

When storing reclaimed water there are some technological solutions or substances that can be added and are often needed, in order to prevent and control the growth of algae, which is a common problem in reservoirs.

The uncontrolled growth of algae in reservoirs covering the water surface causes a sunlight block, impeding its reach to the vegetation which consequently decomposes, consuming all the oxygen available and originating putrefaction. Additionally, this negatively affects the irrigation systems, causing their malfunction and possible failure.

Some of the most common solutions available for this problem are:

- The addition of Bacteria which act as a competitor to the algae population, controlling its growth (Carrasco, P. N., 2015);
- The installation of Ultrasounds in the reservoirs, which also control the algae growth through the rupture of algae's different cellular organs, destroying them (Maestre Valero, J., *et al.*, 2015);
- The addition of Potassium Permanganate, which is an oxidizer, eliminating organic matter and consequently inhibiting the algae growth (S.L., B. S. (s. f.));
- The addition of Hydrogen Peroxide is another oxidizer, working in a similar way as the Potassium Permanganate (Moleaer, 2022).

FIT4REUSE is part of the PRIMA programme supported under Horizon 2020, the European Union's Framework Programme for Research and Innovation.
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[FIT4REUSE] [Call 2018 Section 1 Water]

4 SOIL AQUIFER RECHARGE

The deterioration in groundwater quality has become a major issue for many aquifers. In urban, industrial, and agricultural areas, a vast array of contaminants may be found because they are introduced into aquifers through different recharge sources. Aquifer recharge (AR) and aquifer storage and recovery (ASR) are manmade processes or natural processes enhanced by humans that convey water underground. The processes replenish ground water stored in aquifers for beneficial purposes. Although AR and ASR are often used interchangeably, they are separate processes with distinct objectives. AR is used solely to replenish water in aquifers. ASR is used to store water, which is later recovered for use.

Where soil and groundwater conditions are favourable for artificial recharge of groundwater through infiltration basins, a high degree of improvement in water quality can be achieved by allowing partially treated sewage effluent to infiltrate into the soil and move down to the groundwater.

In the littoral aquifers, the overexploitation of groundwater has tipped the historical balance between fresh groundwater and seawater and evidence of saltwater intrusion is abundant. The higher levels of salt in irrigation water can also increase agricultural land salinity, leading to reduced productivity and possibly the complete destruction of agricultural lands.

To assess the suitability of this site for recharge, the following criteria should be taken into account:

- Topsoil (soil type and thickness);
- Depth to water table (unsaturated zone thickness);
- Infiltration rate (vertical and horizontal aquifer different sizes, the most effective ones are near the coast, permeability);
- Groundwater flow direction and hydraulic gradient;
- Concentration of nitrate and chloride;
- Available area;
- Distance from border.

4.1 Groundwater Recharge

- Developing of artificial underground reservoir by artificial recharging for storing water underground called recharging of underground water.
- The over-allocation of groundwater resources is not specific to Mexico, however, and occurs in many regions where rainfall is scarce and aquifer development is extensive, as groundwater is often the cheapest, most accessible, and most reliable freshwater resource.

4.1.1 Appropriate technology

Several methods of introducing water into an aquifer exist including:

- Surface spreading;
- Infiltrations pits and basins;
- Injection wells.

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Experiences conducted elsewhere had also shown a positive impact of the recharge of the aquifer by treated wastewater e.g., in 1985 at El Paso (Texas, USA) wastewater was treated in tertiary treatment level then used to recharge the aquifer, the water from the latter was used for drinking, agricultural and industrial purposes. This operation served dual purposes: the reuse of the wastewater and the restoration of groundwater.

a) Spreading Method:

In this method, water is spread over the surface of permeable open land and pits from where it directly infiltrates the shallow aquifer. Water is stored in shallow ditches or spread over open areas by constructing low earth dikes.

Rate of recharging depends on permeability of spread area, and the depth of water stored. Also, some chemicals are added to the soil to increase the rate of recharging.

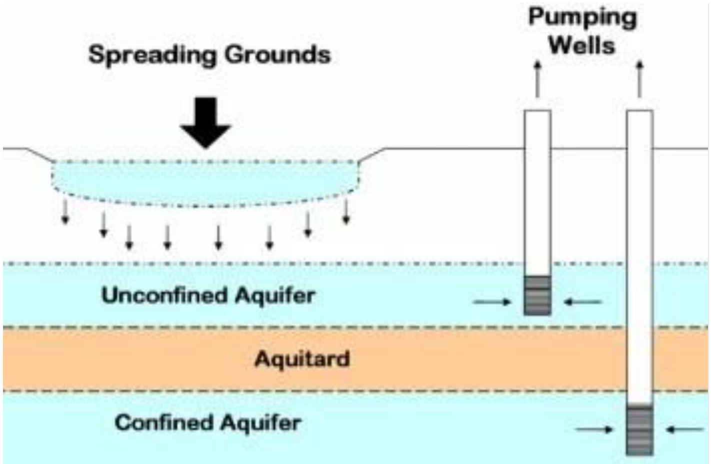


Figure 16: Spreading method for groundwater recharge

b) Recharge well method:

In this method water is injected into the bore holes. Water is fed into recharge wells by gravity or pumped under pressure. Ordinary wells also perform the work of recharging water during off season.

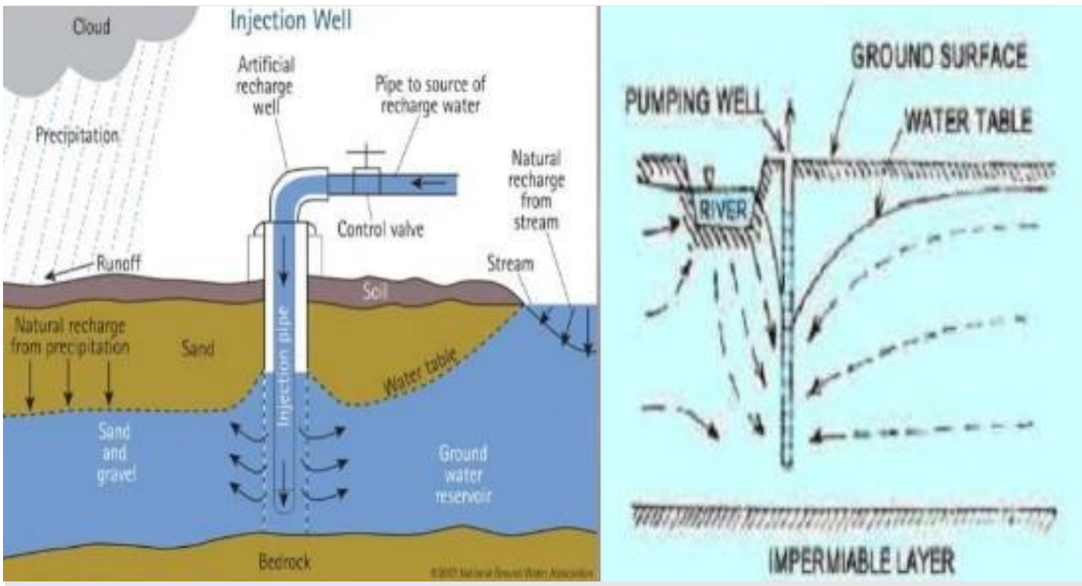


Figure 17: Recharge well method

c) Induced Filtration Method:

In this method water table gradient is increased from source of recharge. In this method special type of wells are constructed near the banks of river having radial collector. The percolating water is collected from radial collector and the discharge as recharge in to lower level aquifer as shown in the figure.

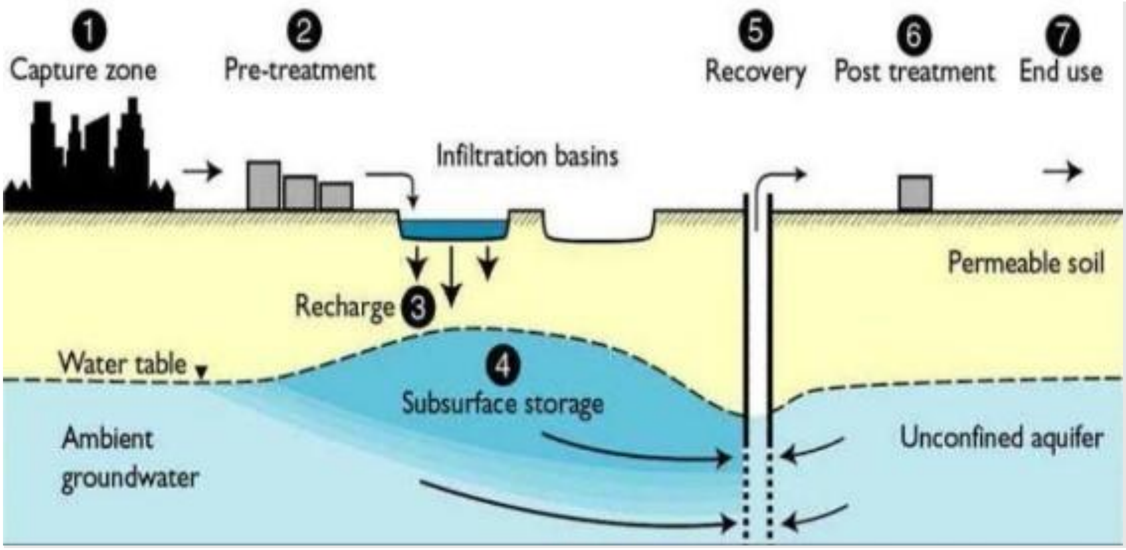


Figure 18: Induced filtration method

4.2 Artificial Ground Water Recharge

Artificial recharge to groundwater is a process by which the ground water reservoir is augmented at a rate exceeding the one under natural conditions or replenishment. Any man-made scheme or facility that adds water to an aquifer may be considered an artificial recharge system.

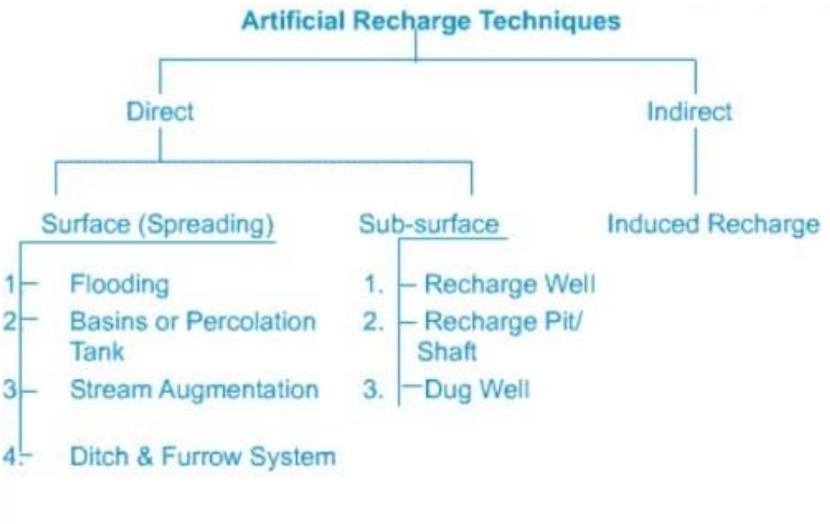


Figure 19: Artificial recharge techniques

Groundwater recharge with reclaimed municipal wastewater presents a wide spectrum of technical and health challenges that must be carefully evaluated prior to undertaking a project. some uncertainties with respect to health risk considerations have limited expanding use of reclaimed municipal wastewater for groundwater recharge, especially when a large portion of the groundwater contains reclaimed wastewater that may affect the domestic water supply.

Natural replenishment of underground water occurs very slowly; excessive exploitation and mining of groundwater at greater than the rate of replenishment causes declining groundwater levels in the long term and leads to eventual exhaustion of the groundwater resource. Artificial recharge of groundwater basins is becoming increasingly important in groundwater management and particularly where conjunctive use of surface water and groundwater resources is considered in the context of integrated water resources management. Groundwater's major beneficial uses include municipal water supply, agricultural and landscape irrigation, and industrial water supply.

The main purposes of artificial recharge of groundwater have been:

- to reduce, stop, or even reverse declines of groundwater levels;
- to protect underground freshwater in coastal aquifers against saltwater intrusion;
- to store surface water, including flood or other surplus water, and reclaimed municipal wastewater for future use.

Groundwater recharge is also indirectly achieved through irrigation, land treatment and disposal of municipal and industrial wastewater via percolation and infiltration.

Advantages

There are several advantages in storing water underground via groundwater recharge including:

- The cost of artificial recharge may be less than the cost of equivalent surface water reservoirs;
- The aquifer serves as an eventual natural distribution system and may reduce the need for transmission pipelines or canals for surface water;
- Water stored in surface reservoirs is subject to evaporation, taste and odor problems due to algae and other aquatic productivity, and to pollution, which may be avoided by soil-aquifer treatment (SAT) and underground storage;
- Suitable sites for surface water reservoirs may not be available or may not be environmentally acceptable;
- The inclusion of groundwater recharge in a wastewater reuse project may provide psychological and esthetic benefits because of the transition between reclaimed municipal wastewater and groundwater. This aspect is particularly significant when a possibility exists in the wastewater reclamation and reuse plans to augment substantial portions of domestic or drinking water supplies.

4.3 Groundwater recharge Techniques

Two types of groundwater recharge are commonly used with reclaimed municipal wastewater: surface spreading or percolation, and direct aquifer injection.

Economical Aspect

The economic aspect of managed aquifer recharge techniques (MAR) is another important issue about recharge process. It is known that there were opportunities for MAR for 16% of the area evaluated and that the additional storage capacity of aquifers in these areas was more than 2.5 times the total storage capacity of all existing surface water dams in Spain.

Table 8: Types of managed aquifer recharge techniques

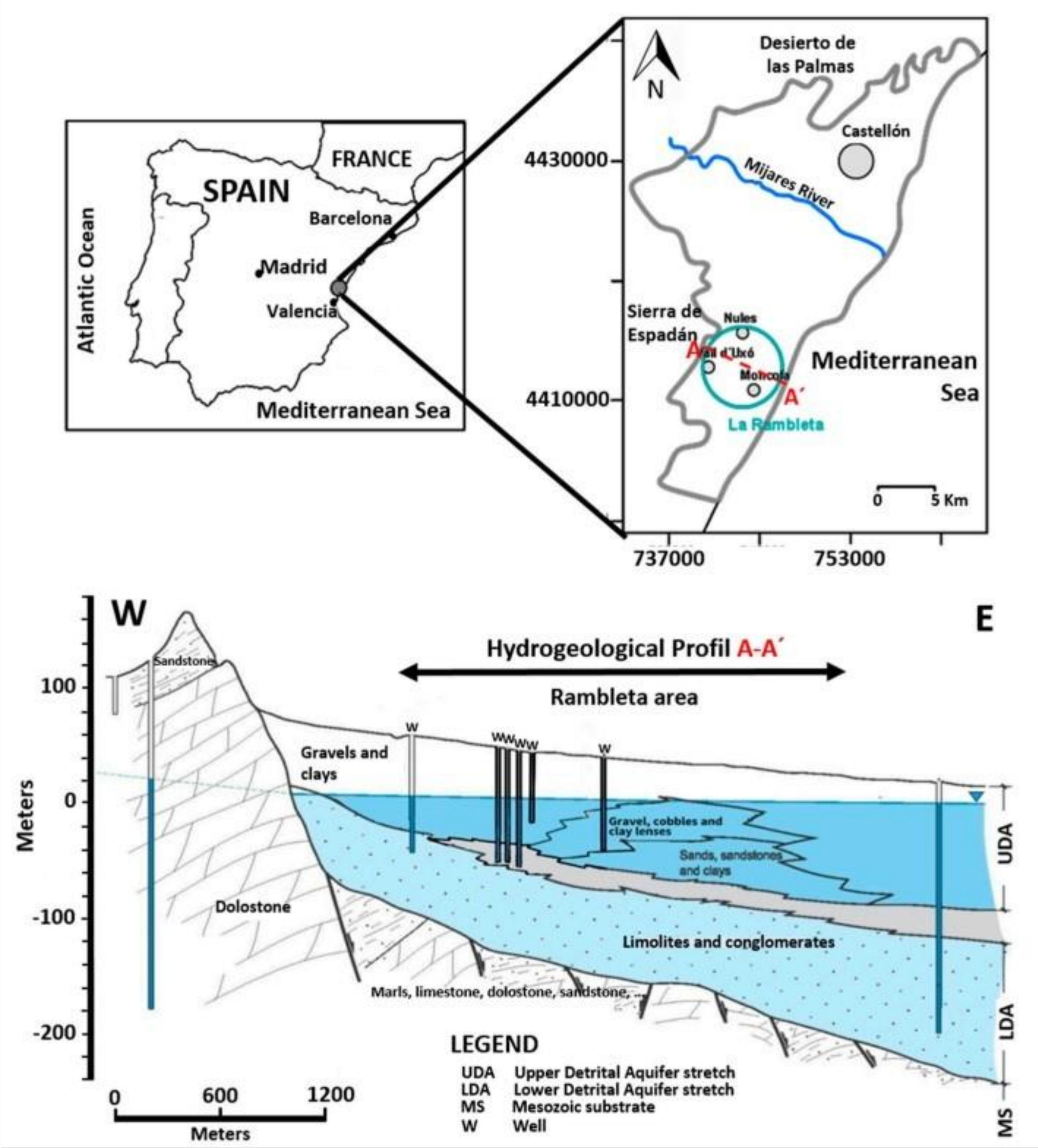
MAR facilities	Number of projects costed of this type	Mean investment cost ratio (€/m^3)
Ponds	18	9.75
Dams	16	0.80
Surface MAR facilities (ponds, channels)	8 ponds/58 km channel	0.21
Deep boreholes	4	0.58
Medium-deep boreholes	25	0.36

The first alternative diverts running water from a river, channeling the water to an adequate aquifer (underground storage). This technique has several advantages including minimal occupation of the surface, less evaporation, preserved water quality, and the relatively low costs for the storage. For example, from the first row, using a river as a source of intake has a potential cost per action (investment ratio) of close to 0.20 €/m^3 for an 8 km conduction pipe and the artificial recharge is performed using channels, infiltration ponds and wells. The cost for each activity is estimated to be close to 1.2 M€. Exploitation and maintenance costs have been estimated at € 0.01 m^3/year.

4.4 CASE STUDIES

La Plana de Castellón

Plana de Castellón (Spain) is a coastal area that has been characterized by intensive citrus agriculture since the 1970s. Traditionally, in the southern sector of Plana de Castellón, 100% of irrigation water comes from groundwater. In recent years, local farmers have been using a mixture of groundwater and reclaimed water from wastewater treatment plants (WWTPs) to irrigate the citrus. This area has a Mediterranean climate characterized by gentle winters, hot summers, and irregular rainfall. From 2007 to 2016, the mean annual rainfall was 506 mm/y and ranged from 696 to 286 mm/year. This area, formerly devoted to agriculture (mostly citrus crops), now supports some small industrial settlements and villages. The high-water demand brings about intense and continuous exploitation of both surface and groundwater resources. Intensive groundwater exploitation, until the late 1970s, caused seawater intrusion that affected a significant portion of the study area and resulted in a subsequent decrease in groundwater quality.



The aims of the study:

1. to assess the occurrences, spatial distributions, and concentrations of selected ECs, including 32 antibiotics, 8 UV filters, and 2 nonsteroidal anti-inflammatory drugs, in groundwater in a common agricultural context;
2. to identify the recharge (pollution) sources acting as the origin of the ECs;
3. to suggest ECs as indicators of reclaimed water arrival in detrital heterogeneous aquifers.

The ECs correspond in most cases to unregulated contaminants, which may be candidates for future regulation, depending on the results of research into their potential effects on health and monitoring data regarding their occurrence. The studies related to ECs can generally be categorized into three main groups:

1. assessments of occurrence in surface waters, such as rivers, wastewater, and treated water (e.g., water from a wastewater treatment plant, WWTP);
2. assessments of the fate and occurrence in groundwater (mainly in urban areas);
3. studies in agricultural areas where water demand is higher than the available natural resources and where wastewater, WWTP effluents, and reclaimed waters constitute an important source for irrigation.

Because of the situation described, the local groundwater hydrochemistry shows three main impacts:

1. salinization by seawater intrusion (i.e., chloride concentrations greater than 700 mg Cl/L in the central part of the upcoming seawater area);
2. high concentrations of compounds related to fertilizers and agro-chemicals;
3. contamination with various urban wastewater compounds (e.g., nitrogen and detergents) due to the use of reclaimed WWTP water for irrigation.

Study Results:

The degradation rates of the compounds during the passage from the WWTP to the GW were greater than 90%. Potential sources of contamination located around the study area were diffuse (agriculture and livestock farming) or were spatially limited. The pesticide concentrations found did not exceed 0.1 µg/L, the maximum allowed for pesticides in water for human consumption. Herbicide concentrations in groundwater vary from site to site, depending on the chemical behavior in various soil types, the particle sizes, organic matter contents, weather conditions (temperature and rain), and field management practices.

Considering the water scarcity in Mediterranean countries, the use of reclaimed water for irrigation is a realistic alternative. This type of water resource will likely become one necessary source of medium-term subsistence if the estimated predictions of climate change and global population growth are fulfilled.

The results show that ECs, including pesticides, have been detected in greater or lesser concentrations at all the sampled points, so the contamination affects the whole study area and not a particular sector. Presently, the conventional WWTPs (primary and secondary treatment systems) have low efficacy for removing most ECs; therefore, it is common to find these pollutants in the EWW, as has been corroborated in this study. On the other hand, it has been observed that in other locations of the planet, ECs and pesticides have been detected, which indicates that contamination is a global problem and not a local problem.

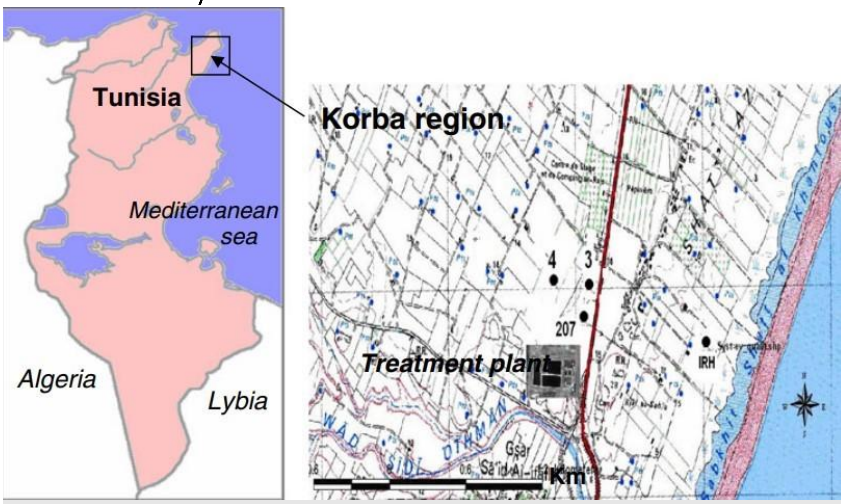
***Tunisia* – KORBA WWT**

Water is a scare resource of vital importance in the Mediterranean countries, especially in Tunisia which is in an arid and semi-arid region. The reuse of treated wastewater (TWW) has been used in Tunisia since 1965. Once appropriately treated, TWW is considered suitable for non-potable purposes such as irrigation and has been adopted as one of the solutions for water scarcity problems which are intensified because of population growth, rising living standards, and accelerated urbanization. Increase in water demand leads to an increase in groundwater and surface water consumption and, particularly in the coastal area, causes sea water intrusion and increased soil salinity.

Water reuse has increasingly been integrated in the planning and development of water resources in Tunisia. Aiming to reuse the treated wastewater in various agricultural activities, water analyses were carried out on the reclaimed water intended for the aquifer recharge and on this area's groundwater. As for underground water before recharge, the results showed:

- no contamination by organic matter;
- no heavy metals;
- high salinity;
- high nitrate, potassium and chloride concentrations detected.

The studied area is in Korba region, in Tunisia (Africa). The 438 km2 Korba coastal aquifer is in the Northeast of the country.



Nitrogen fertilizers used in Korba are basically urea (organic) and ammonium sulfate (mineral), and farmers can mix them together and make a third fertilizer.

The aquifer:

The aquifer system of the Eastern Tunisian coast is formed by two superimposed aquifers, a groundwater sheet whose renewable annual resources are about 50 Mm3 per year and a deep aquifer whose renewable annual resources are about 11.1 Mm3 per year. The piezometry of the plio-quaternary aquifer of Korba region is seeing an alarming reduction and a high increase in salinity due to its over-exploitation.

Table 9: Korba Treatment Plant (5000m^3/day)

Parameter	Influent	Effluent
BOD	3146 kg/d	63kg/d
TSS	2831kg/d	57kg/d

System	Advantage	Disadvantage
Natural Lagooning	excellent elimination of microbiological pollution	the great influence of environmental parameters that induces seasonal variations of
	low operation and capital costs	

	very good landscape integration	water quality and odour pollution occurrence.
	the possibility of agricultural recovery of the produced planktonic biomass and effluents	

Results:

Aquifer Quality

The pH : 7.02 - 7.37 being in the range of natural waters

The organic pollutants: COD < 30 mg O2/L, and BOD_5 < 3 mg O2/L. ***It confirms that there is no contamination of this water by organic matter.***

The trace metal pollutant concentrations as: Aluminum, Cadmium, Copper, Iron, Lead, Zinc, Chromium, Manganese and Nickel are also lower than their detection limits.

The nitrite, ammonia and orthophosphate levels are quiet low, with respective maxima at 0.170, 1.11 and 0.77 mg /L These levels can be attributed to the agricultural practices in this region especially artificial and manure fertilization.

Treated Wastewater Quality:

Nine elements aluminum, cadmium, copper, iron, lead, zinc, chromium, manganese and nickel are analyzed in order to investigate about trace metal pollution in the TWW. Except for two occurrences for aluminum (3.5 mg/L) and iron (0.154 mg/L), all metals concentrations are below their detection limits (0.050 mg/L).

Regarding trace metal pollutants, the TWW can be used without harm for crop irrigation and aquifer recharge, with regular control of trace metal quality. Three main parameters that control physical chemistry of the treated wastewater are pH, temperature, and electrical conductivity. As for pH, resulted there is no worry about the use of this TWW for irrigation or recharge whereas EC fluctuations show an instability of the quality generated by this treatment plant. This can be due to the evaporation phenomena that increases in summer especially in the anaerobic lagoons for tertiary treatment, besides the summer industrial activities of the region mainly tomatoes conservation factories. The groundwater quality of the studied region shows a high contamination with nitrate and bacteria. Additionally, high concentrations of salts were observed reaching 8.50 g/L in some wells. Despite this fact, farmers near the treatment plant do not have access to the freshwater of the canal so do not have the choice, particularly in the dry season, but to use this salty groundwater to irrigate their crops. Fortunately, because of its too bad quality, the underground water of the region is not used for potable purposes. The analysis of the water from the outlet of Korba TWW plant has shown that it contains high levels of ammonia, high SAR and bacteriological contaminants, it can consequently cause problems when used directly in irrigation or aquifer recharge or rejected in the maritime environment. On the other side, if used safely, it can be beneficial in arid and semi-arid countries like Tunisia, which is suffering from the increasing scarcity of water resources and cannot neglect this source of water.

4.5 Soil Aquifer Treatment System

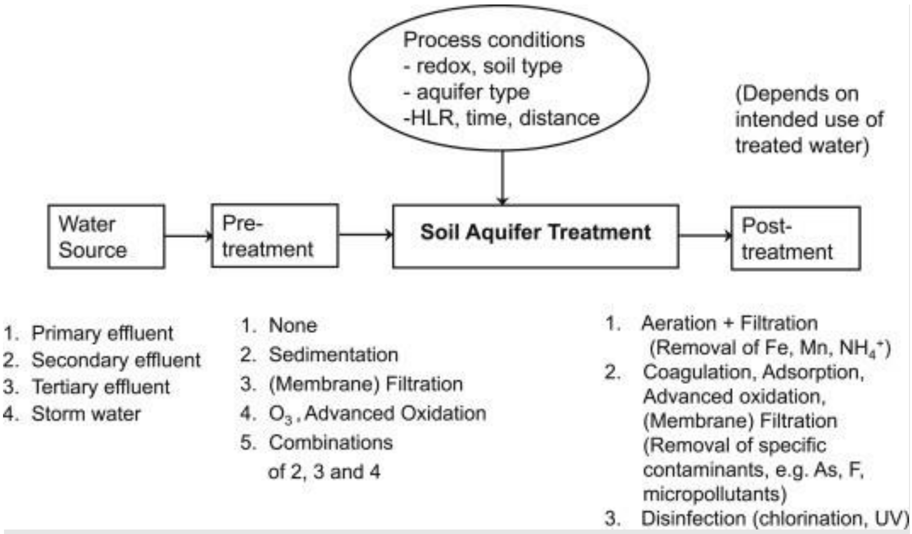


Figure 20: Scheme of Soil Aquifer Treatment

Soil Aquifer Treatment (SAT) system is widely used surface spreading system and an effective method of polishing treated wastewater. The system involves two main units that are flooding of recharge basins and infiltration of the wastewater for reuse purposes. System requirements are the mainly, the intermittent flooding of the reuse basins. Duration and the frequency of the flooding event are decision makers of the amount of the process effluent.

The quality of the reclaimed water is affected by the wetting and drying times of the system. While longer wetting times increase the amount of the effluent that filtered during a cycle, so system achieves higher contamination loading rate as ammonia and organic matter. Drying time affects effectiveness of the system since soil drying accelerates air penetration to the wet zone below the infiltration basins. This effect encourages aerobic processes to decompose contaminants accumulated during the wetting time.

Infiltration time (IR) is affected by both wetting and drying times, that is the single important parameter in SAT. All above hydraulic management of recharge basin is determined by IR, and the physical, chemical, and biological processes that take place in the recharge basin. The relationship between IR and amount of the infiltered effluent is linear. IR is not a constant parameter, since it is determined by many parameters associated with the *soil type* and its *water content.*

The SAT techniques most used in the study areas and which underwent permanent research has been: - Study on the biggest impact that affects the AR facilities: Clogging.

- Influence of the period and flow volume of artificial recharge on the infiltration rate and effectiveness of the facilities (The studies are being carried out in channels and infiltration ponds).

- Action taken on the morphology of the receiving medium (recharge wells, channels and infiltration ponds). - Reduction of air inflow into the aquifer around the AR facilities.

- Cleaning and maintenance operations.

Three MAR facilities in Spain:

1. Santiuste basin (Segovia);
2. Carracillo district (Segovia);
3. Guadiana canal at Ciudad Real (Spain).

1 and 2 consist of f infiltration ponds, channels and recharge wells while 3 is composed of a battery of 25 boreholes.

About Spain:

Some study notes that may be helpful (Escalante and Alamo, 2014)

- In areas where the application of surface-type devices is not possible, alternatives for charging were examined, and studies and tests were carried out on methods for placing subsurface devices placed in pipes that divert water from intake rivers to the MAR.
- The original dams needed modification to facilitate water purification through the river alluvial.
- Air inflow caused problems into the aquifer together with physical clogging.
- Changes to the water quality in adjacent wetlands, changes in the flows of springs have required specific studies, usually based on special induced artificial recharge designs.
- Clogging problems in infiltration ponds at different depths, as well as the generation of carbonated crusts in sectors of the aquifer with a chemism reducer of subterranean waters or originating from recharge during frost cycles.
- Inadequate well designs and recharge probes that enable fines to enter, abundant intake of air in the aquifer and limited infiltration, usually to take advantage of preexisting abandoned wells.
- The unbalanced distribution of clogging processes was detected in the slopes, which made it necessary to modify the morphology of the canals and ponds and design specific cleaning techniques.

4.6 SAT performed in the frame of FIT4REUSE

Dynamic simulation of the infiltration rate of a soil aquifer treatment (SAT) system using machine learning models based on a 5-year database:

The work presents data accumulated between 2015-2020, and historical operation is used to predict IR of individual flooding events. In this research it is stipulated that infiltration rate is constant during the flooding event, thus significantly reducing the computational requirements of the dynamic simulation. ML techniques have been applied successfully to estimate cumulative infiltration rates of soils and to speed up the calibration of parameters, such as hydraulic conductivity.

The study focused on the Shafdan SAT, a reclamation plant that treats approximately 135 million cubic meters per year. The secondary effluent from the Waste Water Treatment Plant (WWTP) flows into an operational reservoir and is then distributed to 70 infiltration basins with a total area of 1.1 km^2. The SAT-treated effluent is extracted from the aquifer by 150 production wells positioned around the infiltration basins. The Shafdan WWTP's effluent volume is expected to exceed the capacity of the current SAT system by 2030. The Shafdan reclamation plant offers a unique location to develop ML methodologies. A vast amount of

historical data has been collected at the Shafdan SAT site, and detailed environmental data exists from the on-site meteorological station.
The raw dataset of operational and environmental data comprised of:

- Static data relating to the physical characteristics of the basins, e.g., basin name, geometry, maximal top water level, soil type;
- Time-series operational data of the basin including e.g., inlet flowrates; water levels; valves' status; tillage indications;
- Environmental data from the meteorological station (e.g., temperature, global radiation, wind speed and direction, humidity, and precipitation rate); and iv) parameters obtained in the previous flooding cycles (*PT*).

A total of forty-three parameters were calculated for each flooding event. The data was statistically processed to form a nominal values database.

The results of the studies were:

The radiation affects photosynthesis, enriches algae and the dissolved oxygen in the infiltrated effluent, and enhances the degradation of microbial polysaccharides that accumulate on the basin's upper layer during the recharge. The temperature, on the other hand, affects the effluent density and viscosity, and the kinetics of microbial and chemical processes.

Shafdan SAT involves over 70 infiltration basins that are all fed by a single source, a reservoir with less than 2 hours of hydraulic retention time. Optimal distribution of the secondary effluent to the different basins, each operated with the optimal wetting time, allows minimization of the untreated effluent and maximization of the drying time of the basins. The study correlated with the knowledge that temperature, radiation, and soil dryness before recharge positive correlation with the IR, while negative correlation occurs between time from last tillage to IR.

All this working logic makes the study comparable and its suitability for different fields debatable. If this study is to be taken as a basis, hydraulic retention time, optimal wetting time, drying time are one of the important points to be considered. This study, in which 27 different parameters are taken into account, reaches the conclusion that the aquifer recharge process is feasible and promising, considering the water scarcity all over the world and especially the Mediterranean countries.

The solutions proposed in the FIT4Reuse document, for the environmental impacts and dysfunctions mentioned, have involved several years of research and progressive improvements. Generally speaking, the initiatives have been a reiterative process, up to the point that there are still several problems that are not adequately resolved, and designs are pending construction. However, the current devices present notable quantitative and qualitative improvements over the initial design built.

And the research presents a methodology of how real-time real-world SAT system data can be transformed into metadata, and how to use the data to feed ML models and predict the infiltration rate. The methodology suggests controlling the SAT system operation regime by defining two key parameters: α and cycle time. Implementation of the Shafdan case study implies that it is theoretically possible to increase the infiltration potential of the basins significantly by optimizing the operational regime.

CONCLUSIONS

Water reuse is a safe practice provided that adequate management practices are taken into account. Knowledge about implementation is generally scattered and there is not a compendium of practical aspects which can be of great help to users of reclaimed water. A precautionary principal leads potential users such as farmers to reject the use of reclaimed water, this also backed on cultural beliefs which tend to repudiate anything related to human excreta. And that is totally understandable because farmers are sometimes overwhelmed by information which is contradictory and not always coming from scientifically sound sources. But the truth is that today's technology is even able to treat wastewater and produce a clean effluent adequate for potable water. There are experiences of potable water reuse in countries like Singapore and Namibia. There is technology available for any use of the water we desire.

These guidelines intend to promote safe use of reclaimed water showing that adequate technologies and good practices in irrigation and aquifer recharge can support to alleviate water scarcity.

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