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Portfolio of different treatment schemes for water reuse

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1. Introduction and purpose of the report

This Portfolio of Different Treatment Schemes for Water Reuse (1.1) serves as a State of the Art (SoA) review of current technologies for wastewater reclamation. It initially focuses on Nature-Based Solutions (NBS) and expands to include "grey" technologies* and hybrid systems. The aim is to identify effective and innovative technologies for wastewater reuse, highlight trends, identify gaps, and explore potential future directions. As a technical resource for the SOLLAGUA project, it provides insights into selecting reuse technologies and developing strategies for various scenarios.

The portfolio includes detailed factsheets of 17 different technologies, exploring their key features, performance metrics, operational requirements, and potential applications. It examines how different approaches—whether green, grey, or hybrid—can be combined to enhance treatment efficiency and meet quality standards. These fact sheets are intended to aid in the decision-making process, offering concise yet informative guidance on the most relevant and innovative wastewater treatment solutions. As the project progresses, additional fact sheets will be developed to cover emerging technologies and address evolving needs in wastewater reuse. Real-world examples illustrate the practical applications and benefits of these technologies across diverse contexts, from small rural setups to centralized systems.

This document draws on an extensive bibliography, in-depth research, and insights from interviews and meetings with experts in reuse and NBS. It includes data from partners managing existing reuse platforms, covering performance metrics and analyses of pathogenic indicators, to ensure that the recommended solutions meet the required performance criteria and operational needs. This serves as a valuable guide for understanding and implementing advanced wastewater treatment solutions for effective water reuse

A significant section is dedicated to the legislative and quality standards for wastewater reuse, covering national and EU regulations. This section outlines the challenges and considerations in meeting diverse regulatory requirements and provides a comparative analysis of standards across the countries involved in the SOLLAGUA project. This information is crucial for understanding the implications of regulations on technology selection and the development of reuse schemes, especially in agriculture.

The report concludes by summarizing the key findings, emphasizing the importance of integrating various types of Nature-Based Solutions (NBS) and grey technologies to achieve effective and sustainable wastewater management that is fit for purpose. It identifies areas requiring further research and outlines the next steps in refining the Decision Tree Tool (DTT) to enhance its utility in guiding technology selection and implementation for wastewater reuse.

2. Overview of Wastewater Treatment Technologies:Key Technologies, Innovations, and DTT Integration

2.1. List of Technologies for Wastewater Treatment and Reuse

During the initial months of the project, a bibliographic review was conducted to evaluate a wide range of technologies used for wastewater treatment, addressing both disposal and reuse applications. This review covered all stages of the treatment process, from primary treatment through to reclamation steps, including various combinations of technologies throughout the entire treatment chain. The aim was to capture the full spectrum of options available for managing wastewater effectively, from initial pretreatment to the final point of use. As illustrated in Table 1, the review identifies numerous technologies across different stages of treatment, highlighting the diversity and potential for combinations to achieve optimal outcomes for various reuse scenarios. The technologies listed include everything from basic pretreatment methods like grease traps and screens, to advanced processes like membrane bioreactors (MBR).

Table 1. List of Technologies for Wastewater Treatment and Reuse

TYPE	CATEGORY	TECHNOLOGIES
Grey technologies	Pretreatment	Grease traps, Screens, Grit chambers, Clarifiers, Neutralization tanks, Equalization basins, Pre-chlorination, Pre-aeration
	Biological (Conventional)	Activated sludge systems, Aerobic granular reactors, Rotating biological contactors, Sequencing batch reactors, Imhoff tanks, Septic tanks
	Physico-chemical (Conventional)	Coagulation and Flocculation, Precipitation processes, Dissolved air flotation, Settlers
	Membrane Technologies	Membrane bioreactors (MBR), Microfiltration (MF), Ultrafiltration (UF), Reverse osmosis (RO), Electrodialysis (EDI), Electrodeionization
	Tertiary Advanced	Advanced Oxidation Processes (AOP), Fenton's reagent, Photo-Fenton, Sono-Fenton, Electrochemical processes, Nanotechnology applications, NERV
	Tertiary Filtration and Disinfection (Grey)	Sand filter, Biological activated carbon, Granular activated carbon (GAC), Powdered activated carbon (PAC), Coagulation, flocculation, and decantation, Chlorination, Sodium hypochlorite, Chlorine dioxide, Ultraviolet (UV) disinfection, Ozonization, Advanced oxidation with UV and hydrogen peroxide (UV_H2O2), Chloramination
Green technologies	Treatment Wetlands	French vertical flow (French_TW), Vertical flow (VSSF_TW), Horizontal flow (HSSF_TW), Free water surface flow (FWS_TW), Intensified reactive media (IRM_TW), Intensified aeration (IA_TW), Intensified recirculation (IR_TW)
	Green Infrastructure	Green roof (GR), Green wall (GW) for vertical spaces

	Hydroponics /Aquaponics	Aquaponics (A_HA), Hydroponics (H_HA) for reuse and food production
	Natural Wetlands	Natural wetlands (NW) for wastewater reuse environmental purposes
	Ponds/Lagoons	Intensified aerated (IA_P/L), Anaerobic (AP_P/L), Facultative (FP_P/L), Maturation (MP_P/L), Ponds with floating plants (FP_P/L)
	Soil-based Treatments	Rapid-rate infiltration systems (SIS_R), Slow-rate infiltration systems (SIS_S) (infiltration-percolation)
	Multi-stage Green Systems	Vertical TW followed by horizontal TW (VSSF + HSSF), Horizontal TW followed by maturation P/L (HSSF + MP), Anaerobic P/L followed by facultative P/L (AP + FP), Anaerobic P/L followed by facultative P/L followed by maturation P/L (AP + FP + MP), Facultative P/L followed by maturation P/L (FP + MP), Facultative P/L followed by free water surface TW
Storage	**Storage**	Retention basin, Storage reservoirs, Elevated tanks, Ground-level storage tanks, On-site detention (OSD) systems
Sludge and Solid Waste Management	**Sludge and Solid Waste Management**	Belt press (for dewatering), Imhoff tank, Sludge blanket systems, Upflow anaerobic sludge blanket digestion (UASB), Upflow Sludge Blanket Filtration (USBF), Centrifugation (for sludge dewatering), Sludge drying beds, Sludge drying red beds, Anaerobic digestion (for biogas production), Composting of biosolids, Thermal drying, Incineration, Pyrolysis and gasification, Lime stabilization, Sludge lagoons

2.2. Classification

Wastewater treatment and reuse schemes can be categorized into three primary groups: Green-Green, Green-Grey, and Grey-Grey technologies. This categorization helps to differentiate between approaches that use natural processes, those that combine natural and conventional methods, and those that rely solely on traditional mechanical or chemical processes. Green-Green Technologies rely entirely on natural processes for wastewater treatment. These systems include various types of treatment wetlands, ponds, and other ecosystem-based approaches that use natural vegetation, soil, and microbial activity to treat water. For example, treatment wetlands can perform multiple roles, such as removing solids, reducing organic loads, and providing natural disinfection through sunlight exposure and microbial action. Similarly, stabilization ponds can serve secondary and tertiary functions, such as reducing organic matter and pathogens through natural processes like sedimentation and solar disinfection.

Green-Grey Hybrid Systems combine green and grey technologies by integrating natural processes with conventional mechanical or chemical treatments. This hybrid approach enhances overall performance and can achieve specific treatment goals. For instance, treatment wetlands can be integrated with mechanical aeration to improve oxygen supply, enhancing the breakdown of organic materials. Another example is the combination of treatment wetlands with UV disinfection, where the wetland handles initial biological treatment, and the UV step provides pathogen reduction.

Grey-Grey systems involve traditional mechanical, chemical, and advanced physical processes. Examples include activated sludge systems, membrane bioreactors (MBR), and various filtration and disinfection methods such as UV, ozone, and chlorination. These systems are typically used in urban and industrial settings where high levels of control and reliability are required to meet stringent reuse standards.

Moving Beyond Conventional Stages: A Flexible Categorization Approach

Traditionally, wastewater treatment technologies have been categorized into primary, secondary, and tertiary stages based on their sequential roles: primary for physical separation of solids, secondary for biological degradation of organic matter, and tertiary for advanced polishing and disinfection. However, this stage-based framework does not always fit well with Nature-Based Solutions (NBS) or green technologies, as many of these systems provide multifunctional treatment that spans across conventional stages. For instance, treatment wetlands can remove solids, reduce organic loads, polish effluent, and even provide some level of disinfection, making them versatile and adaptable.

To better reflect the multifunctionality and integration of green and hybrid systems, a more flexible categorization scheme may be used for a more accurate representation of how these systems function in practice, moving beyond the rigid primary-secondary-tertiary framework. Green-Grey or Grey-Green configurations involve combining specific sub-treatments within the overall system to address different stages of wastewater treatment (eg. $Green_1$ + $Green_2$ + $Grey_3$).

2.3. Overview of Key Technologies and Decision Tree Tool (DTT)

The DTT of SOLLAGUA is designed to assist in selecting appropriate wastewater treatment technologies based on a variety of criteria, including the type of water available, the required quality of the treated water, the distance between the source and the reuse site, and the volume of water that needs to be treated. Given the complex legislative landscape across regions and the numerous combinations of parameters and treatment schemes, Task 1.2 of the project is focused on implementing a DTT that effectively addresses these combinations.

However, due to the complexity and extensive variety of potential combinations, the DTT will concentrate on the most commonly used treatment schemes (outlined in Section 3) and key innovative technologies, thereby ensuring the tool remains practical and user-friendly for stakeholders. A detailed list of the proposed technologies specifically tailored for the SOLLAGUA DTT is provided in Section 5.

To streamline the DTT and maintain focus on core treatment processes, the tool will not include basic pretreatment steps such as screening and grit removal, as these are standard processes applicable across most treatment systems. Additionally, the DTT will not cover the sludge management chain, which involves separate handling and treatment processes, nor will it address storage and distribution systems for the treated water, as these aspects fall outside the direct scope of treatment technology selection. This focused approach allows the DTT to provide targeted guidance on selecting the most effective green, grey, and hybrid technologies for wastewater treatment, while remaining adaptable to the needs and conditions of different regions and reuse applications

2.4. Key Innovations

This section reviews recent advancements and trends in wastewater treatment and reuse technologies, focusing on approaches that enhance efficiency, sustainability, and adaptability. With increasing interest in water reuse due to factors like water scarcity, regulatory requirements, and sustainable resource management, there is ongoing development of new technologies and methods. Innovations include advanced NBS, hybrid systems that integrate green and grey technologies, improved membrane and electrochemical treatments, and the use of digital tools for better system management.

NBS have garnered significant attention for their sustainable approach to managing water challenges, including wastewater treatment and reuse. According to the International Union for Conservation of Nature (IUCN), NBS are actions that protect, sustainably manage, and restore natural or modified ecosystems, addressing societal challenges while simultaneously enhancing human well-being and biodiversity (Cohen-Shacham et al., 2016). Traditional NBS in wastewater treatment include treatment wetlands (TWs) and ponds/lagoons (P/L), which utilize natural processes such as microbial degradation, sedimentation, and plant uptake to remove contaminants from water. The following outlines the latest trends and innovations in **green technologies** for wastewater treatment and reuse.

1. **Intensified Treatment Wetlands.** Recent advancements have led to the development of intensified treatment wetlands, which include vertical flow, horizontal flow, and free water surface systems. These intensified systems are often combined with technologies like intensified aeration or reactive media to enhance their capacity for pollutant removal, particularly for challenging contaminants such as nitrogen and pathogens. By enhancing oxygen transfer rates and increasing contact between wastewater and reactive surfaces, these intensified systems address common limitations of traditional wetlands, such as seasonal performance variability and bed clogging.
2. **Use of Reactive Media**. The use of reactive media in NBS, such as specialized substrates that can bind or transform pollutants, represents a significant innovation in treatment wetlands. Reactive media can include materials like biochar, zeolites, or other engineered substrates that enhance the removal of specific contaminants, including heavy metals, nutrients, and emerging pollutants

like pharmaceuticals and personal care products. This innovation allows for more targeted and efficient treatment, making NBS a viable option for a wider range of applications. Also, a pilot project in the Loire Valley, France, tested the use of biochar and zeolite in maturation ponds to enhance the removal of heavy metals and emerging contaminants from municipal wastewater. Biochar from agricultural residues and natural zeolite were integrated into floating mats and submerged in the pond bed, which significantly improved the adsorption of pollutants like lead and cadmium by up to 80%, as well as pharmaceutical residues. The studies (Zhao, 2019; Abedi et al., 2019) demonstrated that these enhancements not only increased contaminant removal but also promoted biofilm growth, further boosting the ponds' treatment efficiency, making them a promising option for sustainable wastewater reuse in agriculture.

3. **Electro wetlands,** also known as electroconductive or electroactive wetlands, enhance traditional wetland treatment by integrating electrodes that apply a low electrical current, improving the removal of contaminants like organic pollutants, nutrients, heavy metals, and pathogens. This technology leverages electrochemical reactions to achieve higher treatment efficiencies, making it a promising solution for wastewater management, particularly in agricultural and semi-urban settings. Despite their potential, challenges such as electrode maintenance and energy consumption need careful management. Research by Verma et al. (2024) underscores the effectiveness of these systems in achieving superior pollutant removal compared to conventional wetlands, highlighting their potential for broader application in sustainable water treatment strategies.

4. **Biodiversity enhancement in NBS**. The augmentation of biodiversity through biological amendments, such as microorganisms and macroinvertebrates, represents a promising strategy to enhance pollutant removal, increase infiltration capacity thus reduce system footprints, and improve ecological functions. By introducing or enhancing specific biological agents within treatment systems, such as treatment wetlands or bioreactors, these amendments increase the efficiency of pollutant degradation and removal processes. This approach is inspired from natural service of water quality regulation that gets more resilient and efficient when functional biodiversity increases. For instance, adding specialized microorganisms can accelerate the breakdown of organic pollutants and nutrients,

while introducing macroinvertebrates can enhance water infiltration by creating a macroporosity that favors pollutant and deep interstitial biofilm connection and nutrient cycling. This approach not only improves the performance of treatment systems but also supports the development of more resilient and diverse ecosystems. By integrating these biological amendments, systems can achieve greater sustainability and functionality while minimizing their environmental impact and operational costs (La Notte , 2021; Wendling et al., 2021).

5. **Hybrid green-green or green-grey with treatment wetlands.** Hybrid systems that combine different types of TWs (e.g., vertical subsurface flow, horizontal subsurface flow) or integrate TWs with additional treatment technologies such as UV disinfection, have been shown to improve overall performance. These hybrid configurations address the limitations of individual wetland types by optimizing the strengths of each component, such as improved nitrification from vertical flow systems and enhanced pathogen removal from horizontal flow or free water surface systems or UV. This type of combination is particularly valuable in the framework of the new policies regarding compliances of standards.
6. **Green Roofs and Green Walls.** Expanding beyond traditional wetland systems, green roofs and green walls are emerging applications of NBS for wastewater and stormwater management in urban environments. These systems provide multifunctional benefits, including thermal regulation, air quality improvement, and aesthetic enhancement, while also contributing to water management by retaining and treating runoff or greywater.
7. **Storage Ponds.** While storage ponds are typically used for retention rather than active treatment, they have demonstrated significant potential for pathogen removal and nutrient uptake, especially in agricultural reuse contexts. These ponds can effectively reduce pathogens through natural processes like sedimentation, sunlight exposure, and microbial activity, which collectively help lower levels of harmful microorganisms. Additionally, nutrient uptake by algae and aquatic plants can reduce nitrogen and phosphorus levels, enhancing the water quality for irrigation purposes. The integration of storage ponds with other Nature-Based Solutions (NBS), such as treated wetlands, provides a buffering capacity against fluctuations in wastewater quality and flow, thereby enhancing the overall resilience and sustainability of the treatment scheme. In Sicily, studies have shown

that combining storage ponds with treatment wetlands can be particularly effective in semi-arid regions, improving water quality for agricultural reuse by stabilizing effluent parameters and reducing the risk of contamination (Preston et al., 2016).

Grey technologies continue to play a critical role in wastewater treatment, particularly for applications requiring high levels of contaminant removal and where space constraints exist. Recent innovations in grey technologies are focused on enhancing treatment efficiency and integrating advanced processes to meet evolving quality standards. Hereby the latest trends and innovations in grey technologies for wastewater treatment and reuse.

1. **Advancements in Membrane Filtration.** Membrane technologies, including microfiltration, ultrafiltration, and nanofiltration, have seen significant advancements in materials and design, improving their efficiency and reducing energy consumption. The development of hybrid membrane systems that combine biological treatment with membrane filtration, such as Membrane Bioreactors (MBRs), has become a standard approach for achieving high-quality effluent suitable for various reuse applications, including potable reuse. MBR (Membrane Bioreactor) technology can effectively produce high-quality effluent suitable for direct agricultural reuse without the need for additional tertiary treatment. According to Bisco et al. (2024), MBR systems provide efficient removal of pathogens, suspended solids, and nutrients, achieving water quality that meets stringent agricultural standards, such as the Class A standards set by the EU. This makes MBRs a viable and sustainable option for wastewater treatment where direct reuse in agriculture is desired, offering consistent and reliable performance, especially in warm climates that enhance microbial activity. However, energetic and maintenance costs may be considered.
2. **Hybrid Biological Processes.** Combining traditional biological processes with advanced physical or chemical treatments has become a key trend in grey technologies. Examples include integrating activated sludge systems with advanced oxidation processes (AOPs) or electrochemical treatments to enhance the degradation of bio-recalcitrant compounds and remove emerging contaminants that conventional biological processes struggle to address.

3. **Advanced Oxidation Processes (AOPs).** AOPs, such as ozonation, Fenton's reagent, and UV-Hydrogen Peroxide systems, have been increasingly used to complement biological treatment stages, providing a robust solution for breaking down complex organic compounds and achieving disinfection. The integration of AOPs into existing treatment trains allows for more flexible and efficient treatment schemes, particularly for industrial effluents or water intended for high-quality reuse.

In addition to advancements in treatment technologies, there are numerous innovations in the operation and monitoring of systems, especially in grey technologies. The use of **sensors, digital tools,** and automation has become increasingly important for optimizing system performance and controlling water quality in real-time. These technologies enable precise adjustments to operational parameters, enhancing the efficiency and reliability of wastewater treatment processes. Real-time monitoring is particularly crucial for wastewater reclamation, as it ensures compliance with regulatory standards and improves the overall sustainability of reuse schemes by providing immediate feedback and control over treatment outcomes.

The future of wastewater reclamation seems to rely on the development and optimization of hybrid systems that utilise the strengths of both green and grey technologies. These hybrid systems offer the potential to provide high-quality treatment in decentralized and urban settings where space and resource constraints pose significant challenges. By integrating the ecological benefits and sustainability of NBS with the reliability and efficiency of grey technologies, these systems can enhance overall treatment performance, reduce costs, and promote water reuse in line with circular economy principles (Cohen-Shacham et al., 2016; Castellar et al., 2022). Emphasis on modular and scalable designs will support the adaptation of these systems to a wide range of settings, from small rural communities to larger urban applications. This adaptability is crucial for flexible wastewater treatment and reclamation facilities, which need to accommodate varying volumes and qualities of wastewater.

3. Technology Insights, Fact Sheets, and Real-World Schemes

This section outlines wastewater treatment technologies and their successful applications, with a focus on those most relevant to reuse. It includes fact sheets that describe the design, operation, and performance of key technologies, with an example template presented in Section 3.1. Due to the wide range of technologies available, the first phase of the project prioritized fact sheets for the 17 most commonly used and innovative technologies for wastewater reuse. Section 3.2 reviews common treatment trains and combinations, explaining how different technologies are integrated to achieve desired outcomes. Section 3.3 explores hybrid systems that combine green and grey technologies, enhancing treatment efficiency and adaptability. Finally, Section 3.4 highlights successful treatment schemes through real-world case studies.

3.1. Fact Sheets

The initial focus has been on selecting the most important and innovative technologies relevant to our context, particularly those expected to form the foundational basis for the Decision Trees (DTT). These technologies include nature-based solutions, hybrid systems, and advancements in grey technologies, aimed at creating a robust framework for selecting suitable wastewater treatment and reuse methods. So far, 17 factsheets 1) Activated Sludge Systems, 2) Aerobic Granular Reactors, and 3) Sand Filters, 4) Membrane Bioreactors (MBR), 5) Ultraviolet (UV) Disinfection, 6) Ozonization, 7) Chlorination, 8) French Vertical Flow TW (French_TW), 9) Vertical Flow TW (VSSF_TW), 10) Horizontal Flow TW (HSSF_TW), 11) Free Water Surface Flow TW (FWS_TW), 12) Intensified Reactive Media TW (IRM_TW), 13) Intensified Aeration TW (IA_TW), 14) Facultative Ponds (FP_P/L), 15) Maturation Ponds (MP_P/L), and 16) Anaerobic Ponds (AP_P/L) and 17) Slow-Rate Infiltration Systems (SIS_S) (Infiltration-Percolation) have been developed (annex I), with plans to expand this number as the project progresses, covering additional technologies to ensure a comprehensive and effective decision-making process.

The fact sheets provide essential information on the design, operation, and performance of each technology, supporting the implementation of wastewater treatment strategies tailored to specific reuse scenarios, focusing on both commonly used and innovative technologies. The template for each fact sheet includes the following sections:

1. Name of the Technology: Identifies the technology being described.
2. Brief Description: Provides a concise explanation of the technology's function and treatment processes.
3. Key Benefits: Lists the main advantages, such as effectiveness in pollutant removal, resilience, and low operational needs.
4. Drawbacks: Highlights potential limitations or operational challenges that may affect the technology's performance.
5. Type of Wastewater the Technology Can Treat: Specifies the types of wastewater suitable for the technology, including urban, domestic, industrial, and high contaminant load applications.
6. Effluent Variability (Seasonal or Temperature-Dependent): Summarizes the performance consistency under varying seasonal and temperature conditions.
7. Quality Provided (Pollutant Removal Efficiency): Details the technology's effectiveness in removing specific pollutants, such as suspended solids, organic matter, and pathogens.
8. Space (Footprint): Provides estimates of the area required, helping to assess space needs relative to the population served.
9. Main Materials, Works, and Components: Describes the primary materials and construction elements required, such as filter media, plants, plumbing, and control systems.
10. Price per m^2 Construction: Includes estimated construction costs per square meter based on recent data.
11. Figure: Where applicable, includes schemes to provide a clearer understanding of the system layout and components.

12. References: Lists sources and studies that support the information provided, guiding further reading.

3.2. Overview of Common Treatment Trains and Combinations

The most typical combination of technologies used for wastewater reuse involves a multi-step treatment process designed to remove contaminants and pathogens to meet the required quality standards for specific reuse applications. The choice of technologies depends on the intended use of the reclaimed water (e.g., irrigation, industrial use, potable reuse). Here's an overview of the most common technologies typically combined in wastewater reuse systems:

1. Primary Treatment

- Screening and Grit Removal: Removes large solids, debris, and grit to protect downstream equipment.
- Primary Sedimentation: Settles out suspended solids to reduce the organic load.

2. Secondary Treatment

- Biological Treatment (Activated Sludge, MBR, etc.): Involves the use of microorganisms to degrade organic matter. Membrane Bioreactors (MBR) are particularly popular because they combine biological treatment with membrane filtration, offering high-quality effluent.
- Secondary Clarification: Settles out biomass and other suspended solids from biological treatment.

3. Tertiary treatment

- Filtration (Sand, or Membrane Filters): Further removes residual suspended solids and particulate matter.
- Disinfection (UV, Chlorination, Ozone): Destroys pathogens to meet health safety standards. UV disinfection is popular due to its effectiveness and lack of chemical residues.

4. Advanced Treatment (for High-Quality Reuse)

- Reverse Osmosis (RO): Used for the removal of dissolved salts, heavy metals, and other contaminants. Commonly used in potable reuse applications.
- Granular Activated Carbon (GAC) Adsorption: Removes residual organic contaminants, including tastes and odours.Common Combinations for reuse for irrigation and industry:
- For Irrigation Reuse: Secondary treatment + Filtration + Disinfection.
- For Industrial Reuse: Secondary treatment + Tertiary filtration + Disinfection, and sometimes RO if needed.

This multi-barrier approach ensures that the reclaimed water meets the specific quality requirements for its intended reuse, addressing both health and environmental safety concerns.

3.3. Combining Green and Grey Technologies

As mentioned in the last section, hybrid systems that combine green and grey technologies for wastewater treatment are emerging as effective solutions for enhancing treatment efficiency and sustainability.

One example is the system in Sant Pau d'Ordal, Spain, where treatment wetlands are paired with UV disinfection. In this setup, the treatment wetlands use natural processes involving plants, soil, and microbial communities to remove mainly organic matter and nutrients from the wastewater. The subsequent UV disinfection step ensures that pathogens are effectively eliminated without the use of chemicals. This combination is particularly effective for agricultural irrigation, providing high-quality reclaimed water that meets safety standards while reducing environmental impacts (Capodaglio et al., 2021).

In Pavia, Italy, another hybrid system combines Membrane Bioreactors (MBR) with treatment wetlands (ase final treatment) to enhance wastewater treatment for industrial and landscape irrigation. MBR technology offers advanced filtration and high-efficiency removal of suspended solids and pathogens, while the treatment wetlands provide additional nutrient removal and polishing of the effluent. This integration allows the system to handle varying loads and reduce operational costs by leveraging the passive treatment benefits of the wetlands. The treated water from this system is reused in industrial cooling processes and for local irrigation, demonstrating the versatility and effectiveness of hybrid approaches in urban and industrial settings (Capodaglio et al., 2021).

In the Netherlands, a pilot project in Nijmegen showcases a novel combination of algae-based treatment systems and membrane technology (Algal-Based Hollow Fiber Membrane Bioreactors). This hybrid system is designed for small communities and industrial sites, focusing on nutrient removal and energy recovery from wastewater. Algae helps remove nitrogen and phosphorus while also contributing to carbon dioxide reduction, and the bioelectrochemical systems generate energy, enhancing the sustainability of the overall treatment process. This hybrid approach supports non-potable reuse applications, such as industrial water supply and irrigation, and represents a forward-thinking solution that integrates green and grey technologies to address both wastewater management and energy production challenges (Capodaglio et al., 2021).

The advantages of hybrid systems are multiple. They enhance treatment efficiency by combining the strengths of grey and green technologies, resulting in more robust and reliable performance. They also offer cost savings by reducing the reliance on energy-intensive processes typical of conventional grey systems, as green components like wetlands provide passive treatment benefits. However, challenges such as performance variability due to environmental conditions and land use requirements for green components must be carefully managed. Despite their potential, further research is needed to fully document their performance, cost-effectiveness, and land requirements to optimize their application across different settings (Castellar et al., 2022). The table 2 summarizes key schemes, highlighting their applications and advantages. It is important to note that pretreatment steps, primary treatments (such as decantation) for grey technologies, and sludge management processes are not included in these schemes but are essential components of the wastewater treatment systems.

Table 2. Overview of Promising Treatment Schemes for Wastewater Reuse

Type	Scheme	Key Technologies	Applications	Advantages
Green Systems	Treatment Wetlands Sequence	French Vertical Flow Wetlands, Horizontal Flow Wetlands, Free Water Surface Wetlands	Irrigation (urban, agriculture), environmental uses, Small communities	Sustainable, low operational costs
	Ponds Sequence	Anaerobic Ponds + Facultative Ponds + Maturation Ponds	Agricultural reuse, environmental uses, Small communities	Very low cost
	Treatment Wetlands with Reactive Media	Horizontal Flow Wetlands with Reactive Media (Biochar, Zeolites)	Heavy metal removal needed, Agricultural reuse	Targeted pollutant removal, low maintenance
	Mixing Ponds + Wetlands	Anaerobic Ponds , Facultative Ponds + Free Water Surface or Subsurface Wetlands	Agricultural reuse, Small rural settings	Enhanced nutrient recycling and pathogen reduction

Grey Systems	Activated Sludge + Sand Filtration + UV	Activated Sludge System + Sand Filter + Ultraviolet (UV) Disinfection	Urban non-potable reuse, Industrial cooling, Landscape irrigation	High effluent quality, effective pathogen removal
	Membrane Bioreactor	Membrane Bioreactor	Agricultural, urban, industrial	High contaminant removal, compact, meets strict standards
	Activated Sludge + Filtration + Advanced Oxidation Processes + Membranes	Advanced Oxidation Processes (AOPs) + Reverse Osmosis + Ultrafiltration, requires secondary treatment (e.g., Activated Sludge)	All uses including Industrial reuse, aquifer recharge	Effective on emerging contaminants, high-quality effluent
	Sequencing Batch Reactor + Disinfection	Sequencing Batch Reactor (SBR) + Chlorination or UV Disinfection	Urban non-potable reuse, Industrial processes	Flexible operation, efficient space utilization
Hybrid Green-Grey or Grey- Green Systems	Treatment Wetlands + UV	French Vertical Flow Wetlands + Horizontal Flow Wetlands + Intensified Aeration Wetlands + UV Disinfection	Agricultural reuse, Decentralized settings, Small communities	Combines strengths of different green and grey technologies, adaptable

	Primary Treatment + Treatment Wetlands	Septic Tank or Digester + Treatment Wetlands (Horizontal, Vertical, Surface Flow)	Decentralized settings, Restricted irrigation	Simple, Efficient pathogen removal, reduces operational complexity
	Membrane Bioreactor + Treatment Wetlands	Membrane Bioreactor + Horizontal Flow Wetlands	Agricultural reuse, environmental uses	High-quality effluent with enhanced nutrient removal
	Activated Sludge + Ponds + Wetlands	Activated Sludge System + Ponds + Horizontal Flow Wetlands + Free Surface Wetlands	Medium-sized towns, Green spaces, agricultural reuse, environmental uses	Combines high efficiency with natural treatment benefits
	Horizontal Subsurface Flow Wetlands + Grey Technologies	Horizontal Subsurface Flow Wetlands + Advanced Oxidation Processes + Adsorption + Membrane Filtration + Disinfection	Agricultural reuse, Industrial reuse	Provides further biodegradation of organic pollutants and by-products from the grey stage

	Hybrid Vertical and Horizontal Subsurface Flow Wetlands + Advanced Oxidation Processes	Vertical Subsurface Flow + Horizontal Subsurface Flow Treatment Wetlands + Advanced Oxidation and Electrochemical Processes	Agricultural reuse, Industrial reuse	Highly advanced, combines enhanced pollutant removal with multi-stage processes for high-quality effluent

3.4. Successful Treatment Schemes: real case examples

The following examples highlight the diverse approaches and configurations that have been successfully implemented, showcasing the adaptability and effectiveness of various treatment schemes in different real-world scenarios.

3.4.1. Typical grey configurations for villages and small towns (500-50.000PE)

Configuration Overview: A typical configuration for wastewater treatment in medium-sized towns includes an activated sludge system followed by sand filtration and disinfection (using UV or chlorination derivatives). This setup is widely used to achieve high-quality effluent suitable for various urban non-potable applications, such as landscape irrigation, industrial cooling, and toilet flushing. The Costa Brava Consorci in Catalonia, Spain, exemplifies the effectiveness of this configuration, demonstrating its success in real-world applications.

System Components

- Activated Sludge System:
    - Purpose: The activated sludge system is the primary stage for removing organic matter. It uses aerobic biological processes where microorganisms degrade organic pollutants, reducing Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and suspended solids.
    - Process: Wastewater enters aeration tanks where it is mixed with activated sludge (a concentrated mixture of microorganisms). Oxygen is supplied through mechanical aerators or diffused air systems to support microbial activity. After sufficient contact time, the mixed liquor is transferred to secondary clarifiers, where the biomass settles out, and the treated effluent moves on to further treatment stages.

    - Performance: This system achieves significant reductions in BOD (90-95%) and suspended solids, making it suitable for meeting secondary treatment standards.
- Sand Filtration:
    - Purpose: Sand filters act as a polishing step to remove residual suspended solids that pass through the activated sludge system. This step improves effluent clarity and prepares it for disinfection.
    - Process: Effluent passes through layers of sand, where fine particles are trapped and removed. Sand filtration effectively reduces turbidity and lowers suspended solids concentration to meet stringent reuse criteria.
    - Performance: Typically reduces suspended solids to below 10 mg/L, which meets the standards required for urban non-potable reuse.
- Disinfection (UV or Chlorination):
    - Purpose: Disinfection is the final treatment step, ensuring the effluent is safe for reuse by eliminating pathogens. This step is critical for reducing microbial contaminants, such as bacteria, viruses, and protozoa, to acceptable levels.
    - Options:
        - UV Disinfection: Uses ultraviolet light to inactivate microorganisms by damaging their DNA. UV disinfection is effective, leaves no residual chemicals, and is suitable for applications where chemical residues are a concern.
        - Chlorination: Involves adding chlorine or chlorine derivatives (e.g., sodium hypochlorite) to the effluent. This method provides a residual disinfectant, helping to control microbial regrowth in distribution systems.
    - Performance: Achieves microbial reductions that comply with standards for non-potable urban and industrial reuse. For example, *E. coli* levels can be reduced to below 1 CFU/100 mL, meeting strict regulatory requirements.

Implementation Example summary: Blanes, Consorci Costa Brava

Location	**Costa Brava, Catalonia, Spain**
Facility	The Costa Brava Consorci manages several wastewater treatment plants across the region, serving medium-sized urban areas and tourist destinations. A notable facility is the "Depuradora de Blanes," which showcases the use of activated sludge systems followed by sand filtration and UV disinfection. 
Reuse Applications	Treated effluent is reused for various non-potable applications, including: • Landscape irrigation (parks, gardens, and golf courses) • Industrial processes (cooling water for industries) • Environmental enhancement (maintaining ecological flow in rivers and wetlands)
Benefits	• Water Savings: Significant reductions in freshwater demand by reusing treated wastewater. • Compliance: Meets regional and EU water quality standards for urban and industrial reuse. • Sustainability: Reduces environmental impact by conserving water resources and minimizing discharge into natural bodies of water.
Performance Metrics and Cost Considerations	• Effluent Quality: Achieves BOD < 10 mg/L, Suspended Solids < 10 mg/L, and E. coli < 1 CFU/100 mL. • Operational Costs: Moderate-high, with significant expenses associated with energy for aeration and UV disinfection. Cost savings are realized in a global context through water reuse, reducing the need for potable water in non-essential applications. • Maintenance: Requires regular upkeep for aeration systems, sand filters, and UV lamps or chlorination equipment, including periodic backwashing of sand filters and replacement of UV lamps.
For more details	https://www.cacbgi.cat/es/edar/blanes-3/

3.4.2. Combination of Green Technologies for Wastewater Reuse in Agriculture for small communities

Configuration Overview: Inspired by a case study in Senegal, this configuration combines treatment wetlands to provide an effective solution for small communities or industries, particularly for agricultural reuse. The implementation of hybrid treatment wetlands at the University Gaston Berger (UGB) in Saint Louis, Senegal, demonstrates a robust approach to treating urban or domestic wastewater for potential agricultural reuse.

System Components

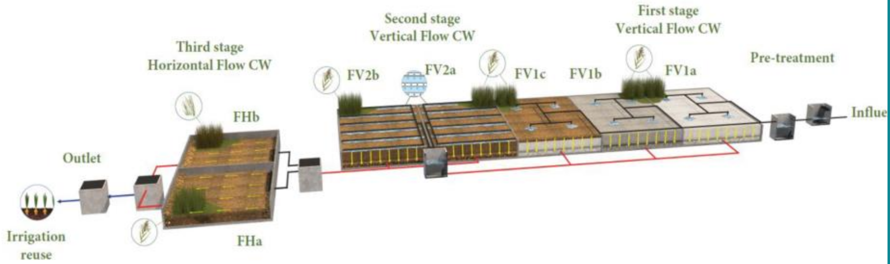
- Hybrid Treatment Wetlands:
    - Purpose: Designed to treat raw urban wastewater, making it suitable for agricultural reuse. The system enhances pathogen removal, minimizes sludge production, and uses locally available materials.
    - Components:
        - Two-Stage French Vertical Flow (VF) Wetland: Includes modifications such as increased sand levels in the second stage to improve pathogen removal efficiency. French VF wetlands handle high organic loads and provide primary and secondary treatment through aerobic degradation and sedimentation.
        - Horizontal Flow (HF) Wetland: Serves as tertiary treatment, focusing on further polishing of the effluent, additional pathogen reduction, and nutrient removal through horizontal subsurface flow.
    - Design and Adaptation:
        - Design Objectives:
            - Produces irrigation-grade effluent suitable for agricultural needs.
            - Minimizes sludge production, reducing management costs.
            - Utilizes locally sourced materials for environmental compatibility and cost feasibility.
    - Performance: The pilot plant effectively reduces pathogen loads to levels suitable for agricultural reuse, combining filtration, sedimentation, and natural disinfection processes.

Implementation Example summary: University Gaston Berger (UGB), Saint Louis, Senegal

Location: **Saint Louis, Senegal**

Facility

Developed as a pilot project to address urban wastewater treatment with a focus on reusing treated water for irrigation. The system combines French VF wetlands with an HF wetland filter. Designed for a capacity of 5 m³/day, corresponding to around 50 population equivalents (PE), making it suitable for small communities or agroindustrial applications.



Reuse Applications

Treated effluent is used for agricultural reuse (unrestricted: aubergines, fruit trees, watermelon,...) supporting local farming activities.

Benefits

- Water Savings: Significant reduction in agricultural water use
- Compliance: Meets WHO standards for reuse in unrestricted irrigation
- Sustainability: Using green technologies that support ecosystem services, recycle nutrients, enable water reuse for agriculture, and minimize energy consumption.

Performance Metrics and Cost Considerations

- Final Effluent Quality:
  - E. coli: Achieves a 3 to 4 log reduction, reaching levels below 100 CFU/100 mL, meeting irrigation standards.
  - Suspended Solids (SS): Effluent has suspended solids below 30 mg/L, suitable for agricultural irrigation.
  - Biochemical Oxygen Demand (BOD): Final effluent quality achieves BOD levels below 20 mg/L.
  - Nutrient Levels: Maintains beneficial nutrient levels for irrigation without exceeding harmful thresholds, with total nitrogen below 15 mg/L and phosphorus below 2

	● Operational Costs: very low associated with pumping for vertical treatment wetlands and reuse irrigation ● Maintenance: minimal management, mainly involving reservoir pump maintenance, routine control checks, and basic tasks such as weed control and species management to maintain optimal performance.
For more details	https://www.mdpi.com/2073-4441/12/11/3139

3.4.3. Combination of Grey and Green Technologies for decentralised wastewater Reuse for irrigation

Configuration Overview: Also inspired by a case study in Senegal, this configuration combines grey and green technologies, specifically septic tanks and treatment wetlands, to provide an effective solution for small communities or industries. The implementation at Gandiol School in Senegal illustrates a robust approach to treating wastewater tailored for decentralised sanitation in areas with limited infrastructure.

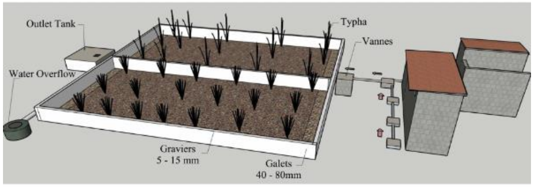
System Components

- Hybrid System at Gandiol School:
  - Purpose: Designed to treat wastewater from rural school settings, making it suitable for restricted irrigation and landscape use. The system combines grey and green technologies to enhance pathogen removal, minimize maintenance, and utilize local resources.
  - Components:
    - Septic Tank (Grey Technology): Provides primary treatment by separating solids from wastewater, reducing organic loads, and providing initial pathogen reduction.
    - Horizontal Flow (HF) Wetland (Green Technology): Serves as the secondary treatment stage, with beds planted with Typha and Vetiver to study their evapotranspiration rates and pollutant removal efficacy. The HF wetland focuses on further polishing of the effluent, achieving additional pathogen reduction and nutrient uptake through horizontal subsurface flow.
  - Design and Adaptation:

- Design Objectives:
  - Produces effluent suitable for restricted irrigation and landscape use, with plans to add UV disinfection for unrestricted irrigation in the future.
  - Designed to be simple and low-maintenance, reducing operational burdens in rural school environments.
  - Uses locally sourced materials for environmental compatibility and cost feasibility.

- Performance: The pilot system effectively reduces pathogen loads to levels suitable for restricted irrigation, combining primary treatment in the septic tank with secondary treatment in the HF wetland, leveraging natural processes for filtration and nutrient uptake.

Implementation Example summary: Gandiol School, Senegal

Location	**Gandiol School, Senegal**
Facility	Developed as a pilot project to address wastewater treatment at Gandiol with a focus on using treated water for restricted irrigation and landscape applications. The system was designed to accommodate the needs of the school, treating wastewater from approximately 500 students, making it ideal for small-scale or decentralized applications. The system includes a septic tank for primary treatment followed by a horizontal flow treatment wetland. The wetland beds were planted with Typha and Vetiver, which were specifically selected and tested for their water treatment capabilities and adaptability to local conditions. 
Reuse Applications	The treated effluent is suitable for restricted irrigation and landscape use, with plans to add a UV disinfection unit to enhance the effluent quality for unrestricted irrigation in the future.
Benefits	The Gandiol School pilot is a successful example of employing a hybrid of grey and green technologies in decentralized configurations, effectively addressing the wastewater treatment needs of rural communities. This approach balances sustainability, cost-efficiency, and local adaptability, offering a replicable model for similar contexts worldwide. Future enhancements, including UV disinfection, will expand the range of potential reuse applications, demonstrating the scalability and flexibility of hybrid wastewater treatment solutions.
Performance Metrics and Cost Considerations	• Final Effluent Quality: ◦ *E. coli*: Achieved reductions suitable for restricted irrigation, below the threshold of 1000 CFU/100 mL. ◦ Suspended Solids (SS): Effluent maintained suspended solids below 30 mg/L, ensuring it meets standards for landscape and restricted irrigation. ◦ Biochemical Oxygen Demand (BOD): Final effluent quality achieved BOD levels below 20 mg/L, making it appropriate for its intended reuse applications. ◦ Nutrient Levels: Balanced nutrient levels beneficial for irrigation without exceeding harmful thresholds, supporting safe agricultural use.
For more details	10.4236/jep.2024.151001

4. Legislation and Quality Standards for Wastewater Reuse

4.1. Regional and EU Legislation Overview and Fit-for-Purpose Approaches

Wastewater reuse regulations differ significantly across Portugal, France, and Spain, with each country establishing specific quality standards based on local environmental, public health, and agricultural requirements. The European Union (EU) provides overarching guidance through directives like the Water Framework Directive (2000/60/EC) and Regulation 2020/741, which set minimum requirements for water reuse across member states. However, individual countries can enforce more stringent standards tailored to their unique conditions. This variability necessitates a customized approach to wastewater treatment and reuse, considering the distinct legal and environmental contexts in each region (European Commission, 2020). In December 12, 2024, the European Union adopted the revised **Urban Wastewater Treatment Directive (UWWTD)**, marking a significant update to modernize wastewater management and enhance sustainability across Member States. This recast of the directive introduces a range of ambitious measures aimed at addressing contemporary environmental challenges. Among the key updates is an expanded scope, lowering the threshold for agglomerations covered by the directive to 1,000 population equivalents (PE), compared to the previous 2,000 PE. Member States are required to ensure these smaller agglomerations are connected to collective sanitation systems by 2035. The directive also mandates **advanced treatment requirements** for larger wastewater treatment plants (WWTPs). These facilities must implement tertiary treatment processes to remove nutrients such as nitrogen and phosphorus, and adopt advanced treatments targeting micropollutants, including pharmaceuticals and microplastics, with compliance deadlines extending to 2045. Furthermore, the directive sets **energy neutrality goals**, requiring WWTPs serving populations of 10,000 PE or more to achieve energy neutrality, contributing to the EU's broader climate objectives. Enhanced **monitoring and reporting requirements** will ensure Member States improve compliance and transparency in wastewater management practices.

A critical component of the directive is its strong emphasis on wastewater reuse, particularly in water-scarce regions. Member States are now obligated to integrate treated wastewater reuse into national water resilience strategies, promoting its adoption as part of the EU's circular economy goals. The directive outlines stringent treatment standards, including advanced technologies for micropollutant removal, to ensure the safety and quality of reused water. These measures aim to alleviate pressure on freshwater resources, reduce environmental impacts, and foster sustainable resource management practices. The directive also introduces **extended producer responsibility**, obliging pharmaceutical and cosmetic industries to fund up to 80% of the costs associated with advanced treatment technologies, aligning with the "polluter pays" principle. Collectively, these updates reflect the EU's commitment to protecting water resources, public health, and the environment while advancing innovative practices in water reuse and promoting sustainability and resilience in the face of climate change. The revised Urban Wastewater Treatment Directive will enter into force on January 1, 2025, with Member States required to transpose its provisions into national legislation by July 31, 2027. The directive outlines a phased implementation timeline to allow for gradual compliance with its ambitious objectives. For instance, agglomerations with populations between 1,000 and 2,000 PE must be connected to collective sanitation systems by 2035, while larger wastewater treatment plants must implement tertiary treatment for nutrient removal by 2045. Similarly, advanced treatment technologies targeting micropollutants, such as pharmaceuticals and microplastics, are mandated for WWTPs discharging into sensitive areas by 2045.

The **EU Regulation 2020/741** establishes minimum requirements for water reuse in agricultural irrigation, defining specific parameters to ensure safety and sustainability. These include microbiological parameters (e.g., *E. coli* limits), physical-chemical parameters (e.g., turbidity and suspended solids), and additional monitoring requirements for chemical contaminants such as heavy metals and nutrients. The regulation emphasizes pathogen control to reduce health risks, while also addressing nutrient management to prevent environmental harm. Monitoring frequency and limits vary depending on the water quality class (A, B, C, or D), ensuring that the standards align with the intended use and associated risk levels. Class A applies to high-risk uses, such as irrigation of crops consumed raw, requiring the strictest limits. Class B is for processed food crops and those without direct water contact, with moderate safety parameters. Classes C and D cover non-food crops, industrial uses, and green spaces, with progressively relaxed standards based on lower health and environmental risks.

In **Portugal**, the legal framework is detailed in Decree-Law No. 119/2019 which adopts a fit-for-purpose approach defining quality standards for treated wastewater intended for specific uses, including agricultural irrigation, urban, and industrial applications. The standards include limits on microbiological parameters such as *Escherichia coli* and Legionella spp., chemical limits on heavy metals and organic pollutants, and physical standards for suspended solids and turbidity (Decree-Law No. 119/2019). The law also incorporates a series of preventive measures and barriers to mitigate potential health risks. These barriers are tailored to the level of exposure risk associated with each application, ensuring that individuals who may come into contact with the reused water are adequately protected. The implementation of these measures may vary depending on the identified risks, with additional safeguards applied where higher exposure levels are anticipated.

Spain's Royal Decree 1620/2007 established a first legal framework for the reuse of treated wastewater, detailing quality requirements for diverse applications, including agricultural and industrial use. This decree outlines specific limits on microbiological, chemical, and physical parameters to ensure safety and environmental protection. It addresses pathogens like *Salmonella* and sets parameters for nitrogen and phosphorus management to mitigate potential environmental harm (*Royal Decree 1620/2007*). Building on this foundation, Spain introduced Royal Decree 1085/2024, which updates and modernizes the regulations governing the production, supply, and use of reclaimed water. This legislation represents a significant step forward, aligning Spanish water reuse practices with the *European Union Regulation (EU) 2020/741*. The new framework ensures compliance with harmonized minimum water quality standards for safe reuse across agricultural, industrial, and other sectors. The updates introduced by *Royal Decree 1085/2024* include several key changes. Firstly, it expands the allowable uses of reclaimed water, incorporating new urban applications such as toilet flushing, while promoting its use in industrial and recreational contexts. Secondly, the decree implements stricter microbiological and chemical standards, such as monitoring for *Legionella spp.* and introducing tiered water quality classifications tailored to different reuse scenarios. Thirdly, the integration of risk management plans is now mandatory, enhancing health and environmental safety through a structured approach to monitoring and mitigation. This updated legislation aims to improve the sustainability of Spain's water resources, align with EU directives, and address the country's pressing water scarcity challenges. By fostering innovative and safe water reuse practices, the framework reinforces Spain's commitment to resource efficiency and environmental protection.

In **France**, the reuse of treated wastewater was initially governed by the Order of 2 August 2010, which established conditions for its application in agricultural and urban contexts. This legislation introduced stringent microbiological standards, such as limits for *Clostridium perfringens*, along with guidelines for chemical contaminants and physical quality parameters to ensure the safe use of treated wastewater and the proper functioning of irrigation systems. Building upon this framework, two separate orders were issued in December 2023 to establish the conditions for water reuse. The order of December 18, 2023, further refined the regulations for the reuse of treated wastewater, specifically focusing on crop irrigation.. This updated legislation integrates the concept of sanitary barriers, allowing for greater flexibility in water quality requirements based on the specific reuse scenario. By incorporating additional measures such as drip irrigation systems or post-harvest cleaning, the regulation ensures safety while enabling broader applications of treated wastewater in agriculture. This evolution highlights France's commitment to sustainable water reuse practices while maintaining public health and environmental standards. The order of December 14, 2023, establishes the reuse regulations for the irrigation of green spaces. Recent updates to the regulatory framework have broadened the scope of treated wastewater reuse, particularly in the food industry. The **Décret n° 2024-769 du 8 juillet 2024** authorizes the use of certain recycled waters as ingredients in the production of final food products and modifies the conditions for their use in establishments within the food sector. Complementing this, the **Arrêté du 8 juillet 2024** sets out specific provisions for using treated wastewater in food preparation, processing, and preservation in food sector companies. These regulations apply to all foodstuffs and goods intended for human consumption, ensuring both safety and quality. In addition, the **Arrêté du 12 juillet 2024** introduces provisions for the recovery of grey water upstream of sanitation systems. This regulation allows the use of innovative treatment systems, provided they pose no health risks and meet stringent quality standards for water categories A or A+. These updates not only enhance safety measures but also expand the potential applications of treated wastewater, particularly in industries where water reuse can play a critical role in promoting sustainability. Together, these regulations form a robust framework for the reuse of treated wastewater in France. They highlight the importance of maintaining high health and environmental standards while encouraging innovative approaches to water management and reuse.

4.2. Legislative Framework in SOLLAGUA: Key Challenges and Opportunities

The legislative landscape within the SOLLAGUA project countries—Portugal, Spain, and France—presents both challenges and opportunities for the implementation of wastewater reuse schemes. While the EU provides a foundational framework, national regulations reflect local conditions, necessitating adaptable treatment solutions that can meet varying regional standards. This context underlines the importance of developing technologies and approaches that can align with diverse legislative requirements while promoting the safe and sustainable reuse of wastewater. Key challenges include navigating the complexity of multiple regulatory frameworks and addressing the specific needs of each country to ensure compliance and public acceptance (Water Reuse Europe, 2024). The table 3 summarizes the key parameters and differences in wastewater reuse legislation across Portugal, Spain, France, and the EU:

Table 3. Table of Legislation Standards comparison

Parameter	Portugal (Decree-Law No. 119/2019)	Spain (Royal Decree 1085/2024)	France (14 & 18 December 2023)	EU (Regulation 2020/741)
Microbiological Limits	*E. coli*, intestinal nematodes, Legionella spp.	*E. coli*, intestinal nematodes, Legionella spp and Salmonella for certain uses	E. coli Coliphage (bactériophages ARN-F spécifiques et/ou phages somatiques , Clostridium perfringens	*E. coli*, intestinal nematodes
Chemical Limits	Heavy metals, organic pollutants	Heavy metals, organic pollutants, nutrients	in 12/12/2024 policy)	Heavy metals, organic pollutants
Physical Parameters	Suspended solids, turbidity	Suspended solids, turbidity	Suspended solids, turbidity	Suspended solids, turbidity
Nutrient Management	Limits on N and P for certain uses	Limits on N and P for certain uses	No limits	No limits, emphasizes nutrient management
Main Reuse Applications	Agricultural, urban, industrial	Agricultural, urban, industrial	Agriculture and green place watering with possible additional barriers	Irrigation: Agricultural, urban green spaces

4.3. Implications for Technology Selection and Treatment Chains

The specific limits established by wastewater reuse regulations in Portugal, Spain, France, and the EU have direct implications for the selection and design of treatment technologies, particularly for treatment wetlands and related systems:

- Microbiological Limits: High microbiological standards, such as low *E. coli* counts, require robust pathogen removal processes. Treatment wetlands, such as horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) wetlands, can significantly reduce pathogens (1-3 ULOG). However, to meet stringent standards, especially for reuse involving human contact or food crops, a multi-stage or multi-barriers approach may be required. This can include a combination of wetlands and ponds, finishing with a final disinfection step, such as UV or chlorination, to ensure compliance with microbiological limits. For technologies like activated sludge, which primarily focus on organic matter removal, additional microbiological treatment—either through green (e.g., maturation ponds) or grey (e.g., UV disinfection) technologies—is often necessary to meet these standards. Regarding multi-barrier systems in France, underground drip irrigation is considered an additional safeguard in the treatment process. This approach allows for the use of lower-quality water at the treatment chain outlet while still ensuring safety and compliance with health standards.
- Chemical Limits: Chemical limits on heavy metals and organic pollutants necessitate treatment steps that specifically target these contaminants. Treatment wetlands with reactive media are effective for heavy metal removal, while organic pollutants may require integration with additional technologies like advanced oxidation processes (AOPs). Combining these systems with traditional methods, such as activated carbon adsorption, can help achieve the desired chemical quality.
- Physical Parameters (Suspended Solids and Turbidity): Meeting limits for suspended solids and turbidity is crucial for maintaining water quality and protecting irrigation systems from clogging. Treatment wetlands generally excel at reducing suspended solids, but they often have "remaining concentrations" of fine particulate matter, which contribute to baseline turbidity levels. To achieve the lower turbidity levels required for more sensitive applications, incorporating sand filtration as a final step can be effective, ensuring that water quality meets the required standards for reuse. In cases where NBS are used, the inherent turbidity might not reach the very low levels achievable by certain tertiary grey technologies unless the final stage incorporates additional filtration like sand or membrane filters.

- Nutrient Management: Where nutrient limits are not strictly defined (e.g., in Portugal and France), treatment wetlands can be used to recycle nutrients beneficially in agricultural settings. However, in regions like Spain, where stricter nutrient limits are imposed, wetlands may need to be enhanced with specific nutrient removal processes, such as intensified nitrification-denitrification stages or phosphorus removal technologies. For technologies like activated sludge, which primarily remove organic matter but not nutrients, additional stages may be required to address these nutrients, depending on the regulatory requirements for the reuse application.

4.4. Wastewater Reuse in Agriculture: Limitations, Challenges, and Considerations

Wastewater reuse in agriculture offers substantial benefits, including reduced freshwater consumption and the recycling of nutrients such as nitrogen and phosphorus, which are beneficial for crop growth. However, it also presents challenges that must be carefully managed. Distribution systems and reservoirs must be designed to handle variability in water quality, and there is often no need for the high nutrient removal required in other reuse applications, such as secondary and tertiary wastewater treatment schemes.

The primary considerations for agricultural reuse include maintaining appropriate pathogen removal to protect public health, managing nutrient levels to avoid environmental issues like eutrophication, and ensuring that irrigation systems are not clogged by suspended solids. Agricultural reuse is further supported by international agencies promoting sustainable development, with significant practices observed in Israel and the USA (Shoushtarian et al., 2020; WWC, 1998). Key considerations for agricultural reuse include the quality of treated wastewater, the type of crops irrigated, and the specific reuse standards that apply. For instance, different crops have varying sensitivity to pathogens, heavy metals, and nutrient concentrations, necessitating tailored treatment approaches.

Challenges

- While **nutrient** recycling is beneficial in agriculture, high nutrient concentrations can lead to eutrophication if not managed properly. NBS offer a balanced approach for agricultural uses for fertirrigation,, but in cases where nutrient limits are more stringent, additional processes for nutrient removal may be required.

- **Suspended solids and turbidity** can affect irrigation systems (drip irrigation, aspersion) by causing blockages. Wetlands and ponds are effective for reducing these parameters, but they often leave "remaining concentrations" of fine particulates. Moreover, ponds and free surface wetlands can have algae in their effluents due to similar processes, which can increase suspended solids (SS) and associated organic matter. This can result in failing to meet the required standards, even if the SS is primarily algae. Therefore, it is recommended to keep the reuse limits for agriculture in mind and take this into account. For example, adjusting the outlet level can help avoid capturing algae that are generally present in the surface layers. Alternatively, a nature-based solution (NBS) incorporating filtration can be used as a finishing step.
- System Design and Distribution: The design of the treatment system and the **distribution network** must account for the specific requirements of agricultural reuse, including the need for reservoirs and distribution systems that can handle varying water qualities and flow rates.

4.4.1. Summary of Legislation Parameters for Wastewater Reuse in Agriculture in Portugal, Spain, and France

This section provides an overview of the key legislative parameters for wastewater reuse in agriculture in Portugal, Spain, and France. It highlights the main standards and regulations each country enforces to ensure the safe reuse of treated wastewater in agricultural practices. These regulations cover aspects such as water quality criteria, treatment requirements, and allowable uses, aiming to protect public health, agricultural productivity, and environmental sustainability. The table 4 summarizes the legislation parameters, providing a comparative view of how each country approaches wastewater reuse in agriculture.

Table 4. Comparative Legislation of Wastewater Reuse in Agriculture in Portugal, Spain, France, and the EU

Parameter	Portugal (Decree-Law No. 119/2019)	Spain (Royal Decree 1085/2024)	France (14/12/2023 decree)	EU (Regulation 2020/741)
Microbiological limits				
E. coli (CFU/100 ml)	For crops consumed raw (Category A): <10 For other uses Categories B-D: <100-<10000	Category 2.1: <100 Category 2.2: <1000 Category 2.3: <10000	Category A: <10 Category B: <100 Category C: <1000 Category D: <10000	Category A: <10 Categories B-D: <100-<10000< 100
Intestinal Nematodes	Categories C-D: <1 egg/L	All Categories: <1 egg/10 L	1 egg/L for pasture	Irrigation of pastures or forage: <1 egg/L
Legionella spp.	Detected for specific usesAccording to specific legislation DL 52/2018	All Categories: <1000 CFU/L if aerosol generation risk (e.g., sprinklers); <100 CFU/L for Category 2.3	< 1 000 CFU/L when aerosol risk	Monitors other pathogens based on specific uses
Physico-chemical parameters				
Heavy Metals	Cadmium, Lead, MercuryCobalt, Iron,Manganese, Vanadium specified	Includes heavy metals and organic micropollutants		Includes organic micropollutantsI
Turbidity	Category A: <2 NTU for high-quality water	Category 2.1: <10 NTU Categories 2.2 & 2.3: Not specifically defined	Category A: <5 NTU Category B-D: no limits	Category A: <2 5 NTU; less stringent for lower categories
Suspended Solids (SS)	Categories A-E: <30 10 mg/L - <40 mg/L	Category 2.1: <20 mg/L Categories 2.2 & 2.3: <35 mg/L	Category A: <10 mg/L Category B-D set water quality limits at the	Category A: <Not specifically limit10 mg/Led; other categories in accordance

			WWTP outlet for effluent discharged into nature	with Directive 91/271/EEC
Reuse Applications				
Agricultural	All crop types, including crops consumed raw under strict controls	Category 2.1: Green areas and public spaces with restricted access Category 2.2: Non-food crops Category 2.3: Industrial and energy crops	All categories, with possible additional barriers like drip-system or underground irrigation for food crops with category B-C (forbidden with category D)	Categories A-D for all food and non-food crops

4.4.2. Implications for Technology Selection and Treatment Chains in Agricultural Reuse

The specific regulatory limits for wastewater reuse in Portugal, Spain, France, and the EU directly influence the selection and configuration of treatment technologies. To comply with these regulations, especially in agricultural reuse, it is crucial to strategically combine natural and conventional treatment systems, as agricultural reuse generally has less stringent requirements compared to other applications such as potable or industrial reuse.

Treatment wetlands, including Horizontal Subsurface Flow (HSSF), Vertical Subsurface Flow (VSSF), and Free Water Surface (FWS) wetlands, provide flexible options for wastewater treatment in agricultural settings. Depending on their design and configuration, these systems can function as primary, secondary, or tertiary treatments. They are particularly effective in pathogen reduction, nutrient recycling, and suspended solids removal, all of which are crucial for agricultural applications. Maturation and facultative ponds, commonly used for secondary or tertiary treatment, further enhance microbiological removal and polishing of the effluent.

By combining multiple stages of wetlands or integrating them with ponds, it is possible to achieve the desired quality for agricultural reuse, especially when nutrient recycling is beneficial. Green techs as secondary treatment systems can be sufficient for certain categories (e.g., Category 2.3 under Spanish law). However, for applications requiring very low turbidity levels and extremely low *E. coli* counts (e.g., Category A under EU regulations), additional filtration methods, such as sand filters, may be necessary to meet the required standards. For managing turbidity, NBS might leave "remaining concentrations" of fine particulate matter. In such cases, final-stage filtration, such as sand or membrane filters, is recommended to reach the desired water clarity, although in agricultural reuse, these requirements are generally more lenient. Treatment wetlands and ponds might require additional disinfection steps, such as UV or chlorination, to fully meet high safety standards, particularly for reuse involving crops consumed raw or in public spaces.

Regarding specific pollutants, such as heavy metals, treatment wetlands with reactive media are highly effective in targeting these contaminants. For managing turbidity, Nature-Based Solutions (NBS) may leave residual concentrations of fine particulate matter. To achieve the desired water clarity, particularly for stricter reuse applications, final-stage filtration methods such as sand or membrane filters are recommended.

The concept of sanitary barriers, promoted by the United Nations for years, offers a more flexible approach to water reuse by emphasizing not only the treatment chain but also additional protective measures. This model allows for tailored solutions that adapt to specific reuse scenarios, providing flexibility to lower water quality requirements when effective sanitary barriers are implemented. However, while it facilitates broader reuse opportunities, this approach can be more complex for administrators to implement due to the need for careful planning, monitoring, and integration of multiple protective measures. France has adopted this multi-barrier concept in its legislation, which regulates treated wastewater reuse for crop irrigation. This regulation allows for adjusting required water quality levels (e.g., A, B, C, or D) based on the application, provided that additional barriers such as drip irrigation or post-harvest vegetable cleaning are in place. Such frameworks demonstrate how the multi-barrier approach can balance safety and practicality, enabling sustainable water reuse while maintaining public health standards.

Given that limits vary greatly depending on agricultural use, so do the types of treatment needed. To ensure a **fit-for-purpose approach**, it is essential to consider not only the type of use (e.g., agriculture) but also the specific subcategory to optimize system design.

5. Proposed Technologies for the DTT

During Task 1.1, work has been carried out in parallel and in collaboration with Task 1.2 to ensure that the State of the Art (SoA) effectively informs the Decision Tree Tool (DTT). In the first phase, the most relevant technologies were selected to build the initial alpha version of the DTT, completed in July 2024 (see deliverable 1.2.1). The technologies chosen align with the SOLLAGUA proposal, focusing on integrating green and hybrid systems that have proven their efficiency or shown potential to meet required water quality standards. The selection emphasizes adaptability, sustainability, and cost-effectiveness, making them suitable for rural contexts. These include technologies that perform well in small-scale applications, like treatment wetlands to those fit for centralized treatment, such as membrane bioreactors or advanced disinfection techniques.

In parallel, Task 1.1 has been continuously updating the portfolio with innovative green technologies, including reactive media, subsurface flow wetlands (horizontal, vertical), French treatment wetlands, and infiltration-percolation systems. The focus is also on updating grey systems that are easy to maintain and suitable for decentralized settings, like hydrolytic digesters and membrane systems. These updates aim to refine the DTT by integrating these advanced NBS, grey systems, and other technologies, potentially including them in the beta version of the DTT. This will provide more tailored options to support decision-making and better adapt to various contexts and treatment scenarios, aligning with the project's overall goals. Table 5 summarizes the technologies included in the alpha version and those proposed for the beta version. The Beta version integrates all the technologies from the Alpha version while introducing additional innovative and advanced technologies.

Table 5. Technologies in DSS Alpha (α) and Proposed Beta (β) Versions

<table>
<tr><th>Category</th><th>Technologies in α-DTT</th><th>New Proposed Technologies for β-DTT</th></tr>
<tr><td rowspan="6">Green Technologies</td><td>Free Surface Wetlands</td><td>French Vertical Flow Wetlands</td></tr>
<tr><td>Subsurface Flow Wetlands</td><td>Intensified Reactive Media Wetlands</td></tr>
<tr><td>Anaerobic Ponds</td><td>Intensified Aeration Wetlands</td></tr>
<tr><td rowspan="3">Maturation Ponds</td><td>Facultative Ponds</td></tr>
<tr><td>Slow-Rate Infiltration Systems</td></tr>
<tr><td>Solar Disinfection</td></tr>
<tr><td rowspan="8">Grey Technologies</td><td>Activated Sludge Systems</td><td>Upflow Anaerobic Sludge Blanket Reactors</td></tr>
<tr><td>Membrane Bioreactors</td><td>Hydrolytic Digesters</td></tr>
<tr><td>UV Disinfection</td><td>Membrane Technologies (Microfiltration, Ultrafiltration)</td></tr>
<tr><td>Ozonation</td><td rowspan="5">Granular Activated Carbon</td></tr>
<tr><td>Chlorination</td></tr>
<tr><td>Septic Tank</td></tr>
<tr><td>Imhoff (sedimentation/digestion)</td></tr>
<tr><td>Hydrocyclone</td></tr>
</table>

Hybrid (Combinations)	Currently combines Grey/Green secondary treatments with Grey tertiary treatments	Green-Green (eg. wetlands combinations, wetlands + ponds)
		Green-Grey (e.g. wetlands + UV)
		Grey-Grey (e.g. activated sludge + sand filter + UV)
		Grey-Green (eg. septic tank + wetlands, activated sludge + ponds)

5.1. Proposed Green Technologies for DTT

Green technologies utilize natural processes for wastewater treatment, offering sustainable and cost-effective solutions. These technologies are particularly suited for decentralized applications in rural settings. The proposed green technologies for the Beta DTT version include:

- **Treatment Wetlands:** Treatment wetlands are versatile and can be adapted as primary, secondary, or tertiary treatment systems depending on their type and configuration. The subtypes include:
    - French Vertical Flow Wetlands (French_TW): Typically used for primary treatment due to their ability to handle high solids loads.+
    - Vertical Subsurface Flow Wetlands (VSSF_TW): Used for secondary treatment, effective at nitrification and organic matter removal.
    - Horizontal Subsurface Flow Wetlands (HSSF_TW): Employed as secondary treatment systems, effective in removing suspended solids and Biochemical Oxygen Demand (BOD).
    - Free Water Surface Flow Wetlands (FWS_TW): Often used as tertiary systems for pathogen reduction and final effluent polishing.

  - Intensified Reactive Media Wetlands (IRM_TW): Can be used for secondary or tertiary treatment, enhanced for specific contaminant removal.
  - Intensified Aeration Wetlands (IA_TW): These provide advanced secondary or tertiary treatment with improved aeration and contaminant removal capabilities.
  - Solar photo-disinfection (SODIS):. This process leverages the natural disinfection properties of sunlight, often combined with other processes or enhancements, such as photocatalysts (e.g., titanium dioxide) or natural materials, to improve its efficiency.

- **Facultative and Maturation Ponds:**
  - Facultative Ponds: Typically used as secondary treatment systems, combining aerobic and anaerobic processes to degrade organic matter.
  - Maturation Ponds (MP_P/L): Generally utilized as tertiary treatment systems, focusing on pathogen reduction and stabilization of effluent, making them ideal for pathogens high-quality reuse applications. But it can be some problems with algae in the effluent (meaning turbidity and SS)

- **Infiltration and Percolation Systems**:
  - Slow-Rate Infiltration Systems (Infiltration-percolation) (SIS_S): More suitable as tertiary treatments due to their extended contact times and ability to polish effluent. However, their implementation is often constrained by the availability of suitable sand, making them less feasible in areas with limited space.

- **Solar photo-disinfection (SODIS)** refers to the use of sunlight, particularly ultraviolet (UV) and thermal energy, to disinfect water by inactivating or killing pathogens such as bacteria, viruses, and protozoa. This process leverages the natural disinfection properties of sunlight, often combined with other processes or enhancements, such as photocatalysts (e.g., titanium dioxide) or natural materials, to improve its efficiency.

- UV Radiation: UV-A (320–400 nm) and UV-B (280–320 nm) radiation damage the DNA or RNA of microorganisms, preventing their replication.
- Thermal Effect: In some cases, the heat generated by solar exposure contributes to pathogen inactivation.
- Photocatalysis (optional): The addition of catalysts, such as titanium dioxide (TiO_2), can generate reactive oxygen species (ROS) under sunlight, further enhancing disinfection.

A practical example of solar photo-disinfection in wastewater treatment is its use in **waste stabilization ponds (WSPs)** or **treatment wetlands**:

- **Treatment Wetlands with Solar Disinfection:** Wastewater flows through shallow, plant-vegetated channels or basins where exposure to sunlight provides disinfection. This is often enhanced with **low-cost materials like transparent plastic covers** to maximize UV exposure.
- **Enhanced Pond Systems:** In semi-arid regions, shallow ponds are designed for maximum sunlight exposure, where sunlight's UV radiation helps to significantly reduce microbial loads, making the treated wastewater suitable for agricultural reuse.

This technique is particularly valuable in decentralized systems or resource-limited areas, as it relies on renewable energy and has low operational costs, aligning well with sustainable water management practices.

5.2 Proposed Grey Technologies for DTT

Grey technologies provide robust, scalable solutions for both decentralized and centralized systems, especially where higher treatment efficiencies are required or space constraints exist. The proposed grey technologies include:

- Classic primary systems for small communities
    - **Septic Tanks**: Septic tanks provide a simple and effective method for primary treatment of domestic wastewater in decentralized settings. They allow for the settling of solids and the partial digestion of organic matter

through anaerobic processes. While effective for basic treatment, effluent from septic tanks often requires further treatment to meet reuse or discharge standards.

  - **Imhoff Tanks (sedimentation/digestion):** Imhoff tanks combine the functions of sedimentation and digestion within a single structure, separating solids from wastewater and digesting them anaerobically in a lower chamber. This system is well-suited for small communities as it efficiently reduces organic load and sludge volume while requiring minimal operational oversight. Imhoff tanks are commonly used where space is limited and where more advanced anaerobic systems, like UASB reactors, are not feasible.

- Anaerobic Treatment for Small Communities:
  - **Upflow Anaerobic Sludge Blanket (UASB) Reactors**: Effective for organic load reduction and biogas recovery in small to medium-sized communities.
  - **Hydrolytic Digesters:** Suitable for primary treatment in rural settings with high organic matter, providing efficient organic matter breakdown and energy recovery. Used in agrofood industries..
- Aerobic Processes:
  - **Activated Sludge Systems:** Conventional systems used for secondary treatment, effective at removing organic matter and nutrients. Always combined with primary and secondary decantation,
  - **Membrane Bioreactors (MBR):** Advanced secondary treatment technologies combining biological treatment with membrane filtration, suitable for high-quality effluent production and reuse with no need for tertiary treatment.
- Tertiary and Disinfection Technologies:

- **Membrane Technologies (Microfiltration, Ultrafiltration):** Used for tertiary treatment to remove fine particulates and pathogens, essential for high-quality effluent.
- **Basic Filtration (Sand Filters):** Employed as tertiary treatment for polishing effluent and reducing turbidity.
- **Granular Activated Carbon:** a highly effective technology used in tertiary wastewater treatment to remove organic contaminants, chlorine, taste and odor compounds, and various other pollutants
- **Disinfection Technologies (UV Radiation, Ozonation, Chlorination):** Critical for pathogen removal and ensuring effluent meets safety standards for various reuse applications.

5.3. Combinations and Integration for DTT

Combining the selected technologies within the DTT framework enables the development of flexible and tailored treatment schemes to meet diverse reuse needs.

Hybrid Systems (Grey-Green and Green-Grey): Integrating treatment for example wetlands with disinfection technologies like UV or chlorination, or combining conventional activated sludge systems with natural ponds, can significantly enhance overall treatment performance. Another combination might start with an anaerobic treatment process to handle high organic loads, followed by a treatment wetland for secondary treatment, and conclude with UV disinfection for pathogen removal. Another example is a sequence involving a UASB reactor for initial organic load reduction, followed by a vertical flow wetland for nitrification and additional pollutant removal, and culminating in a maturation pond or sand filter to achieve final polishing and pathogen reduction.

Grey-Grey Sequential Treatment Trains: Designing treatment trains that incorporate multiple steps, such as aerobic processes followed by tertiary disinfection, offers robust solutions that meet the diverse regulatory requirements across various reuse applications, including agricultural and non-potable urban uses. Activated sludge systems, including variations like extended aeration and sequencing batch reactors

(SBRs), are highly effective for treating wastewater with high organic loads. In urban and periurban environments systems (eg. small towns in rural areas), activated sludge processes are often followed by secondary clarification and advanced filtration steps, such as sand or membrane filtration, to remove residual solids and pathogens. Finally, disinfection methods like UV, ozone, or chlorination are commonly employed to ensure the effluent meets stringent reuse standards, particularly for urban non-potable uses such as landscape irrigation and industrial cooling. However, their application in small communities and decentralized settings poses challenges due to the high maintenance demands, technical complexity, and operational costs associated with these systems. Adaptations for small-scale use include integrating activated sludge with natural systems like wetlands or ponds to reduce overall operational complexity while maintaining high treatment performance. It's important to note that MBRs can produce high-quality effluents that meet the standards required for reuse in agriculture, without the need for additional tertiary treatments.

Multiple Green-Green Combinations: As discussed in previous sections and illustrated in the examples, where space is sufficient, particularly in decentralized or small population settings, the use of multiple green-green combinations should not be overlooked. For agricultural reuse, employing a sequence of green technologies—such as French vertical flow wetlands (two stages) followed by horizontal subsurface flow wetlands or maturation ponds—can provide effective treatment across primary, secondary, and even tertiary stages. This approach leverages the natural treatment capabilities of wetlands, ensuring nutrient recycling and pathogen reduction, while also maintaining low operational costs and minimal energy consumption. Treatment Wetlands with Solar Disinfection: Wastewater flows through shallow, plant-vegetated channels or basins where exposure to sunlight provides disinfection. This is often enhanced with low-cost materials like transparent plastic covers to maximize UV exposure. Enhanced Pond Systems: In semi-arid regions, shallow ponds are designed for maximum sunlight exposure, where sunlight's UV radiation helps to significantly reduce microbial loads, making the treated wastewater suitable for agricultural reuse.

Flexibility and Adaptability: The targeted focus within the DTT ensures that stakeholders are equipped with practical tools to design and manage wastewater reuse schemes effectively. The selection of technologies for the DTT could differentiate between various scales and contexts, enabling tailored treatment recommendations based on specific needs. The DTT could consider factors such as the equivalent inhabitants, distinguishing between centralized approaches (e.g., a small town of 2000 inhabitants) and very decentralized setups (e.g., individual farms or greywater reuse systems). It is also important to account for industrial contexts (e.g., wastewater reuse in wineries or other rural industries), as the type of wastewater—whether domestic, non-domestic, or mixed—will influence the appropriate treatment technology and design. By factoring in these variables, the DTT could guide the selection of technologies that best fit the scale, type of water, and reuse goals of the community or industry.

One of the main **challenges of the DTT is identifying optimal combinations** that integrate multiple stages of treatment. The complexity lies in selecting and aligning these combinations to address varying water quality requirements, regulatory standards, and operational constraints, while also considering factors like cost-effectiveness and adaptability to local conditions.

6. Research Gaps, Technical Challenges, and Future Development Pathways in Wastewater Reuse

The field of wastewater reuse is evolving rapidly, driven by growing demands for sustainable water management solutions in response to increasing water scarcity and stringent environmental regulations. However, several **research gaps** and technical challenges remain that need to be addressed to optimize the performance, reliability, and applicability of both green and grey wastewater treatment technologies.

1. Gaps in Understanding Contaminant Removal. A significant gap exists in understanding the effectiveness of current technologies in removing specific contaminants, such as heavy metals, pharmaceuticals, personal care products, microplastics as emerging pollutants. While traditional technologies like activated sludge and treatment wetlands are effective at removing organic matter and nutrients, they often fall short in addressing these emerging contaminants. For example, the variability in the performance of NBS under different environmental conditions, such as seasonal temperature variations, can lead to inconsistent removal rates for pathogens and micropollutants (Mero et al., 2023; (Rizzo et al., 2023; Tang et al., 2023). Additionally, the transformation and fate of micropollutants in hybrid systems that combine green and grey technologies are not fully understood, necessitating further research to refine these processes and ensure regulatory compliance (Verma et al., 2024).

2. Technical Challenges in System Integration. Integrating multiple treatment technologies, particularly hybrid systems that combine green and grey components, poses technical challenges related to system design, operation, and maintenance. Hybrid systems require careful design to ensure that each component functions effectively within the overall treatment train. Issues such as hydraulic % compatibility, the risk of clogging in wetland systems, and the energy requirements of advanced oxidation processes for membrane technologies need to be addressed to optimize these systems (Moreira et al., 2020). Moreover, there is a need for standardized guidelines and protocols for integrating different technologies to ensure consistent performance across varied contexts and scales.

3. Lack of Data on Long-Term Performance and Resilience. There is a lack of long-term performance data for many innovative wastewater treatment technologies, and often are in laboratory scale. Understanding the resilience of these systems to varying loads, climatic conditions, and operational challenges is crucial for scaling up and ensuring their long-term sustainability. Research is needed to develop adaptive management strategies and resilient system designs that can maintain high performance under a range of operational conditions (Kumar et al., 2024; Sha et al., 2024).

4. Challenges in Monitoring and Digital Integration. Advancements in digital tools, sensors, and real-time monitoring systems offer significant potential to enhance the operational control and efficiency of wastewater treatment processes, especially for grey technologies. However, integrating these digital solutions into existing treatment infrastructure presents challenges related to data management, the interoperability of systems, and the need for skilled personnel to interpret and act on real-time data. The adoption of smart technologies and automation in wastewater treatment remains limited, particularly in decentralized and rural settings where resource constraints and a lack of technical expertise can hinder implementation. Further research into cost-effective and user-friendly digital solutions tailored to the specific needs of these settings is essential (Verma et al., 2024).

5. Pathogen and trace elements Removal Data Gaps. Despite advancements, significant gaps remain in the available data on the removal and transformation of specific contaminants, posing challenges for the effective implementation of these technologies. One critical area lacking data involves the removal of certain pathogens, including helminth eggs, Giardia, Cryptosporidium, and other protozoan parasites, which are particularly resilient and pose serious health risks if not adequately removed from treated wastewater. Existing studies often do not provide sufficient data on the effectiveness of various treatment technologies in addressing these microbiological parameters, which are included in some legislative frameworks but remain under-researched (Rizzo et al., 2023). Similarly, data on the removal of heavy metals and other trace elements is often incomplete. Technologies like reactive media in treatment wetlands show promise in adsorbing these contaminants, but more research is needed to quantify their long-term effectiveness and develop standardized approaches for integrating these media into broader treatment schemes (El Barkaoui et al., 2023). There is also a pressing need for more cost-effective, rapid, and easy-to-implement pathogen detection techniques. Such techniques would facilitate the study and monitoring of technologies, overcoming the difficulties currently faced due to the complexity and high costs of existing methods. Improving detection methods is crucial for advancing the development and application of effective treatment technologies.

6. Quality Management Beyond Treatment Facilities. A notable challenge in wastewater reuse is ensuring that the quality of the reclaimed water is maintained not just at the wastewater treatment plant (WWTP) or reclamation unit but also throughout the storage and distribution systems. These stages can either improve or degrade the water quality, significantly impacting the suitability of the water at the point of use, which is critical in applications such as agriculture where the point of use may be distant from the treatment facility. This challenge shows the importance of monitoring and maintaining water quality throughout the entire supply chain, not just at the treatment exit point.

7. Greywater Reuse. Greywater reuse, especially in small settings, presents a significant yet under-explored opportunity. Greywater is generally easier to treat than mixed wastewater streams, making it a promising area for development as it can significantly reduce freshwater consumption and wastewater generation. Despite its potential, greywater reuse lacks regulatory frameworks, which hinders widespread adoption and optimization (Moreira et al., 2020). Addressing this gap is critical, as targeted greywater reuse could provide simpler, cost-effective solutions with substantial sustainability benefits, especially in decentralized applications.

8. Decentralised sanitation. Decentralized wastewater reuse, particularly in isolated locations, industries, and agri-businesses, remains a challenge as effective treatment and reuse systems must be closely aligned with the generation site, which often lacks sophisticated infrastructure.

9. Challenges in Phosphorus Removal with NBS. Phosphorus removal is an ongoing challenge in NBS when aiming for very low phosphorus concentrations required for certain reuse applications. While treatment wetlands and soil-based systems can reduce phosphorus through sedimentation and adsorption, achieving consistently low levels suitable for sensitive applications remains difficult. Advanced materials such as specific reactive media can enhance phosphorus removal but require further research to optimize their use and ensure sustainability.

10. Footprint reduction on NBS. Expanding on the need to reduce the footprint of NBS such as soil-based systems and ponds is crucial for increasing their feasibility in urban and space-constrained settings. NBS combinations can achieve a wide range of water quality targets, making them suitable for various reuse applications, including agriculture, landscape irrigation, and even some industrial processes. However, their effectiveness is often limited by the large spatial requirements, which can increase costs and restrict their deployment in areas where land is scarce or expensive. Innovations in materials and system design offer potential solutions to this challenge. For example, the use of engineered substrates, recirculation or compact designs can enhance pollutant removal while significantly reducing the land area needed for treatment. In addition to material innovations, optimizing system configurations—such as layering multiple treatment processes within a single footprint—can further enhance performance and reduce spatial demands. For example, integrating vertical flow wetlands with compact sedimentation units or combining ponds with floating treatment wetlands can enhance treatment efficiency without significantly increasing the footprint. Reducing the spatial requirements of NBS will not only lower the costs but also make these systems more adaptable to diverse settings, including urban environments and industrial sites with limited space.

11. Water transport. One research gap in the implementation of green treatment systems is the energy demand associated with water transport and interconnection between treatment units. Unlike gravity-fed systems, many green infrastructures rely on external energy inputs to ensure water circulation and facilitate reuse, which poses challenges to their sustainability. This issue is particularly significant when considering the Life Cycle Analysis (LCA), as energy consumption during these processes contributes substantially to the overall environmental footprint of the system. Addressing this challenge requires an understanding of the energy dynamics within the system and a focus on minimizing these inputs to enhance efficiency and sustainability. Future research should focus on the development of innovative, low-energy, or energy-autonomous solutions to tackle these challenges. For example, the incorporation of pendular box systems, siphons, or solar-powered pumps could reduce dependency on external energy sources while maintaining system functionality. These methods have the potential to transform green treatment systems into fully energy-independent configurations, thereby improving their scalability and alignment with sustainable development goals.

Advancing these technologies will be crucial for ensuring that green systems not only achieve their ecological objectives but also contribute to broader efforts in sustainable resource management.

Opportunities for Innovation and Future Research Directions: Addressing these gaps presents opportunities for innovation and the development of next-generation wastewater treatment technologies. Future research may focus on:

1. **Advanced Materials and Biodiversity Enhancement in NBS:** Investigate the use of reactive media, biochar, and electroactive components, along with the augmentation of biodiversity through biological amendments (e.g., microorganisms, macroinvertebrates) to improve pollutant removal, reduce system footprint, and enhance ecological functions.
2. **Development of Modular Hybrid Systems:** Design modular and scalable hybrid systems that integrate green and grey technologies, adaptable to various scales and reuse requirements, allowing for flexible treatment solutions.
3. **Digital and Automated Systems Integration:** Implement digital tools, sensors, and real-time monitoring to optimize treatment processes and ensure consistent effluent quality, particularly in decentralized applications.
4. **Resource Recovery and Circular Economy:** Focus on integrating energy recovery, nutrient recycling processes within treatment systems to support circular economy principles and enhance sustainability.
5. **Greywater Reuse and Regulatory Development:** Explore innovative approaches for greywater reuse in decentralised sanitation, addressing current regulatory gaps to facilitate broader adoption.
6. **Advanced Pathogen Detection**: Enhance research on easy, advanced, and rapid techniques for detecting and managing pathogens such as specific viruses, bacteria, helminths, Giardia, and Cryptosporidium to ensure safety in reuse applications.
7. **Effluent Quality Management in Distribution:** Investigate methods to maintain and improve water quality during storage and distribution, crucial for ensuring safe reuse at the point of use, particularly in agricultural settings.
8. **Water transportation:** A significant research priority in green treatment systems is addressing the often-overlooked energy demands associated with water

transport and interconnection between treatment units. These processes, while not directly related to pollutant removal, have a substantial impact on sustainability and must be optimized to reduce energy consumption and align with sustainable development goals.

7. Conclusions

7.1. Summary of Key Findings

This report identifies a broad spectrum of technologies for wastewater reuse, emphasizing the potential of hybrid systems that integrate Nature-Based Solutions (NBS) with conventional grey technologies. These **hybrid approaches** are well-suited for decentralized and rural settings, where resource efficiency and adaptability are crucial.

The initial emphasis has been on selecting the most significant and innovative technologies relevant to the context, especially those expected to form the basis for the Decision Trees. The **portfolio includes factsheets for 17 technologies:** 1) Activated Sludge Systems, 2) Aerobic Granular Reactors, 3) Sand Filters, 4) Membrane Bioreactors, 5) Ultraviolet Disinfection, 6) Ozonization, 7) Chlorination, 8) French Vertical Flow Treatment Wetlands, 9) Vertical Flow Treatment Wetlands, 10) Horizontal Flow Treatment Wetlands, 11) Free Water Surface Flow Treatment Wetlands, 12) Intensified Reactive Media Treatment Wetlands, 13) Intensified Aeration Treatment Wetlands, 14) Facultative Ponds, 15) Maturation Ponds, 16) Anaerobic Ponds, and 17) Slow-Rate Infiltration Systems (Infiltration-Percolation). These factsheets outline each technology's key features, performance metrics, and space and costs requirements, aiming to provide a framework for selecting wastewater treatment and reuse methods.

Key innovations in green technologies highlighted in the portfolio include intensified treatment wetlands, reactive media or enhanced biodiversity in NBS, which improve pollutant removal and expand the applicability of Nature-Based Solutions beyond traditional setups. Combining various types and subtypes of green technologies, such as different wetlands and ponds, creates a natural treatment sequence from primary to tertiary steps. This approach is effective for agricultural wastewater reuse, suitable for small flows, and when space is available, offering a sustainable solution for pathogen reduction.

Regarding grey techs, MBRs are a leading option, combining biological degradation with membrane filtration to produce high-quality effluent suitable for direct agricultural reuse, including compliance with stringent standards like those of the European Union Class A. While Membrane Bioreactors provide high contaminant removal, they also involve high operational and maintenance costs due to significant energy consumption and the need for frequent membrane cleaning and replacement.

In centralised medium-sized agglomerations, conventional grey technologies, such as activated sludge systems followed by sand filtration and disinfection, remain the predominant choice for wastewater treatment and reuse.

The study also identified **gaps in current knowledge**, particularly regarding the removal or transformation of specific microbiological parameters such as Legionella, Clostridium, and heavy metals. Additional data on the performance of Nature-Based Solutions and hybrid systems in addressing these contaminants is needed to optimize their effectiveness and ensure compliance with diverse regulatory standards.

The report notes that the removal or transformation of **emerging pollutants,** such as pharmaceuticals and personal care products, is not yet fully addressed, as this is an evolving area of research. Although these pollutants are not covered by current legislation, they represent an important area for future investigation to improve the sustainability and safety of wastewater treatment and reuse practices.

7.2. Implications for the Project and Next Steps

The SOLLAGUA project's Water Oriented Living Labs (WOLLs) can apply findings from this report to explore new treatment technologies and/or configurations, especially those combining multiple green technologies or hybrid green-grey systems that have not been extensively tested. By doing so, the WOLLs can contribute to the validation and optimization of these approaches, potentially establishing effective new configurations suitable for various reuse applications. Building on these findings, the next steps involve:

- **Testing and Evaluation.** The WOLLs may explore the integration of innovative NBS and hybrid technologies in practical settings, generating performance data that can fill existing knowledge gaps, particularly for specific microbiological contaminants and heavy metals. This data would support the development of robust, compliant treatment schemes.

- **Focus on Specific Contexts.** The selection of technologies within the DTT could differentiate based on specific contexts, such as small rural communities, decentralized industrial applications (e.g., wastewater reuse in agricultural or industrial settings), etc.
- **Refining Decision Tools and Stakeholder Support.** Enhancing the DTT to reflect insights from ongoing tests and ensuring its practical application by stakeholders will be critical. The tool may guide stakeholders in selecting appropriate treatment schemes that comply with regulatory standards and meet operational needs.
- **Expansion of Fact Sheets.** The fact sheets provided in the annex offer essential design and performance information on key technologies. Expanding these resources to include more technologies and operational data will further assist stakeholders in implementing effective treatment solutions, adapted to their specific conditions and reuse goals.

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ANNEX I Wastewater reuse technology

FACT SHEETS

- Free Water Surface Flow TW (FWS_TW)
- Horizontal Flow TW (HSSF_TW)
- Vertical Flow TW (VSSF_TW)
- French Vertical Flow TW (French_TW)
- Intensified Reactive Media TW (IRM_TW)
- Intensified Aeration TW (IA_TW)
- Anaerobic Ponds (AP_P/L)
- Facultative Ponds (FP_P/L)
- Maturation Ponds (MP_P/L)
- Slow-Rate Infiltration Systems (SIS_S) (Infiltration-Percolation)
- Activated Sludge Systems
- Membrane Bioreactors
- Aerobic Granular Reactors
- Sand Filters
- Ultraviolet (UV) Disinfection
- Ozonizatation
- Chlorination

Free Surface Flow Wetlands (HSSF_TW)

Brief Description

A free water surface (FWS) treatment wetland is a nature-based solution that mimics natural wetlands. It consists of a shallow basin (0.5–1-meter-deep) with various aquatic plants (floating, emergent, and submerged) that help treat wastewater through physical, chemical, and biological processes. The structure of the plants serves as a substrate for biofilm, and the wetland system reduces suspended solids, organic matter, and pathogens, contributing to nutrient removal.

Key Benefits

- Provides habitat for wildlife.
- Effective for sedimentation and nutrient uptake.
- No electrical energy required.
- Can be built and repaired with locally available materials.
- Robust against load fluctuations.
- Lower construction price than subsurface flow treatment wetlands.
- Can be combined with aquaculture and agriculture.
- Low operating costs.

Drawbacks

- Potential mosquito habitat.
- Requires a large land area.
- Seasonal treatment variability.
- Requires supervision.
- Long start-up time to work at full capacity.
- Not very tolerant to cold climates.

Type of Wastewater Technology Can Treat

- Urban: Yes
- Domestic: Yes
- Mixed (Urban + Industrial): Yes
- Industrial: Needs Primary Treatment
- Charged (High contaminant load): Needs Primary Treatment

Space (Footprint)

- Very High: >6 m^2/PE

Effluent Variability (Seasonal or Temperature-Dependent)

- Consistency: Medium

Quality Provided (Pollutant Removal Efficiency) I

- Suspended Solids: High (80-90%)
- Total Organic Matter: Medium (60-70%)
- Biodegradable Organic Matter: High (70-80%)
- Nitrogen: Medium (40-60%)
- Phosphorus: Medium (40-50%)
- Nitrification: Low (30-40%)

Quality Provided (Pollutant Removal Efficiency) II

- Bacteria pathogens: Moderate-High (2-3.5 log removal)
- Helminths: High (2-3 log removal)
- Other parasites (Giardia, etc): ND
- Viruses: Moderate (1.5-3)

Main Materials, Works, and Components

- Construction Works: Installation of wetland basins.
- Materials:
    - Basin: Lined with impermeable barriers (clay or geo-textile).
    - Plants: Various aquatic plants (floating, emergent, and submerged).
- Complementary Structures: Pre-filtration systems to ensure water clarity.
- Control Elements and Electrical Cabinet: Control panels for monitoring and maintenance.

Price per m² Construction (Info 2018-2023):

5-22 €/m²

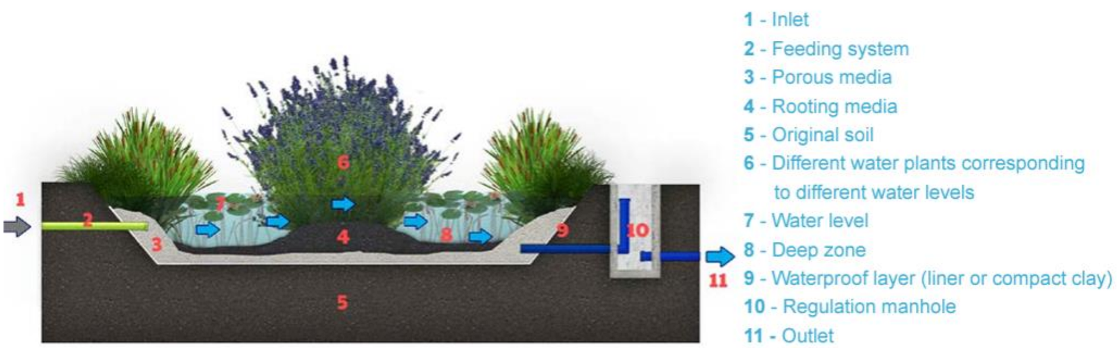

Figure from https://snapp.icra.cat/factsheets/

More Detailed Description

A free water surface constructed wetland (FWS) is a series of shallow, planted channels or basins designed to replicate the processes of natural wetlands, marshes, or swamps. Water flows slowly through the wetland, allowing particles to settle, pathogens to be destroyed, and nutrients to be taken up by plants and microorganisms. The wetland consists of various types of aquatic plants, which provide physical substrate for biofilm and uptake nutrients like nitrogen and phosphorus. The plants, along with microbial communities, play a crucial role in the treatment process.

In a typical FWS wetland, pre-treated wastewater enters the basin via a weir or distribution pipe. The water flows through the basin, allowing heavier particles to settle and nutrients to be removed through plant and microbial uptake. Pathogens are eliminated by natural decay, predation, sedimentation, and UV irradiation. Free water surface (FWS) wetlands can achieve high fecal coliform removal efficiencies. Studies indicate that FWS wetlands can remove fecal coliforms with efficiencies ranging from 98% to 99.99% (up to 3-5 log removal). This high level of removal is due to various processes, including natural decay, predation by higher organisms, sedimentation, and UV irradiation from sunlight, which are enhanced in these wetland systems. Proper design and maintenance are crucial to maximize these removal efficiencies and ensure the overall effectiveness of the treatment system.

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Horizontal Flow Wetlands (HSSF_TW)

Brief Description: A horizontal flow treatment wetland is a nature-based solution for wastewater treatment where water flows horizontally through a filter bed, allowing interaction with plant roots and microbial communities. The wetland utilizes the natural processes of vegetation, soil, and associated microbial populations to remove contaminants. This system is effective in reducing suspended solids, organic matter, and pathogens, and can also contribute to nutrient removal. The process is resilient to flow variations and requires low operation and maintenance, making it a sustainable and eco-friendly wastewater treatment option.

Key Benefits: Suitable for suspended solid, organic matter and pathogens removal, with high resilience to flow variations, very simple technology, Low operation and maintenance and process stability.

Drawbacks: Little nutrient removal; risk of clogging, depending on pre- and primary treatment.

Type of Wastewater Technology Can Treat:

- Urban: Yes
- Domestic: Yes
- Mixed (Urban + Industrial): Yes
- Industrial: Needs primary
- Charged (High contaminant load): Needs primary

Space (Footprint):

High: 3-6 m²/PE

Effluent Variability (Seasonal or Temperature-Dependent):

Variability: low

Quality Provided (Pollutant Removal Efficiency) I:

- Suspended Solids: High (80-90%)
- Total Organic Matter: Medium (60-70%)
- Biodegradable Organic Matter: High (70-80%)
- Nitrogen: Medium (40-60%)
- Phosphorus: Medium (40-50%)
- Nitrification: Low (30-40%)

Quality Provided (Pollutant Removal Efficiency) II:

- Bacteria pathogens: Medium (1.5-3 log removal)
- Helminths: Moderate-High (2-4 Ulog removal)
- Other parasites (Giardia, etc): Low-Medium 1-2 (2-4 Ulog removal)
- Viruses: Medium (1-2 log removal)

Main Materials, works and Components

- Construction Works: Movements of earth.
- Materials:
  - Filter Media: Gravel, sand, soil (usually gravel)
  - Plants: Emergent vegetation.
- Complementary Structures: Inlet devices (distribution system), outlet reservoir with water level control system
- Plumbing: Distribution elements, drainage pipes.
- Impermeabilization and Protection: Clay or synthetic liner (HDPE or PVC), geotextile.
- Control Elements and Electrical Cabinet (if applicable): Control systems, electrical cabinet.

Price per m^2 construction (info 2018-2023)
90-250 €/m^2

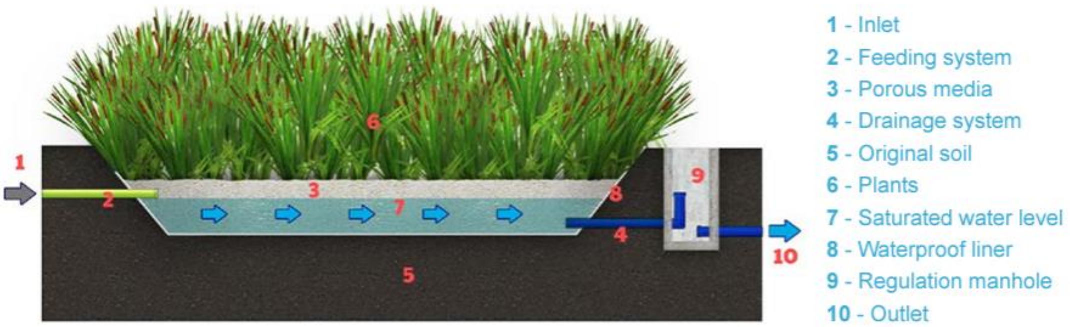

Figure from https://snapp.icra.cat/factsheets/

More Detailed Description

In HSSF_TWs, wastewater is fed in at the inlet and flows slowly through the porous medium under the surface of the bed in a more or less horizontal path until reaching the outlet zone where it is collected prior to exiting via level control arrangement at the outlet. During this passage, the wastewater will enter into contact with a network of aerobic, anoxic and anaerobic zones. The aerobic zones are found around the roots and rhizomes that leak oxygen into the substrate. The reactor is mainly anaerobic, with complex physical, chemical and biological mechanisms: bacterial reduction and oxidation, filtration, settling and chemical settling. Water flows underground with theoretical plug-flow, passing through the porous support media and contacting the biofilm formed over the support and plant roots. Hydraulic retention times (HRT) vary from a few to several days, depending on the management and objectives. HFCWs consist basically of: an inlet pipe, an outlet pipe with water level control (e.g., adjustable standpipe); A clay or synthetic (HDPE or PVC) liner; filter media (treatment zone: the bed filling material is sized to offer an appropriate hydraulic conductivity being the most frequently used media are coarse gravel, fine gravel and coarse sand and to furnish a large available surface for the biofilm growing); distribution and collection zone: the inlet and outlet zones use a large filling material, such as stones, in order to ensure easy cleaning in the case of clogging; emergent vegetation: being *Phragmites australis* , *Typha* spp. and *Scirpus* spp. the most used.

The sizing of the HFCWs systems depends on many parameters that should be examined during the preliminary feasibility assessment. After defining the treatment goals and the most appropriate treatment scheme, the sizing procedure may be performed using well known and scientifically approved methods. Area requirements are determined based on design equations such as the various commonly used first order kinetic equations for the pollutants removal and the Darcy law for the hydraulic aspects. As an alternative and simpler method, it is possible to use “rule of thumb” approaches for the design, based on areal coefficients such as “area per PE” and “area per gram of COD”. To reduce clogging, some authors have recommended limiting organic load rates to 6 g BOD_5/m^2·day for HFCWs (García and Corzo 2008). Until now, only simple deterministic models could be calibrated for the provision of performances assuming the horizontal subsurface flow system as a plug-flow reactor and applying the first-order removal equation.

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Vertical Flow Wetlands (HSSF_TW)

Brief Description:

Vertical Flow Wetlands (VSSF_TW) are a nature-based solution for wastewater treatment where water flows vertically through the substrate, enhancing aerobic microbial activity. These wetlands are designed to mimic natural wetland processes, providing an effective treatment for various pollutants. Wastewater is intermittently applied to the surface of the wetland, allowing it to percolate down through the substrate. This vertical movement facilitates high levels of oxygen transfer, which is crucial for the aerobic degradation of organic matter and nitrification processes.

Key Benefits:

- Effective in removing organic matter, suspended solids, and nutrients.
- High resilience to flow variations and load fluctuations.
- Low operational and maintenance efforts.
- Can be combined with other main treatment wetland types, e.g., horizontal flow (HF) and free water surface (FWS) wetlands, depending on the treatment goal.
- Suitable for decentralized treatment systems.
- Can be integrated into urban landscapes, providing green spaces and habitat for wildlife.
- Does not produce mosquito problems like Free-Water Surface wetlands.
- Less clogging than Horizontal Subsurface Flow Constructed Wetlands.
- Requires less space than Free-Water Surface or Horizontal Flow Wetlands.

Drawbacks:

- Requires careful pre-treatment to prevent clogging.
- Performance can be affected by extreme weather conditions and seasonal variations.
- Requires regular maintenance to ensure effective operation and prevent plant overgrowth or media clogging.
- Requires expert design and construction, particularly the dosing system.
- Requires a constant source of electrical energy.
- Long start-up time to work at full capacity.
- Not very tolerant to cold climates.
- High-quality filter material can be expensive and not locally available.

Type of Wastewater Technology Can Treat:

- Urban: Yes
- Domestic: Yes
- Mixed (Urban + Industrial): Yes
- Industrial: Needs Primary Treatment
- Charged (High contaminant load): Needs Primary Treatment

Space (Footprint):

- Medium: 1-3 m^2/PE

Effluent Variability (Seasonal or Temperature-Dependent):

- Consistency: Medium Performance can be affected by extreme weather conditions and seasonal variations (very cold climates need more area)

Quality Provided (Pollutant Removal Efficiency) I:

- Suspended Solids: High (90-95%)
- Total Organic Matter: High (80-90%)
- Biodegradable Organic Matter: High (85-95%)
- Nitrogen: High (70-80%)
- Phosphorus: Medium (40-60%)
- Nitrification: High (70-80%)

Quality Provided (Pollutant Removal Efficiency) II:

- Bacteria pathogens: Medium (1-3 log removal)
- Helminths: Medium (1-2 log removal)
- Other parasites (Giardia, etc): Medium (1-2 log removal)
- Viruses: Medium (1-2 log removal)

Main Materials, Works, and Components:

- **Construction Works:** Excavation and preparation of the wetland area, installation of liner and drainage system.
- **Materials:**
    - **Filter Media:** Layers of gravel, sand, and soil.
    - **Plants:** Reed species like Phragmites australis, Typha sp., or Echinochloa pyramidalis.
    - **Complementary Structures:** Inlet distribution systems, outlet structures with water level control.
    - **Plumbing:** Piping for influent distribution, effluent collection.
    - **Impermeabilization and Protection:** Clay or synthetic liner (HDPE or PVC), geotextile.
    - **Control Elements and Electrical Cabinet (if applicable):** Monitoring and control systems for automated operations.

Price per m² Construction (Info 2018-2023):

- 80-200 €/m²

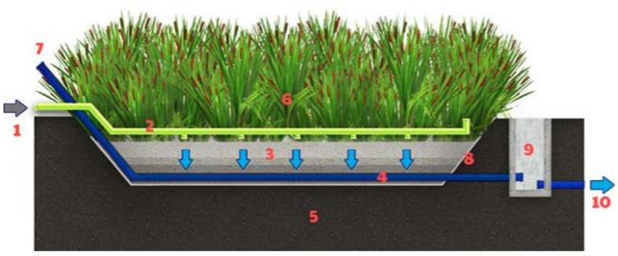

Figure from https://snapp.icra.cat/factsheets/

More Detailed Description:

Vertical Flow Wetlands (VSSF_TW) are designed to optimize the treatment of wastewater through vertical percolation. Wastewater is fed in at the surface and flows vertically down through the filter media, allowing for effective contact with plant roots and microbial communities. This process promotes aerobic degradation of organic matter and efficient nitrification. The systems typically consist of several layers of media, including coarse gravel, fine gravel, and sand, providing different filtration and treatment stages. The use of emergent vegetation like Phragmites australis helps to enhance the microbial processes and stabilize the system.

The design and sizing of VSSF_TWs depend on various parameters, including the desired treatment goals, influent characteristics, and local climatic conditions. Regular maintenance and monitoring are crucial to ensure long-term performance and prevent issues such as clogging and overgrowth of plants.

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French Vertical Flow Wetlands (F_TW)

Brief Description

French Vertical Flow Wetlands or French Reed Beds are a multi-stage subsurface vertical flow wetland system designed for wastewater treatment. These systems are typically unsaturated during operation, promoting efficient nitrogen removal through nitrification. In a French Reed Bed, wastewater is distributed evenly across the surface of a gravel bed planted with reeds. The water percolates vertically through the bed, where plant roots and a microbial biofilm on the media facilitate the degradation of organic pollutants and the conversion of ammonia to nitrate (nitrification). French Reed Beds are designed in multiple stages to optimize the treatment process. The first stage typically involves sedimentation and primary treatment, followed by several stages of vertical flow beds that progressively remove organic matter, nitrogen, and other contaminants. The unsaturated condition of the beds allows for effective aeration, enhancing microbial activity and ensuring high treatment efficiency.

Key Benefits:

- Can treat raw wastewater with high SS concentration
- No need for pretreatment
- High efficiency in organic matter removal
- High ammonia removal (nitrification)
- Very low sludge generation (can be used after years as agriculture amendment)

Drawbacks:

- Low or zero denitrification
- Disinfection performances low-medium (depending on media materials)
- In general needs pumps for water application

Type of Wastewater Technology Can Treat:

- Urban: Yes
- Domestic: Yes
- Mixed (Urban + Industrial): Yes
- Industrial: Needs Pretreatment if inhibitors
- Charged (High contaminant load): Yes. It can treat raw wastewater (without primary treatment)

Space (Footprint):

Medium: 1-3 m²/PE

Effluent Variability (Seasonal or Temperature-Dependent):

Variability: Moderate-Low

Quality Provided (Pollutant Removal Efficiency) I:

- Suspended Solids: High (90-95%)
- Total Organic Matter: High (80-90%)
- Biodegradable Organic Matter: High (85-95%)
- Nitrogen: High (70-80%)
- Phosphorus: Medium (40-60%)
- Nitrification: High (70-80%)

Quality Provided (Pollutant Removal Efficiency) II:

- Bacteria pathogens: Medium (1-3 log removal; < 1 Ulog first stage gravel, 1-2 Ulog second stage sand)
- Helminths: Medium 1-3
- Other parasites (Giardia, etc): Medium (1-2 log removal)
- Viruses: Medium (1-2 log removal)

Main Materials, works and Components

- Construction Works: Movements of earth.
- Materials:
    - Filter Media: Gravel, sand.
    - Plants: Emergent vegetation.
- Complementary Structures: Inlet devices (feeding and distribution system) including siphons, tipping buckets, networks of perforated pipes; reservoirs with or without pumps depending on multiple factors.
- Plumbing: Distribution elements, drainage pipes, valves.
- Impermeabilization and Protection: Clay or synthetic liner (HDPE or PVC), geotextile.
- Control Elements and Electrical Cabinet (if applicable): Control systems, electrical cabinet.

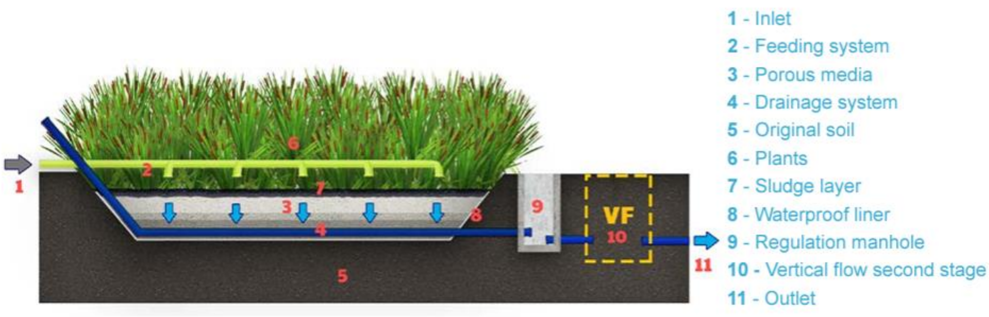

Figure from https://snapp.icra.cat/factsheets/

Price per m² construction (info 2018-2023)
150-420 €/m²

More Detailed Description

French vertical flow constructed wetlands were developed by Cemagref (now INRAE) over 20 years ago, and were applied by the SINT company during the 1990's. French VFCWs have become the main systems implemented in small communities under 2000 PE in France. More than 2500 plants are in operation for the treatment of domestic wastewater (up to 4500 PE). Most of these plants have been built according to the classical French design of two VFCWs stages, having well known guidelines and performance. The particularity of this system is that it accepts raw sewage directly onto the first stage allowing for easier sludge management as compared to dealing with primary sludge from an Imhoff settling/digesting tank. These CWs operate like the infiltration percolation systems: they are fed intermittently with loading and resting periods.

The feeding with raw wastewater causes the accumulation of a layer of solids on the top of the bed, which in turn acts as a filter. The alternation of cycles of feeding and resting promotes mineralization of the solid deposits during the resting phases. The feeding of the filters in hydraulic batches (by a storage and high capacity feeding system) ensures an optimum distribution of wastewater across the entire infiltration area and improves oxygen renewal. The flow of raw sewage (over the short dosing period) onto the first stage must be greater than the infiltration speed (infiltration rates) in order to correctly distribute the sewage over the entire bed Surface (Molle 2014). The deposits accumulating on the surface contribute to reduce the intrinsic permeability of the media and thus improve the distribution of wastewater. Plants limit surface clogging, since the stems pierce the accumulated deposits. When the difference in height between the inlet and outlet of the plant is sufficient, the plant operates without an energy source thanks to syphons. The granulometry of the filters differs depending on the stage: the media for the first stage consists of several gravel layers. The primary layer is fine gravel (approximately 2-8 mm). The second stage is made up of a layer of calibrated sand having the same granulometry as in the infiltration- percolation systems. The sizing of the filters is based on an acceptable organic load, expressed as a filter surface unity per PE. Current recommendations are two stages of filters, the first of which is divided into three filters and the second into two filters.

Area coefficients for sizing French VFCWs

Type of wastewater	Equation	Observations
Raw wastewater (first stage)	A (m^2) = 1.2 PE A (m^2) = 1.5 PE	Separate sewerage system Combined sewerage system
Treated wastewater (second stage)	A (m^2) = 0.8 PE A (m^2) = 1.0 PE	Separate sewerage system Combined sewerage system

In the first stage of the French VFCWs, the special design and operating conditions allow for a higher organic loading rate to be applied than in the other VFCWs: applied OLR values of up to 180 g BOD_5 /m^2 day and 300 g COD/m^2·day. This configuration has been found to permit a significant removal of COD, SS and almost complete nitrification.

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Intensified Reactive Media Wetlands (IRM_TW)

Brief Description

Intensified Reactive Media Wetlands (IRM_TW) are advanced treatment wetlands that utilize reactive media to enhance pollutant removal efficiency. These systems incorporate materials specifically designed to react with and remove pollutants such as phosphorus and nitrogen from wastewater. The reactive media enhances the natural processes of the wetland, providing higher removal rates for specific contaminants.

Key Benefits

- High Removal Rates: Efficient in removing specific contaminants like phosphorus and nitrogen.
- Enhanced Treatment Efficiency: Suitable for a wide range of wastewater types with high pollutant loads.
- Compact Footprint: Requires less space compared to conventional treatment systems.

Drawbacks

- Complex Technology: Requires more sophisticated design and construction compared to traditional wetlands.
- Higher Initial Costs: More expensive to implement due to the use of specialized materials.
- Maintenance Requirements: Needs regular monitoring and maintenance to ensure optimal performance.

Type of Wastewater Technology Can Treat

- Urban: Yes
- Domestic: Yes
- Mixed (Urban + Industrial): Yes
- Industrial: Needs pretreatment
- Charged (High contaminant load): Needs pretreatment

Space (Footprint)

- Medium-high: 1-4 m^2/PE (depending on the type of wetland: horizontal-vertical)

Effluent Variability (Seasonal or Temperature-Dependent)

- Consistency: High

Quality Provided (Pollutant Removal Efficiency) I

- Suspended Solids: High (90-95%)
- Total Organic Matter: High (80-90%)
- Biodegradable Organic Matter: High (85-95%)
- Nitrogen: Can be High depending on the type and materials (60-99)
- Phosphorus: Can be High depending on the type and materials (70-90%)
- Nitrification: Can be High depending on the type and materials (60-99%)

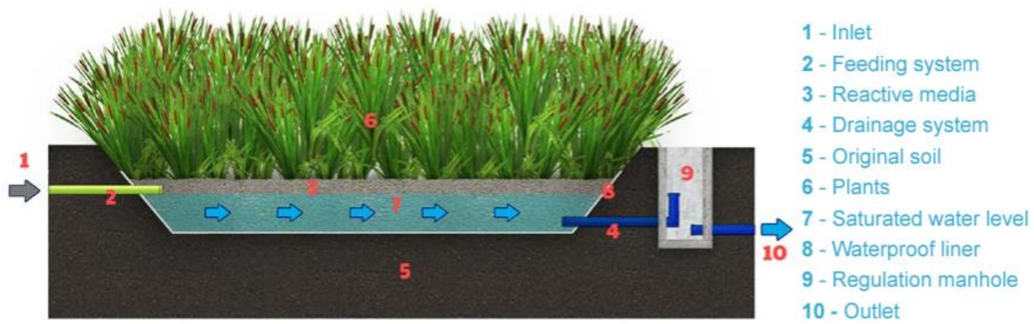
Quality Provided (Pollutant Removal Efficiency) II

- Bacteria pathogens: Low-medium depending on the type (1-3 log removal)

Main Materials, Works, and Components

- Construction Works: Earthworks and installation of media.
- Materials:
  - Filter Media: Specialized reactive media for enhanced pollutant removal.
  - Plants: Emergent vegetation.
- Complementary Structures: Similar to Vertical Flow Treatment Wetlands (VFTW) or Horizontal Flow Treatment Wetlands (HFTW).
- Plumbing: Distribution elements, drainage pipes.
- Impermeabilization and Protection: Clay or synthetic liner (HDPE or PVC), geotextile.
- Aeration (if applicable): Air pump connected to a subsurface network of air distribution pipes
- Control Elements and Electrical Cabinet: Control systems, electrical cabinet.

Price per m² Construction (Info 2018-2023)
Estimated Cost: 160-600 €/m² (depending on materials)



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More Detailed Description
Intensified Reactive Media Wetlands (IRM_TW) use enhanced filtration materials to improve the treatment efficiency of traditional wetland systems. These systems are designed to maximize the removal of specific contaminants through biological and chemical interactions within the media. The reactive media allows for higher rates of nutrient removal, particularly for phosphorus and nitrogen, making these wetlands suitable for areas with stringent discharge requirements. In these systems, wastewater flows through the wetland, interacting with the reactive media and vegetation. The media provides a surface for microbial communities to thrive and perform biodegradation processes, while also chemically binding pollutants. This dual action results in higher pollutant removal efficiencies compared to standard wetland systems.

Design Criteria: The type of influent can be primary treated wastewater or secondary treated wastewater. Treatment efficiency for TP ranges from 50–99%. Requirements include implementing a single layer of the selected reactive media, maintaining homogeneous hydraulic conductivity, with a media capacity ranging from 1 to 15 g P/kg of reactive media. Electricity needs can be operated by gravity flow; otherwise, energy for pumps is required. The hydraulic loading rate (HLR) ranges from 0.2–1 m³/m²/day, with a hydraulic residence time of 1 day (from a few hours to several days, depending on the media). Media size should be 5–15 mm for very reactive media, smaller sizes (about 1 mm) for natural occurring rocks.

Operation and Maintenance: Regular maintenance includes checking outlet pH, especially for industrial by-products and very alkaline compounds, monthly monitoring of effluent concentrations, particularly PO4, flow, and water distribution, removing invasive plant species and weeds from the filter (if unplanted), and conducting tracer tests after 1–2 years of operation to check for clogging. Extraordinary maintenance involves replacing the media once saturated with phosphorus or implementing a new reactive media filter. Troubleshooting includes addressing issues such as clogging, high outlet pH, and low removal efficiencies in case of low inlet concentrations.

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Intensified Aerated Wetlands (IA_TW)

Brief Description
Aerated treatment wetlands or Intensified Aeration Wetlands are an advanced type of treatment wetlands (TWs), (usually subsurface flow) which allow more efficient removal of contaminants from wastewater owing to the higher availability of oxygen. Wetlands with forced aeration to enhance microbial degradation processes and reduce footprint.

Key Benefits

- Improved Treatment Efficiency: Enhanced removal of organic matter, and other parameters.
- High Organic Load Capability: Effective for wastewater with high organic concentrations.
- Reduced Land Footprint: Requires less space than passive TW systems.

Drawbacks

- Technological Complexity: Involves delicate components not needed in passive TWs.
- Higher Energy Consumption: Increased energy use due to aeration.

Type of Wastewater Technology Can Treat

- Domestic: Yes
- Mixed (domestic/urban + Industrial): Yes
- Industrial: yes, but need pretreatment for SS
- Charged (High contaminant load): yes, but need pretreatment for SS

Space (Footprint)

Medium: 1-3 m^2/PE

Effluent Variability (Seasonal or Temperature-Dependent)
Variability: low

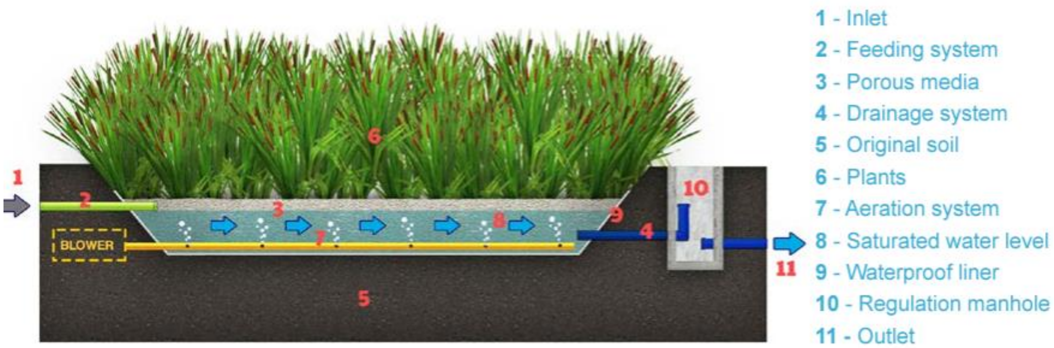
Quality Provided (Pollutant Removal Efficiency) I
- Suspended Solids: High (90-95%)
- Total Organic Matter: High (80-90%)
- Biodegradable Organic Matter: High (85-95%)
- Nitrogen: High (70-80%)
- Phosphorus: High (70-80%)
- Nitrification: High (70-80%)

Quality Provided (Pollutant Removal Efficiency) II
- Bacteria pathogens: Medium (2-3.5 log removal)
- Helminths: N/D
- Other parasites (Giardia, etc): N/D
- Viruses: Medium (1-2 log removal)

Main Materials, works and Components

- Construction Works: Movements of earth.
- Materials:
    - Filter Media: Gravel, sand
    - Plants: Emergent vegetation.
- Complementary Structures: idem to VFTW or HFTW
- Aeration: air pump connected to a subsurface network of air distribution pipes
- Plumbing: Distribution elements, drainage pipes.
- Impermeabilization and Protection: Clay or synthetic liner (HDPE or PVC), geotextile.
- Control Elements and Electrical Cabinet (if applicable): Control systems, electrical cabinet.

Price per m² construction (info 2018-2023)
180-400 €/m²



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More Detailed Description

A wetland equipped with an air pump connected to a subsurface network of air distribution pipes is called aerated CW (Hassan et al. 2021). The air bubbles introduced by the air pump can increase the oxygen transfer rate in horizontal flow or vertical flow type wetlands and effectively create aerobic conditions. The estimated oxygen consumption rate in CW could be 250 g of O_2/m^2.day with air flow rate and distribution to be ≥0.6m^3/m^2.h and 30 cm×30 cm, respectively. Mechanically aerated wetlands can provide higher oxygen transfer rates. Aerated treatment wetlands have become an increasingly recognized technology for treating wastewaters from domestic and various industrial origins under different climate conditions.

The main advantage of this technology is its high oxygen supply to the microbial community present, which enables increased rates of aerobic microbial degradation of pollutants. As wastewater discharge standards become increasingly stringent, aerated treatment wetlands offer effective removal of key pollutants such as organic carbon, ammonium nitrogen, and pathogens and also have a reduced land requirement compared to conventional treatment wetland designs. Different operation strategies and innovative designs can be used in order to intensify the performance of CW systems. Aerated wetlands testing different regimes of aeration "on" and "off", nitrification or denitrification processes can be enhanced. Aerated treatment wetlands have higher operation costs compared to passive treatment wetland design, but compared to the activated sludge technology, aerated wetlands have lower operational costs.

This technology allows the removal rates of biologically-oxidable contaminants (e.g., ammonia, BOD) to increase to almost complete elimination levels (HIGGINS et al. 2010a). While any kind of wetland cell can be operated in the aerated mode, subsurface flow (SSF) cells are mainly used (HIGGINS 1997). Aerated SSFIAWs generally have much smaller surface area, even 5-10 times less size of the equivalent passive sub-surface CWs. Aeration was found to profoundly affect treatment performances. When aerated at 0.85 m^3 of air per hour per m^3 of wetland bed, the volumetric (2TIS) BOD_5 removal rate constant averaged 5.4 day^{-1} with a temperature coefficient (θ) of 1.03, based on experiments conducted at 22°C and 4°C. In contrast, the non-aerated wetland had a rate coefficient of 0.55 day^{-1}. So they are capable of achieving >95% removals of most pollutants, during summer and winter, in facilities which are only a fraction of the size of traditional CWs. Aerated treatment wetlands have higher operation costs compared to passive treatment wetland design, but compared to the activated sludge technology, aerated wetlands have lower operational costs. As regards to the consumption of energy, it depends of the type of wastewater and the oxygen demand: i.e. to treat the urban wastewater of a municipality in Eastern Ontario, an external energy input of only 0.16 kWh/m^3 is required and this energy input is considerably less than activated sludge processes (2.39 – 0.51 kWh/m^3).

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Anaerobic pond/lagoon (A_P/L)

Brief Description

Anaerobic ponds are a nature-based solution (NBS) for wastewater treatment (pond subtype) where anaerobic processes dominate, making them suitable for high-strength wastewater. These ponds facilitate the breakdown of organic matter without oxygen, producing biogas (methane and carbon dioxide) that can be captured and used as an energy source. Anaerobic ponds are used for the initial treatment of wastewater and therefore, they are designed to receive a very high organic load, meaning that they are virtually free of dissolved oxygen and algae. Their main function is to eliminate solids and organic matter in suspension through sedimentation and subsequent anaerobic digestion. The anaerobic ponds have relatively small surface areas and a typical depth of between 2 and 5 m, with a short hydraulic retention time, between 1 and 6 days.

Key Benefits

- Effective in reducing high organic loads.
- Produces biogas which can be harnessed for energy.
- Suitable for various wastewater types, including high-strength industrial effluents.
- Low operational costs compared to aerobic processes.

Drawbacks

- Potential odour issues due to anaerobic conditions.
- Requires large land area for pond construction.
- Slower treatment process compared to aerobic systems.
- Requires pretreatment to remove solids and prevent clogging.

Type of Wastewater Technology Can Treat

- Urban: Yes
- Domestic: Yes
- Mixed (Urban + Industrial): Yes
- Industrial: Yes, usually used as primary treatment
- Charged (High contaminant load): Yes

Space (Footprint):

- Medium: 1-3 m^2/PE

Effluent Variability (Seasonal or Temperature-Dependent)

- Consistency: Medium (free surface flow systems are more sensitive to temperature changes)

Quality Provided (Pollutant Removal Efficiency)

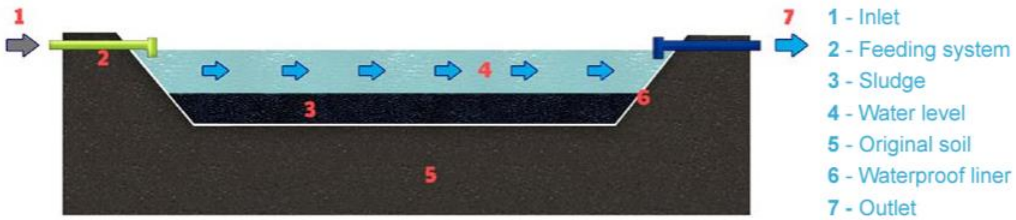
- Suspended Solids: High (80-90%)
- Total Organic Matter: High (80-90%)
- Biodegradable Organic Matter: High (85-95%)
- Nitrogen: Medium (40-60%)
- Phosphorus: Medium (40-50%)
- Nitrification: Low (30-40%)

Quality Provided (Pathogen Removal Efficiency)

- Bacteria Pathogens: Low-Medium (1-2 log removal)
- Helminths: Low-Medium (1-2 log removal)
- Other Parasites (Giardia, etc.): Low-Medium (1-2 log removal)
- Viruses: Low-Medium (1-2 log removal)

Main Materials, Works, and Components

- Construction Works: Earth movement and pond excavation.
- Materials: Impermeable liners (e.g., clay or synthetic materials).
- Complementary Structures: Inlet and outlet structures, biogas collection systems.
- Plumbing: Distribution and drainage pipes.



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Cost per m² Construction

- Typically ranges €4 to €15 per m² (mainly depends on the type of soil)

More Detailed Description

Anaerobic ponds are designed to replicate natural processes, facilitating the breakdown of organic matter in the absence of oxygen. The wastewater is introduced into the pond where heavier particles settle at the bottom, and anaerobic bacteria break down the organic matter, producing biogas as a byproduct. This biogas can be collected and utilized as a renewable energy source. The pond's design includes inlet and outlet structures to control the flow and prevent short-circuiting.

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Facultative Ponds (FP_P/L)

Brief Description

Facultative ponds are a nature-based solution (NBS) for wastewater treatment characterized by having both aerobic and anaerobic zones. This setup allows for the treatment of organic matter through aerobic processes at the surface and anaerobic processes at the bottom. Facultative ponds are effective in removing non-settleable organic matter, pathogens, and nutrients. These ponds usually have a depth of 1.5 to 2 meters and are distinguished by the green color of the water, indicating the presence of algae.

Key Benefits

- Cost-Effective: Low construction and operational costs compared to other treatment systems.
- Low Operational Requirements: Requires minimal maintenance and operational effort.
- Versatile Treatment: Capable of treating a variety of wastewater types, including urban and industrial effluents.
- Natural Treatment Process: Utilizes natural processes and sunlight for treatment, making it environmentally friendly.

Drawbacks

- Large Land Area Required: Requires significant land area for construction.
- Odour Issues: Potential for odour problems, especially during periods of low dissolved oxygen.
- Seasonal Performance Variability: Treatment efficiency can vary with changes in temperature and sunlight.
- Slow Treatment Process: Longer retention times compared to more advanced treatment systems.

Type of Wastewater Technology Can Treat

- Urban: Yes
- Domestic: Yes
- Mixed (Urban + Industrial): Yes
- Industrial: Needs primary
- Charged (High contaminant load): needs primary

Space (Footprint)

- High: 3-6 m^2/PE

Effluent Variability (Seasonal or Temperature-Dependent)

- Consistency: Medium, dependent on temperature

Quality Provided (Pollutant Removal Efficiency)

- Suspended Solids: High (80-90%)
- Total Organic Matter: High (80-90%)
- Biodegradable Organic Matter: High (85-95%)

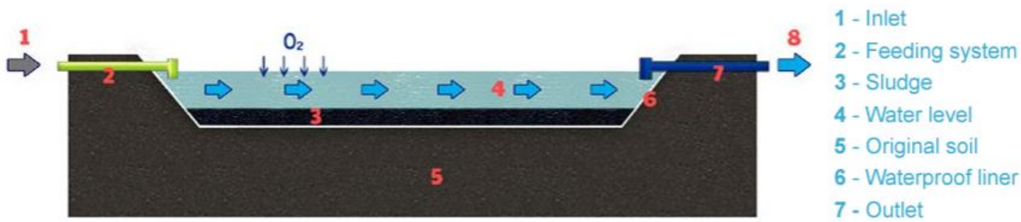
- Nitrogen: Medium (40-60%)
- Phosphorus: Medium (40-50%)
- Nitrification: Medium (50-70%)

Quality Provided (Pathogen Removal Efficiency)

- Bacteria Pathogens (E. coli): Medium (1-2 log removal)
- Helminths: Medium (1-2 log removal)
- Other Parasites (Giardia, etc.): Medium (1-2 log removal)
- Viruses: Medium (1-2 log removal)

Main Materials, Works, and Components

- Construction Works: Earth movement and pond excavation.
- Materials: Impermeable liners (e.g., clay or synthetic materials).
- Complementary Structures: Inlet and outlet structures, aeration systems.



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Cost per m² Construction

- Typically ranges: €4 to €15 per m² (mainly depends on the type of soil)

More Detailed Description

Facultative ponds are designed to replicate natural processes, facilitating the breakdown of organic matter through both aerobic and anaerobic mechanisms. The wastewater is introduced into the pond where heavier particles settle at the bottom. In the upper layers, algae produce oxygen through photosynthesis, which supports aerobic bacteria in breaking down organic matter. In the deeper layers, anaerobic bacteria continue the digestion process, reducing the organic load and producing gases such as methane and carbon dioxide. Proper design and maintenance are essential to maximize treatment efficiency and minimize issues such as odours.

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Maturation Ponds (MP_P/L)

Brief Description

Maturation ponds, also known as polishing ponds, are shallow ponds (usually between 1 and 1.5 meters deep) designed for the final polishing of treated wastewater. These ponds are characterized by the presence of dissolved oxygen in virtually all of their volume, often in oversaturation. Whereas anaerobic and facultative ponds are designed for BOD removal, maturation or polishing ponds are essentially designed for pathogen removal and retaining suspended stabilized solids. Maturation ponds operate after other purification processes, as they must receive a very low organic load to maintain aerobic conditions. Their main function is to eliminate pathogenic microorganisms through elevated temperatures, basic pH, light (UV radiation), and the activity of concurrent microorganisms.

The size and number of maturation ponds depend on the required bacteriological quality of the final effluent. The principal mechanisms for faecal bacterial removal in facultative and maturation ponds are hydraulic retention time (HRT), temperature, high pH (> 9), and high light intensity.If used in combination with algae and/or fish harvesting, this type of pond is also effective at removing the majority of nitrogen and phosphorus from the effluent

Key Benefits

- **Pathogen Removal**: Effective in removing bacteria, viruses, and other pathogens.
- **Nutrient Uptake**: Helps in the removal of remaining nutrients from the wastewater.
- **Algae Control**: Supports the growth of algae that contribute to the treatment process.

Drawbacks

- **Large Land Area Required**: Requires significant land area for construction.
- **Odor Issues**: Potential for odor problems during certain conditions.
- **Seasonal Performance Variability**: Treatment efficiency can vary with changes in temperature and sunlight.

Type of Wastewater Technology Can Treat

- **Urban**: Yes
- **Domestic**: Yes
- **Mixed (Urban + Industrial)**: Yes, as tertiary treatment
- **Industrial**: No
- **Charged (High contaminant load)**: No

Space (Footprint)

- **High**: 3-7 m^2/PE

Effluent Variability (Seasonal or Temperature-Dependent)

- **Consistency**: low. Performance vary depending on sunlight and temperature.

Quality Provided (Pollutant Removal Efficiency) I

- **Suspended Solids**: High (80-90%)

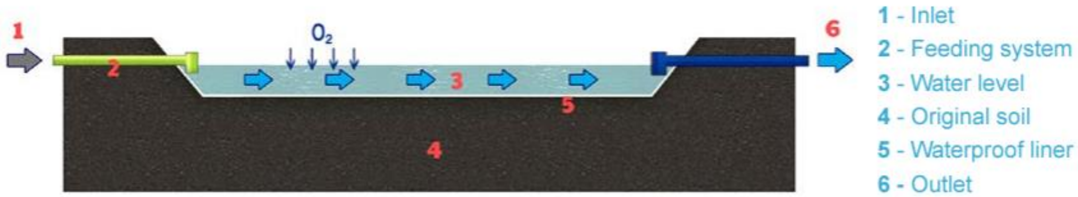
- **Total Organic Matter**: High (80-90%)
- **Biodegradable Organic Matter**: High (85-95%)
- **Nitrogen**: Medium (40-60%)
- **Phosphorus**: Medium (40-50%)
- **Nitrification**: Medium (50-70%)

Quality Provided (Pathogen Removal Efficiency)

- **Bacteria Pathogens**: High (2-4 log removal)
- **Helminths**: Medium (1-2 log removal)
- **Other Parasites (Giardia, etc.)**: Medium/high (1-3 log removal)
- **Viruses**: Medium/high (1-3 log removal)

Main Materials, Works, and Components

- **Construction Works**: Earth movement and pond excavation.
- **Materials**: Impermeable liners (e.g., clay or synthetic materials).
- **Complementary Structures**: Inlet and outlet structures, aeration systems.



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Cost per m² Construction

- **Typically ranges**: €4 to €15 per m² (mainly depends on the type of soil)

More Detailed Description

Maturation ponds are designed to replicate natural processes, facilitating the final polishing of treated wastewater through aerobic mechanisms. These ponds receive pre-treated wastewater with low organic loads, allowing for the maintenance of aerobic conditions. The primary biochemical reactions include aerobic oxidation of organic material and photosynthesis, which help in pathogen elimination. The shallow depth allows sunlight penetration, enhancing UV radiation's disinfection effect. Pathogenic microorganisms are removed by the elevated temperatures, basic pH, and biological activity within the pond.

Maturation ponds play a crucial role in disinfection, significantly reducing the number of pathogenic microorganisms. They support the growth of specific algae populations that differ from those in facultative ponds, contributing to the overall treatment efficiency.

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Infiltration-percolation (IP-S)

Brief Description

Infiltration-percolation (IP) systems, also known as slow infiltration systems, are a nature-based solution (NBS) for wastewater treatment. IP utilizes aerobic biological filtering through a fine granular medium to treat wastewater. Originating in the United States in the 1940s, IP systems are now widely adopted globally, with modifications enhancing efficiency. In Spain, modified IP systems were developed to enhance pathogen removal for wastewater reuse in the 90s. The process involves the intermittent application of pre-treated wastewater onto sand beds, where it undergoes physical filtration and biological oxidation. IP systems are commonly used as tertiary treatment for wastewater reclamation and reuse.

Key Benefits

- High water quality effluent: Effective removal of BOD5, COD, and suspended solids.
- High nitrification levels: Efficient transformation of nitrogen compounds.
- Excellent disinfection capacity: Significant pathogen reduction.
- Compact footprint: Requires less surface area compared to natural ponds.
- Moderate investment costs: Cost-effective solution for high-quality effluent production.

Drawbacks

- Almost exclusive use for urban wastewater.
- Requires large quantities of sand: Can lead to high capital costs if not available locally.
- Needs effective primary treatment: To prevent clogging.
- Sensitive to hydraulic overloads and freezing: Requires proper management and resting periods.
- Maintenance is more demanding than ponds.

Type of Wastewater Technology Can Treat

- **Urban**: Yes, as secondary or tertiary treatment
- **Domestic**: not recommendable for autonomous sanitation
- **Mixed (Urban + Industrial)**: no
- **Industrial**: no
- **Charged (High contaminant load)**: no

Space (Footprint)

- **Medium**: 1-2 m^2/PE

Effluent Variability (Seasonal or Temperature-Dependent)

- **Consistency**: high

Quality Provided (Pollutant Removal Efficiency)

- **Suspended Solids**: High (80-95%)
- **Total Organic Matter**: High (80-95%)
- **Biodegradable Organic Matter**: High (85-95%)

- **Nitrogen**: Medium-high (40-85%)
- **Phosphorus**: Medium (40-50%)
- **Nitrification**: High (70-90%)

Quality Provided (Pathogen Removal Efficiency)

- **Bacteria Pathogens**: High (2-3.5 log removal)
- **Helminths**: High (2-3 log removal)
- **Other Parasites (Giardia, etc.)**: High (2-3 log removal)
- **Viruses**: High (2-3 log removal)

Main Materials, Works, and Components

Construction works for IP systems involve earth movement and sand bed construction.
The materials required include high-quality, washed sand with specified granulometry. Complementary structures such as storage and delivery systems, feeding devices, and distribution and drainage pipes are essential.
Control systems are also necessary to regulate hydraulic loads and feeding cycles.

Cost per m² Construction

The estimated construction cost for IP systems ranges from €80 to €250 per m², depending mainly on local sand availability.

More Detailed Description

Infiltration-percolation (IP) systems treat wastewater through a combination of surface filtration and biological oxidation as water passes through a sand medium. These systems emerged in the 1940s and have been widely adopted, with modifications over time to improve efficiency and adaptability. The sand beds used in IP systems must have specific characteristics to ensure effective treatment, including a defined granulometry to balance filtration and percolation rates. The depth of the sand bed varies depending on the treatment goals, with thicker beds required for pathogen removal. Modified IP systems were developed in Spain to enhance pathogen removal for wastewater reuse, with several examples found in Catalonia.

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Activated Sludge (AS)

Brief Description
The activated sludge process involves introducing pretreated wastewater into a reactor containing a suspended bacterial culture (sludge). Air is supplied to ensure the organic matter is biologically oxidized to carbon dioxide and water. Subsequently, a settler separates the suspended solids (sludge) and the treated water. Activated sludge consisting of suspended flocs of active bacteria is mixed with the wastewater. The organic pollutants are used for growth by bacteria and thereby transformed to water, CO2, and new cell material. In some variants total nitrogen is removed by nitrification/denitrification, and phosphorus is either removed chemically or biologically and accumulated in the excess sludge. Excess sludge requires a further treatment chain.

Variants of Activated Sludge Process
1. Complete Mix (CM): All contents in the reactor are mixed uniformly.
2. Plug Flow (PF): Wastewater flows in a plug-like manner through the reactor.
3. Contact Stabilization (CS): Consists of separate contact and stabilization tanks.
4. Step Feed (SF): Wastewater is introduced at multiple points in the reactor.
5. Extended Aeration (EA): Longer aeration time for more complete oxidation of organic matter.
6. Oxidation Ditches (OD): Circular or oval channels providing continuous flow and aeration.
7. Sequencing Batch Reactor (SBR): Operates in batch mode with fill, react, settle, and decant stages.

Key Benefits
- High efficiency in removing organic matter.
- Capable of handling variable loads.
- Produces high-quality effluent.
- Can be modified to remove nitrogen and phosphorus.
- High removal efficiency for a large range of wastewaters.

Drawbacks
- Requires continuous aeration and energy input.
- Produces excess sludge that needs further treatment.
- Sensitive to toxic loads and temperature changes.
- Higher operational and maintenance costs compared to simpler systems.
- Highly mechanized system requiring expert design, operation, and maintenance as well as mechanical spare parts. Large energy requirements (e.g., for aeration).
- High-tech centralized system, not adapted for decentralised sanitation (<50 PE).

Type of Wastewater Technology Can Treat
- Urban: Yes
- Domestic: Decentralised not recommendable
- Mixed (Urban + Industrial): Yes, with primary treatment
- Industrial: Yes, with primary treatment
- Charged (High contaminant load): Yes, with primary treatment

Space (Footprint)
- Low: 0.25 to 0.5 m^2 PE

Effluent Variability (Seasonal or Temperature-Dependent)

- Variability: Moderate, sensitive to temperature changes and shock loads.

Quality Provided (Pollutant Removal Efficiency) I

- Suspended Solids: High (80-100%)
- Total Organic Matter (BOD/COD): High (BOD: 85-100%, COD: 60-90%)
- Nitrogen: Medium to High (60-90%, depending on configuration)
- Phosphorus: Medium to High (70-90%, depending on configuration)
- Nitrification: High

Quality Provided (Pollutant Removal Efficiency) II:

- Fecal coliform bacteria: Low (0.5-1.5 log removal)
- Viruses: Low (< 1 log removal)
- Helminth eggs: Low-Medium (1-2 log removal)
- Other parasites (Giardia, etc): Low (0.5-1.5 Ulog removal)

Main Materials, Works, and Components

- Construction Works: Reactor construction, aeration system installation, settler construction.
- Materials:
  - Reactor: Concrete or steel tanks.
  - Aeration System: Diffusers, blowers, or surface/submerged turbines.
  - Settler: Concrete or steel clarifiers.
- Complementary Structures: Inlet and outlet structures, sludge return system.
- Plumbing: Piping for influent distribution, effluent collection, and sludge recirculation.
- Control Elements and Electrical Cabinet: Aeration control systems, electrical cabinets for operational control.

Costs per m² Construction (Info 2018-2023):

Varies significantly based on scale and location: approximately 100-400 €/m²

More Detailed Description

The activated sludge process involves introducing the wastewater (usually pretreated) into a reactor containing a suspended bacterial culture (sludge) to which air is supplied to ensure the organic matter is biologically oxidized to carbon dioxide and water. Subsequently, a settler separates the suspended solids (sludge) and the treated water. Simplifying the process, microorganisms use the oxygen present in the water to consume the substrate or food, in this case, the biodegradable organic matter contained in the wastewater. As a result of this consumption, microorganisms obtain the necessary energy to maintain their vital functions while generating new individuals.

Most of the sludge separated in the settler is returned to the biological reactor, while a small fraction is purged daily from the system and sent to the sludge line; this prevents the biomass present in the system from increasing and aging excessively. The daily purge amount ultimately determines the cell residence time (CRT), which can be simply defined as the average time the biomass remains in the reactor.

The concentration of suspended solids (sludge or biomass) in the reactor depends on the characteristics of the wastewater to be treated, the hydraulic residence time (HRT), and the cell residence time (CRT). The aerated tank is usually open to the atmosphere and has equipment for oxygen transfer and maintaining the sludge in suspension within the reactor. Often, a single device achieves both purposes. Typical elements for air supply include air diffusers and turbines, both surface and submerged.

By modifying the configuration of these systems to include aerobic, anoxic, and anaerobic zones or phases, it is possible to remove organic matter, nitrogen, and phosphorus. There are different types of activated sludge configurations, and their classification can vary according to the consulted literature. However, the flow models are complete mix (CM) and plug flow (PF), leading to different technologies. Thus, depending on the treatment desired for water, the stages, primarily the conditions of the reaction stage, will be modified. If only organic matter removal is needed, only oxygen supply is necessary to achieve this. Conversely, if the goal is to also remove nitrogen, aerobic and anoxic stages must be alternated for nitrification and denitrification. It is even possible to remove phosphorus; in this case, anaerobic conditions must be achieved during filling. This last possibility still presents some operational difficulties and is not practically applied. To design a conventional activated sludge system, equations derived from the substrate and biomass balance for a continuous reactor with solids recirculation are used. Two parameters will determine the process design: hydraulic residence time and cell residence time.

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Membrane bioreactors (MBR)

Brief Description

Membrane Biological Reactor (MBR) technology combines biological treatment processes with membrane filtration, serving as both secondary and tertiary treatment for wastewater. This advanced system is effective for recycling wastewater for non-potable applications and is increasingly being considered for potable reuse schemes due to its high treatment efficiency.

Key Benefits

- **High-Quality Effluent**: Produces high-quality treated water suitable for reuse.
- **Compact Design**: Requires less space compared to traditional wastewater treatment systems.
- **Effective Pathogen Removal**: Capable of removing bacteria, viruses, and protozoa efficiently.
- **Reduced Sludge Production**: Generates less sludge than conventional treatment processes.
- **Adaptability**: Can handle variable wastewater flows and loads.

Drawbacks

- **High Capital and Operating Costs**: More expensive to install and operate due to advanced technology.
- **Energy Intensive**: Requires significant energy for membrane operation and maintenance.
- **Maintenance Requirements**: Membranes need regular cleaning and replacement.
- **Complex Operation**: Requires skilled personnel for operation and maintenance.

Type of Wastewater Technology Can Treat

- **Urban**: Yes
- **Domestic**: Yes
- **Mixed (Urban + Industrial)**: Yes
- **Industrial**: Yes, usually requires pretreatment
- **Maximum BOD**: Typically up to 500 mg/L
- **Maximum SS**: Typically up to 200 mg/L

Space (Footprint)

- **Low**: MBR systems are compact and require significantly less space compared to traditional treatment systems. Approximately 0.2-0.3 m^2/PE.

Effluent Variability (Seasonal or Temperature-Dependent)

- **Consistency**: High. MBR systems provide consistent effluent quality regardless of seasonal or temperature variations.

Quality Provided (Pollutant Removal Efficiency)

- **Suspended Solids**: High (90-95%)
- **Total Organic Matter**: High (80-90%)
- **Biodegradable Organic Matter**: High (85-95%)
- **Nitrogen**: High (80-90%)

- **Phosphorus**: High (70-90%)
- **Nitrification**: High (90-95%)

Pathogen Removal Efficiency (Ulog)

- **Bacteria Pathogens**: Very High (4-6 log removal)
- **Helminths**: Medium (2-3 log removal)
- **Other Parasites (Giardia, etc.)**: Medium (2-3 log removal)
- **Viruses** : Very High (4-5 log removal)

Main Materials, Works, and Components

- **Construction Works**: Installation of bioreactors and membrane modules.
- **Materials**:
  - **Membranes**: Hollow fiber or flat sheet membranes for filtration.
  - **Bioreactors**: Tanks or basins for biological treatment.
  - **Aeration Systems**: To supply oxygen for biological processes.
  - **Pumps and Piping**: For water circulation and membrane cleaning.
  - **Control Systems**: Monitoring and control equipment for system operation.

Price per m² Construction (Info 2018-2023)

- **Estimated Cost**: Approximately 500-1500 €/m², depending on the scale and specific system design.

More Detailed Description

MBR technology integrates biological degradation of waste with membrane filtration, which physically separates solids from the liquid. Wastewater enters the bioreactor where microorganisms degrade organic matter. The mixed liquor then passes through the membrane units where the treated water is filtered out, leaving behind concentrated waste for further processing or disposal. MBR systems offer superior effluent quality with reduced footprints compared to conventional activated sludge processes. They are particularly suitable for areas with space constraints and stringent discharge requirements. The high removal efficiencies for organic matter, nutrients, and pathogens make MBR an excellent choice for water reuse applications.

MBRs require careful monitoring and maintenance to prevent membrane fouling and ensure consistent performance. Regular cleaning and occasional replacement of membranes are necessary to maintain efficiency.

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Granular Activated Carbon (GAC)

Brief Description

Granular Activated Carbon (GAC) is a highly effective technology used in tertiary wastewater treatment to remove organic contaminants, chlorine, taste and odor compounds, and various other pollutants. GAC operates by adsorbing contaminants onto the surface of activated carbon granules, which have a high surface area due to their porous structure.

Key Benefits

- **Effective Contaminant Removal**: Removes a wide range of organic compounds, including micro-pollutants and emerging contaminants.
- **Improves Water Quality**: Enhances taste, odor, and color of treated water.
- **Versatility**: Suitable for treating various types of wastewater, including municipal, industrial, and stormwater.
- **Environmental Benefits**: Reduces the need for chemical treatment and lowers the production of harmful by-products.

Drawbacks

- **High Initial Costs**: Implementation and setup can be expensive.
- **Regular Maintenance**: Requires frequent replacement or regeneration of the carbon media.
- **Potential for pH Adjustment**: Initial pH spikes in effluent water may require correction.
- **Backwashing Requirements**: Needs periodic backwashing to remove accumulated solids and fines.

Type of Wastewater Technology Can Treat

- Urban: Yes, usually used as tertiary treatment
- Domestic: Yes, usually used as tertiary treatment
- Mixed (Urban + Industrial): Yes, usually used as tertiary treatment
- Industrial: Yes, with a lower concentration of organic matter
- Charged (High contaminant load): Yes, with a lower concentration of organic matter

Space (Footprint)

- **Medium**: 2–10 $m^3/m^2 \cdot day^{-1}$ depending on design and treatment goals.

Effluent Variability (Seasonal or Temperature-Dependent)

- **Consistency**: High, although performance can vary with changes in contaminant load and water temperature.

Quality Provided (Pollutant Removal Efficiency)

- **Suspended Solids**: High (90-95%)
- **Total Organic Matter**: High (85-95%)
- **Biodegradable Organic Matter**: High (85-95%)
- **Nitrogen**: Medium (40-60%)

- **Phosphorus**: Medium (40-50%)
- **Nitrification**: Low (30-40%)

Quality Provided (Pathogen Removal Efficiency)

- **Bacteria Pathogens**: High (2-3 log removal)
- **Helminths**: Low-Medium (1-2 log removal)
- **Other Parasites (Giardia, etc.)**: High (2-3 log removal)
- **Viruses**: Low (0-1 log removal)

Main Materials, Works, and Components

- **Construction Works**: Installation of GAC contactors and backwash systems.
- **Materials**:
  - **GAC Media**: Typically made from bituminous coal, lignite, wood, or coconut shell.
  - **Contactors**: Vessels or reactors where GAC is housed and wastewater is treated.
  - **Backwash Systems**: Equipment to clean and maintain the GAC media.
  - **Control Systems**: Monitors and controls for flow rates, pressure, and backwashing.

Cost per m² Construction (Info 2018-2023)

- **Estimated Cost**: 400-800 €/m² depending on design and operational requirements.

Costs per m³ Treated

- **Estimated Cost**: Approximately 0.05-0.15 €/m³, varying with scale and treatment efficiency.

More Detailed Description

Granular Activated Carbon (GAC) filtration systems are designed to enhance the quality of wastewater through adsorption processes. These systems use GAC media with a high surface area to adsorb organic and inorganic contaminants from the wastewater. The carbon granules are housed in large contactors where the wastewater flows through, allowing contaminants to be trapped on the surface of the granules. Over time, the GAC media becomes saturated and must be replaced or regenerated. The implementation of GAC systems involves significant upfront investment but provides substantial benefits in terms of water quality improvement and contaminant removal. Regular maintenance, including backwashing and pH adjustment, is necessary to ensure optimal performance. The system's efficiency in removing pathogens, organic compounds, and other pollutants makes it a valuable component of advanced wastewater treatment processes.

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Sand Filters -tertiary treatment (SF_TT)

Brief Description

Sand filtration is a process used in wastewater treatment to remove suspended matter, floating particles, and sinkable particles through a fine bed of sand and/or gravel. The wastewater flows vertically through the sand bed, where particles are removed by absorption or physical encapsulation. It is often used as a tertiary treatment method to produce high-quality effluent suitable for reuse.

Key Benefits

- **High Efficiency**: Effective removal of suspended solids, BOD, and COD.
- **Versatility**: Can be used in various stages of water management.
- **Low Operational Costs**: Simple system with minimal maintenance requirements.

Drawbacks

- **Chemical Use**: Sometimes requires chemicals to improve yield.
- **Maintenance**: Requires periodic cleaning and disposal of polluted rinse water.
- **Limited Load Handling**: Preliminary sedimentation may be necessary for heavily loaded wastewater.

Type of Wastewater Technology Can Treat

- **Maximum SS**: 10-50 ppm (mg/L)
- **Maximum BOD**: Up to 50 mg/L

Space (Footprint)

- 1–3 $m^3/m^2 \cdot day^{-1}$

Effluent Variability (Seasonal or Temperature-Dependent)

- **Consistency**: High

Quality Provided (Pollutant Removal Efficiency)

- Suspended Solids: High (90-95%)
- Total Organic Matter: High (80-95%)
- Biodegradable Organic Matter: High (80-95%)
- Nitrogen: Low (20-50%)
- Phosphorus: Low (10-30%)
- Nitrification: Low (30-50%)

Quality Provided (Pathogen Removal Efficiency)

- Bacteria Pathogens: High (2-4 log removal)
- Helminths: High(2-4 log removal)
- Other Parasites (Giardia, etc.): High (2-3 log removal)
- Viruses: Low-Medium (1-3 log removal)

Main Materials, Works, and Components

- **Construction Works**: Earthworks and installation of sand beds.
- **Materials**: Fine sand and gravel, often with an impermeable liner.
- **Complementary Structures**: Pre-filtration systems to reduce load.
- **Plumbing**: Distribution and drainage pipes.
- **Control Elements**: Monitoring systems for flow rates and filtration performance.

Costs per m² Construction (Info 2018-2023)

- **Estimated Cost**: 50-180 €/m² depending on design and operational requirements.

More Detailed Description

Sand filtration is widely used due to its simplicity and effectiveness in removing suspended solids and other contaminants from wastewater. The system can be configured as continuous or discontinuous filters. Continuous filters often use upward flow, where polluted sand is continuously removed, rinsed, and re-used. Discontinuous filters, on the other hand, are periodically cleaned by reversing the flow and using air bubbles to agitate the sand bed. These systems are versatile and can be used in various sectors, including drinking water production, industrial wastewater treatment, and groundwater remediation.

In sand filtration, the wastewater is filtered through a bed of sand, which removes particles by surface and depth filtration. Surface filtration captures larger particles above the sand bed, while depth filtration captures smaller particles within the sand bed. To improve filtration efficiency, coagulants or flocculants may be added. However, the cleaning process generates polluted rinse water that must be treated and disposed of properly.

Sand filtration is beneficial for its simplicity, high yield, and ability to produce effluent suitable for reuse. However, it requires careful maintenance to prevent clogging and manage rinse water. The system's effectiveness depends on proper design and operation, including the use of appropriately sized sand and regular monitoring and maintenance.

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Ultraviolet (UV)

Brief Description:

Ultraviolet (UV) light treatment is a disinfection process used in tertiary wastewater treatment. The wastewater flows under banks of UV lights, and the light sterilizes microorganisms by damaging their genetic structures. UV light does not typically kill viruses and bacteria, but it renders them unable to infect humans or wildlife. This process is highly effective in disinfecting water that has already undergone aggressive treatment to remove residual organic matter.

Key Benefits:

- Effective disinfection without the use of chemicals.
- Does not produce harmful disinfection by-products.
- Rapid treatment process with high efficiency.
- Safe and environmentally friendly.
- Highly effective for disinfecting Cryptosporidium and Giardia.
- Does not significantly alter water quality (e.g., total organic carbon, pH, turbidity).
- Relatively inexpensive with low capital and operating costs compared to other disinfection options for protozoa.
- Easy to operate with fast disinfection times in the range of a few seconds.
- Small footprint, suitable for retrofitting into existing water treatment plants.

Drawbacks:

- Requires clear water free of suspended solids to be effective.
- High energy consumption.
- UV lamps require regular maintenance and cleaning.
- Effectiveness decreases if the water has high turbidity.
- No residual disinfection capacity, requiring additional chemicals for maintaining residuals in distribution systems.
- Difficult to continuously monitor UV dose; reliance on secondary measurements such as sensor readings, UV transmittance, and water flow rates.
- Potential mercury hazard due to breakage of UV lamps.
- Susceptible to power interruptions, which can cause UV lamps to extinguish for short periods, leading to potential under-disinfection.

Type of Wastewater Technology Can Treat:

- Maximum SS: 10-20 ppm (mg/L). High levels of suspended solids can shield microorganisms from UV light, reducing the effectiveness of the disinfection process.

Space (Footprint):

- Low: UV systems are typically compact and can be integrated into existing treatment facilities.

Effluent Variability (Seasonal or Temperature-Dependent):

- Variability: Low, UV effectiveness is consistent but depends on water turbidity.

Quality Provided (Pathogen Removal Efficiency):

- **Bacteria:** Very High 3-5 Ulog removal
- **Viruses:** Moderate to High 2-4 Ulog removal
- **Protozoa:** High 3-4 Ulog removal
- **Helminth eggs:** Moderate to High 2-4 Ulog removal

Main Materials, Works, and Components:

- **Construction Works:** Installation of UV reactors.
- **Materials:**
  - **UV Reactors:** Stainless steel or other durable materials.
  - **UV Lamps:** Low or medium pressure mercury vapor lamps.
  - **Quartz Sleeves:** Protect lamps and ensure optimal UV transmission.
- **Complementary Structures:** Pre-filtration systems to ensure water clarity.
- **Control Elements and Electrical Cabinet:** UV intensity sensors, control panels for monitoring and maintenance.

Costs per m² Construction (Info 2018-2023):

- Varies significantly based on scale and location: approximately 500-1000 €/m²

Costs per m³ Treated:

- Approximately 0.05-0.20 €/m³, depending on the scale and operational efficiency.

More Detailed Description

Ultraviolet (UV) light treatment is a common disinfection method in tertiary wastewater treatment. The process involves the passage of wastewater through a reactor containing UV lamps. The UV radiation penetrates the cells of microorganisms, damaging their DNA and rendering them inactive. This method is particularly effective for bacteria, viruses, and protozoa, ensuring that the treated water is safe for discharge or reuse. The effectiveness of UV treatment depends on the clarity of the water; any suspended solids or turbidity can shield microorganisms from the UV light, reducing the efficiency of the disinfection process. Therefore, UV treatment is usually applied after other treatment processes have removed most of the particulate matter. To reduce water turbidity, filters are often employed in systems equipped with UV disinfection units. Water flow through the UV system should be at a rate that provides adequate contact time between the water and UV light radiation to ensure sufficient inactivation of bacteria and other microorganisms. Water flow that is too turbulent may prevent sustained UV contact time, requiring multiple passes through the UV system and increasing overall costs.

Types of UV Lamps and Their Characteristics:

Low-Pressure Mercury Lamps (LP):

- Achievable radiation intensity is low, with optimal discharge conditions maintained at power loads below 0.5 watts per centimeter (W/cm).
- These lamps emit UV light at specific wavelengths, primarily 254 nm, which is effective for disinfection but has limitations in intensity.

Low-Pressure-High-Output (LPHO) Lamps:

- Use an amalgam and decreased tube diameter, allowing mercury pressure to remain the same with increased power input up to 2 W/cm.
- This technology increases the specific radiant power up to three times that of LP lamps.
- Dependent on water temperature, with higher operating costs and decreased UV output effectiveness at higher temperatures.

Medium-Pressure Mercury Lamps (MP):

- Highly effective for disinfection of Cryptosporidium and Giardia.
- Do not significantly alter water quality (e.g., total organic carbon, pH, turbidity).
- Inexpensive with low capital and operating costs compared to other disinfection options for protozoa.
- Easy to operate with fast disinfection times in the range of a few seconds.
- Small footprint, suitable for retrofitting into existing water treatment plants.

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Ozone (O_3)

Brief Description

Ozone treatment is a powerful disinfection process used in tertiary wastewater treatment. Ozone is a strong oxidant that rapidly reacts with and destroys microorganisms, organic pollutants, and other contaminants. The process involves generating ozone on-site using an ozone generator and then dissolving it in the wastewater to achieve disinfection.

Key Benefits

- Effective in destroying a wide range of pathogens including bacteria, viruses, and protozoa.
- Produces fewer disinfection by-products compared to chlorine.
- Oxidizes and removes organic and inorganic contaminants, improving water quality.
- Enhances the biodegradability of organic compounds.
- Decomposes back to oxygen, leaving no harmful residuals in the treated water.
- Can reduce color, odor, and taste issues in water.
- Can be used to remove micro-pollutants and emerging contaminants.

Drawbacks

- Requires on-site generation of ozone, which can be complex and costly.
- Ozone is highly reactive and must be carefully controlled to avoid equipment corrosion and safety hazards.
- High energy consumption for ozone generation.
- Requires proper off-gas destruction systems to handle excess ozone.
- Effectiveness can be reduced by the presence of high levels of suspended solids and organic matter.
- Short half-life of ozone necessitates immediate use upon generation.
- Formation of disinfection by-products (DBPs) such as bromate, aldehydes, and nitrosamines like NDMA, which are challenging to control.

Type of Wastewater Technology Can Treat

- Tertiary treatment with Maximum SS: 10-20 ppm (mg/L). High levels of suspended solids can shield microorganisms from ozone, reducing the effectiveness of the disinfection process. Also BOD5 levels should typically be below 20 mg/L for effective ozone treatment. Higher BOD can consume ozone and reduce its effectiveness for disinfection.

Space (Footprint)

- Low: Ozone systems require space for ozone generators, contactors, and off-gas destruction units.

Effluent Variability

- Variability: Moderate: effectiveness can vary with temperature and organic load in the wastewater.

Quality Provided (Pollutant Removal Efficiency):

- Bacteria: Very High 4-5 log removal
- Viruses: Moderate-High 2-4 log removal
- Protozoa: High 4-5 log removal
- Helminth eggs: Effective removal depending on contact time and concentration

Main Materials, Works, and Components:

- Construction Works: Installation of ozone generators, contactors, and off-gas destruction units.
- Materials:
  - Ozone Generators: Electrical equipment to produce ozone from oxygen or air.
  - Contactors: Chambers or reactors where ozone is mixed with wastewater.
  - Off-Gas Destruction Units: Equipment to safely decompose excess ozone.
- Complementary Structures: Pre-filtration systems to reduce suspended solids and organic load.
- Control Elements and Electrical Cabinet: Monitoring and control systems for ozone concentration and flow rates.

Costs per m² Construction (Info 2018-2023):

- Varies significantly based on scale and location: approximately 800-1500 €/m²

Costs per m³ Treated

- Approximately 0.10-0.30 €/m³, depending on the scale and operational efficiency.

More Detailed Description:

Ozone treatment is an advanced oxidation process used for disinfection and oxidation of pollutants in tertiary wastewater treatment. Ozone is generated on-site using an ozone generator, typically from oxygen or ambient air. The generated ozone is then dissolved in the wastewater through contactors where it reacts with and destroys microorganisms, organic pollutants, and other contaminants. Ozone is a well-known disinfectant that has been applied in water treatment applications for decades. Recent studies demonstrate similar efficacy in water reuse. Ozone reacts relatively fast with microorganisms, with reaction rates of 10^5–10^6 M^-1 s^-1 and 1.04 × 10^5 M^-1 s^-1 reported for enteric viruses and E. coli, respectively. Ozone is also effective at inactivating chlorine-resistant microorganisms such as Cryptosporidium parvum. Pilot validation studies have shown greater than 6.5 log removal of MS2 in filtered secondary wastewater effluent. Ozone also efficiently oxidizes trace organic contaminants (TrOCs). However, the primary drawback to ozone application is the formation of disinfection by-products (DBPs) such as bromate, aldehydes, and nitrosamines like NDMA.

Types of Ozone Systems and Their Characteristics:

Corona Discharge Ozone Generators:

- Most common method for industrial ozone generation.
- Produces high concentrations of ozone.
- Requires a source of dry air or oxygen.

UV Light Ozone Generators:

- Used for smaller applications.
- Lower ozone production compared to corona discharge.
- Less efficient and higher operational costs.

Electrolytic Ozone Generators:

- Produces ozone from water instead of air or oxygen.
- Emerging technology with potential for specific applications.

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Chlorination (Cl)

Brief Description

Chlorination is a widely used disinfection process in wastewater treatment. It involves adding chlorine to wastewater to kill or inactivate pathogens, including bacteria, viruses, and protozoa. Chlorine can be applied in various forms, such as chlorine gas, sodium hypochlorite, or calcium hypochlorite.

Key Benefits

- **Effective Pathogen Removal**: Chlorine is highly effective against a broad spectrum of microorganisms.
- **Residual Disinfection**: Provides a residual effect, ensuring continued disinfection in the distribution system.
- **Cost-Effective**: Relatively low capital and operational costs compared to other disinfection methods.
- **Established Technology**: Well-understood and widely implemented in wastewater treatment.

Drawbacks

- **Formation of Disinfection By-Products (DBPs)**: Can form harmful by-products like trihalomethanes (THMs) and haloacetic acids (HAAs).
- **Corrosive Nature**: Chlorine and its by-products can be corrosive to pipes and equipment.
- **Handling and Safety Concerns**: Requires careful handling and storage due to its hazardous nature.
- **Reduced Effectiveness with High BOD and SS**: High levels of organic matter and suspended solids can reduce the effectiveness of chlorination.

Type of Wastewater Technology Can Treat

- **Treated Wastewater**: Effective for disinfecting treated wastewater with a BOD5 below 30 mg/L and SS between 10-20 ppm.

Space (Footprint)

- **Low**: Chlorination systems typically require minimal space for the installation of chlorinators and contact tanks.

Effluent Variability

- **Moderate**: Effectiveness can vary with changes in temperature, pH, and organic load in the wastewater.

Quality Provided (Pollutant Removal Efficiency)

- **Bacteria**: Very High (4-5 log removal)
- **Viruses**: Moderate-High (2-4 log removal)

- **Protozoa**: Moderate (1-2 log removal)
- **Helminth eggs**: Moderate (1-2 log removal)

Main Materials, Works, and Components

- **Construction Works**: Installation of chlorinators, contact tanks, and dechlorination systems if needed.
- **Materials**:
  - **Chlorinators**: Equipment for dosing chlorine gas or hypochlorite solutions.
  - **Contact Tanks**: Chambers where chlorine is mixed with wastewater.
  - **Dechlorination Units**: Systems to remove excess chlorine from treated effluent.
- **Control Elements and Electrical Cabinet**: Monitoring and control systems for chlorine concentration and flow rates.

Costs per m² Construction (Info 2018-2023)

- **Estimated Cost**: Approximately 100-300 €/m², depending on the scale and operational efficiency.

Costs per m³ Treated

- **Estimated Cost**: Approximately 0.05-0.20 €/m³, depending on the scale and operational efficiency.

More Detailed Description

Chlorination involves the addition of chlorine to treated wastewater to achieve disinfection. The process can effectively inactivate a wide range of pathogens, ensuring the safety of the treated effluent for discharge or reuse. Chlorine is typically dosed to exceed the chlorine demand, ensuring the presence of free chlorine residuals for continued disinfection. However, the formation of disinfection by-products (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAAs) is a major concern with chlorination. These DBPs are regulated due to their potential health impacts. To control DBPs, proper dosing and contact time must be managed, and dechlorination may be required before discharge to the environment.

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