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Athens, Greece, 24-26 May 2023

Agenda item 7: Technical Guidelines

Report of the Regional meeting to review guidelines on available treatment technologies for urban wastewater and sludge, industrial pre-treatment, and environmental standards and available desalination treatment technologies (22-23 November 2022)

UNEP/MAP
Athens, 2023

REPORT

Draft Report of the Regional meeting to review guidelines on available treatment technologies for urban wastewater and sludge, industrial pre-treatment, and environmental standards and available desalination treatment technologies

FINAL DRAFT

26 January 2023

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Report of the Meeting

Introduction

1. In accordance with the UNEP/MAP Programme of Work 2022-2023 adopted in Decision IG.25/19 by COP 22 (Antalya, Türkiye, 7-10 December 2021), the Secretariat (MED POL) organized the "Regional meeting to review guidelines on available treatment technologies for urban wastewater and sludge, industrial pre-treatment, and environmental standards and available desalination treatment technologies." The Meeting was held in Ankara, Türkiye on 22 and 23 November 2022.

2. The Meeting was kindly hosted by the Ministry of Environment, Urbanization and Climate Change of Türkiye.

3. The objectives of the Meeting were to review: (a) Available treatment technologies for urban wastewater and sewage sludge and decision support systems (DSS) for their selection; (b) Pre-treatment standards and applicable BATs for industrial sectors eligible to discharge to urban wastewater collection systems; and (c) Regional standards for discharge from desalination plants and decision support systems for sustainable desalination technologies in the Mediterranean.

Participation

4. The meeting was attended by representatives from the following Contracting Parties: Albania, Algeria, Bosnia and Herzegovina, Croatia, Cyprus, Egypt, Israel, Lebanon, Libya, Montenegro, Spain, Slovenia, Morocco, Tunisia and Türkiye. The following representative were present as observers: Palestine and EBRD. The United Nations Environment Programme (UNEP), including the Mediterranean Action Plan/ Barcelona Convention Secretariat (UNEP/MAP) were also represented.

5. The full list of participants is attached as Annex I to the present report.

Agenda item 1: Opening of the Meeting

6. The Meeting was opened at 9:30 AM on 25 October 2022 by the Secretariat to the Barcelona Convention, the United Nations Environment Programme/ Mediterranean Action Plan, represented by Mr. Mohamad Kayyal, MED POL Programme Management Officer. Mr. Kayyal welcomed the participants and provided information on the process of the preparation of the three Guidelines which are submitted for review to the Meeting. He indicated that two guidelines were developed to assist the Contracting Parties for the implementation of two Regional Plans i.e., Decision IG.25/8 - Regional Plans on Urban Wastewater Treatment and Sewage Sludge Management in the Framework of Article 15 of the Land Based Sources Protocol. These three Guidelines address' a number of technical aspects included in the adopted measures of these regional plans, more specifically, resource recovery and beneficial use of the treated sludge. He explained that the first Guideline (UNEP/MED WG.540/3) provides insights on potential for Resource Recovery Routes (RRR) from treatment processes, as well as available technologies for water, energy and nutrients recovery including their advantages and limitations. He pointed out that the second Guideline (UNEP/MED WG.540/4) provides information on the feasibility of pre-treatment of industrial effluents, permitting requirement, monitoring of pre-treated effluents as well as application of BAT and implementation of BEP for the pre-treatment of industrial effluents to be applied on-site as well as off-site industrial facilities. Finally, he gave information about the third Guideline (UNEP/MED WG.540/5) which builds on the notion of sustainable desalination by recommending proven desalination technologies as well as proposing common discharge standards to be established, at the regional level. He concluded by underlining the aim of the meeting which is set to review the three Guidelines and agree to their submission to the Meeting of MEDPOL Focal Points planned in May 2023.

Agenda item 2: Organizational matters

a) Rules of Procedure for the Meeting

10. The Rules of Procedure for Meetings and Conferences of the Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean and its Protocols was applied mutatis mutandis to the present Meeting (UNEP/IG.43/6, Annex XI).

b) Election of Officers

11. Subject to Rule 20 of the rules of procedure mentioned at para. 2(a) for meetings and conferences of the Contracting Parties, the Meeting elected one (1) Chair, two (2) Vice Chairs and one (1) Rapporteur from among the participants, as follows:

Chair: Bosnia and Herzegovina,
Ms. Selma Gencic

First vice chair: Israel,
Ms. Maisa Inibtawi

Second vice chair: Croatia,
Mr. Miroslav Mušnjak

Rapporteur: Turkiye,
Mr. Mehmet Tamer Cobanoglu

c) Adoption of the Provisional Agenda

12. Subject to Rule 14 of the Rules of Procedure mentioned at para. 2(a), the proposed agenda appearing in document UNEP/MED WG.540/1 and annotated in the UNEP/MED WG.540/2 document was reviewed and accepted, with a proposal by One Contracting Party to add an item under Any Other Business (AoB) for further information on legally binding requirements of Decision IG.25/8: "Regional Plans on Urban Wastewater Treatment and Sewage Sludge Management in the Framework of Article 15 of the Land Based Sources Protocol" and their implementation timetable. The Chair accepted the proposed item and the Annotated Agenda was adopted by the Meeting as appended in Annex II to the present document.

d) Organization of Work

13. The discussions were proposed to be held in two plenary sessions over two days, from 9:30 to 12:30 and 14:30 to 17:30.

14. Simultaneous interpretation in English and French was available for all sessions. All documentation was available in English and French. Participants were encouraged to download the documentation onto their computers in advance of the session.

15. The Meeting addressed all Agenda items during the two-day meeting. The Meeting closed on 23 November 2022 after adopting its Conclusions and Recommendations appended to this present document.

Agenda item 3: Treatment technologies for urban wastewater and sewage sludge

16. Under this agenda item, Mr. Erol Cavus, MED POL Pollution Officer, presented the document UNEP/MED WG.540/3 "Regional guidelines on available treatment technologies for urban wastewater and sewage sludge and decision support systems (DSS) for their selection." He explained the rational of the document that built on three main pillars being (i) the recovery of materials and substances from wastewater treatment plants including supply of water, energy and nutrients; (ii) resource recovery technologies for municipal wastewater treatment plants including water reclamation

and reuse technologies, energy recovery technologies, and fertilizers (nutrients) reclamation and recovery technologies; and (iii) decision support systems for selection of environmentally friendly technologies for wastewater treatment aiming to complement a more scientific based decision support for decision makers. He explained how the document would contribute to the implementation of the Regional Plan on Urban Wastewater Treatment and Sewage Sludge Management by underlining the main technologies for resource recovery routes for water, energy and nutrients.

17. One Contracting Party proposed to use the term “nutrient recovery” rather than “recovery of fertilizers”, referred to in the Guideline, explaining that the recovered materials might not be used as fertilizers in all cases. The Contracting Party substantiated this proposal with an example that, in some cases, recovered Nitrogen and/or Phosphate could be used as supplements. The Meeting agreed and requested the Secretariat to use the technical term of “nutrient recovery” in the document and replace the “recovery of fertilizers”.

18. During the proceedings, a Contracting Party requested from the Secretariat to revisit “the resource recovery routes” applicable for primary treatment technologies, which was referred to in Table 1 of the document. Consequently, the Meeting recommended more specific links for the potential routes to be introduced under primary treatment technologies; however, underlined those primary technologies are alone not sufficient for the purpose of resource recovery. Following the discussion and agreement by the Meeting, the Secretariat modified Table 1 taking into consideration the request.

19. The Meeting made a clear distinction between the use of the disinfection technologies which include chlorination, UV radiation and ozonation considered as the final application during wastewater treatment, where the final use is intended for reclaiming the water, and advanced oxidation technologies which can be used effectively in lieu of disinfection. The Meeting suggested that this distinction should be used at the beginning of any planning at national level which would consequently have an impact of the preceding secondary treatment technologies. The Secretariat modified the paragraph 21(d) accordingly which was agreed by the Meeting.

20. One Contracting Party inquired why nature-based solutions were not included in the proposed Guideline. The Meeting discussed the issue in depth. Several Contracting Parties noted that despite possible examples given, nature-based solutions could not be considered as a single technology aiming to explicitly reclaim any material or energy recovery as such. The Meeting agreed to further explore and invite the Contracting Parties to submit good examples applied at national scale especially regarding constructed wetlands. One Contracting Party committed to share such practices especially regarding sludge management aiming to use the treated sludge as biosolids. The Secretariat was asked to examine any proposal, if submitted after, the Meeting, by the Contracting Parties in order to be added to the Guideline.

21. Another Contracting Party, suggested to explore green technologies which are biotechnology based, focusing on emerging technologies for inclusion in the Guideline. The Meeting agreed to add to the proposal and requested the Secretariat to search for such technologies and include them in the Guideline. Further to this discussion, the Meeting agreed to include this request to the Conclusions and Recommendations of the Meeting as appended to this document.

22. A representative of group of countries, submitted their comments in written format during the meeting, the comments were introduced to the Meeting by the Secretariat and were read by the Chair. The Meeting addressed the submitted comments accordingly, and upon agreement, requested the Secretariat to introduce them in session into the Guideline,. These agreed changes were shared with the participants at the end of the Meeting.

23. The conclusions and recommendations under this agenda item are presented in Annex III of this report.

Agenda item 4: Pre-treatment standards for industrial sectors

24. Under this agenda item, Mr. Erol Cavus, presented the document UNEP/MED WG.540/4 “Regional guideline on pre-treatment standards and applicable BATs for industrial sectors eligible to discharge to urban wastewater collection systems.” He briefed the Meeting on the current Guideline which aims to provide relevant information and knowledge on application of BAT and implementation of BEP to enable industrial facilities to meet the pre-treatment effluent standards i.e., the Emission Limit Values (ELVs) for discharge of industrial wastewater into collecting systems.

25. Mr. Cavus, explained the rational of the Guideline, re-iterating its three key objectives, i.e., protect the collecting systems and the treatment plant; ensure that the operation of the WWTP and the treatment of the sludge are not impeded; and ensure that discharge effluents do not adversely affect the Mediterranean marine environment, particularly for priority substances originating from industrial effluents.

26. The Meeting thoroughly discussed the terminology of “light industry”, as brought to attention by a Contracting Party, and its definition indicating that it could cause confusion across the Mediterranean as it might require also to define what is heavy industry. The Meeting agreed that the terminology proposed might lead to different interpretations than intended. Further to the discussions, it was agreed to use “eligible industries”, in lieu of “light industry” for discharging to collecting systems which also, were well suiting with proposed eligibility criteria. Consequently, the Meeting requested the Secretariat to change the terminology in the document accordingly, which was done in session.

27. The Meeting also welcomed the list of proposed industries designated with NACE codes establishing clear linkages with the National Baseline Budget (NBB) nomenclature used UNEP/MAP for reporting which, in turn, were aligned with (e) PRTR nomenclature. The Meeting advised the Contracting Parties to take into consideration high loads when issuing permits for eligible industries connecting to collecting systems.

28. One Contacting Party suggested to include emergency planning for the eligible industries as it would bring an added value for any fugitive pollution/substances and/or unintended spills entering collection systems. The Secretariat was asked to explore the issue after the Meeting and consider its possible introduction to the Guideline, if appropriate.

29. Another Contracting Party re-iterated that blood from slaughterhouses (as one of the eligible industries) was a major problem for their collection and treatment systems and that loads to collection systems should be taken into consideration before any permit is given, especially for slaughterhouse agglomerations.

30. Following the discussion on the parameters stemming from the Regional Plans, the Meeting suggested to revisit Table 3 in the main text and Table 1 in its Annex in the Guideline. The Meeting requested the Secretariat to double check the consistency of parameters proposed and to label the agreed parameters as “minimum ELVs”. The Secretariat undertook the requested changes and amended the above-mentioned tables.

31. Finally, after elaboration of the possible characterization of the sludge generated by pre-treatment plants, the Meeting suggested to include an indication for sludge management. Specifically noting that if the sludge contains hazardous chemical, it should be treated as hazardous waste and not disposed of to regulated landfills. The Secretariat addressed the request in session.

32. The conclusions and recommendations under this agenda item are presented in Annex III of this report.

Agenda item 5: Regional standards on desalination technologies

33. Under this agenda item, Mr. Cavus introduced the document UNEP/MED WG.540/5 “Guideline on Reginal Standards for Discharge from Desalination Plants and Decision Support Systems for Sustainable Desalination Technologies in the Mediterranean.” He further explained that the Guideline complements the “Updated Guidelines on the Management of Desalination Activities (2017).” He explained that the current Guideline is built upon the following three pillars (i) available state of the art desalination technologies and their possible implementation in the context of sustainable desalination solutions (ii) recommended emission limit values based on prevailing regional standards for seawater desalination and (iii) recommendations on Decision Support Systems (DSS) based on multi criteria analysis and life cycle assessment, with the aim to assist policy makers.

34. One Contracting Party indicated the construction of desalination facilities would also require a construction of infrastructure in marine environment which should be taken into consideration. The Meeting discussed the issues regarding construction of a seawater desalination facility which includes laying underwater infrastructure such as pipelines, outlets and intakes which include potentially harmful techniques such as dredging, cofferdams, and excavation of sensitive habitats, as highlighted in the Guideline. The Secretariat responded to the issue by pointing out already developed Guidelines on “Common methodologies and techniques for the assessment and monitoring of adverse impacts of dumping activities” (UNEP/MED.WG. 509/41) which aim to support the Contracting Parties on monitoring of dredging operations from harbours, ports, navigation channels and infrastructure projects such as cables and pipelines. The Secretariat included the response to the Guidelines, in session which refers to the UNEP/MED WG. 509/41.

35. Regarding the recommended Emission Limit Values (ELVs), the Meeting reiterated the need to add more available parameters since ELVs would be important to cover as much as relevant parameters used by the Contracting Parties, pointing out the lack of such ELVs at regional level. Furthermore, the Meeting requested the Secretariat to collect ELVs from the Contracting Parties and to add them to the proposed parameters in the Guideline.

36. Additionally, the Meeting agreed to collect from the Contracting Parties the frequency of monitoring of the added parameters based on the submitted ELVs and to consequently prepare an additional annex for the submitted set of ELVs. Within this context, the Meeting requested the Secretariat to update Table 3 by including agreed parameters together with monitoring frequencies at regional level and asked the Secretariat to add this request to the Conclusions and Recommendations.

37. One Contracting Party suggested to consider using “near field modeling” for appropriate planning and positioning of outfall basins including minimizing the effect of salinity/optimal dilution. the Meeting agreed on the importance of using relevant modeling tools for such operations during the planning phase to minimize environmental hazards and habitat loss. Furthermore, the Meeting agreed that using P free anti-scaling agents should be considered to reduce the potential eutrophication problem in nearby zones of the plant.

38. The Meeting discussed the Environmental Impact Assessment (EIA) for desalination facilities in depth, confirming its importance and as well as underlining the importance of public participation to this process. One Contracting Party recommended to add contingency planning to the EIA process, another Contracting Party suggested to indicate the importance of setting a monitoring programme during the EIA process. Consequently, the meeting requested the Secretariat to update Annex III of the Guideline (Process for conducting EIA for desalination) in line with the recommendations and resubmit it also in the French language.

39. Lastly, the Meeting highlighted the importance of using renewable energy or at least low emission fuels such as natural gas in their processes of desalination due to their extensive need of energy. The Meeting requested the Secretariat to incorporate this aspect in the Guideline, which was addressed in session.

40. The conclusions and recommendations under this agenda item are presented in Annex III of this report.

Agenda item 6: Any Other Business

41. Under this Agenda item, as agreed during the adoption of the Agenda, the Secretariat gave brief information on the adopted Regional Plans on Urban Wastewater Treatment Plants and Management of Sludge; their aim and approach to achieve the agreed ELVs which promote energy efficiency and material recovery. Additionally, the Secretariat explained the legally binding provisions of the Regional Plans and the timeline for their implementation, along with the steps to be undertaken by the Contracting Parties.

Agenda item 7: Conclusions and Recommendations

42. The Meeting reviewed, commented on, and approved the draft Conclusions and Recommendations as amended and attached to the present report as Annex III including its appendices revised as appropriate by the Meeting.

Agenda item 6: Closure of the Meeting

43. The Coordinator of the Secretariat, Ms. Tatjana Hema, congratulated the representatives of the Contracting Parties for their deliberations while underlining the importance of the Regional Plans Decision adopted in COP 22, Antalya, Türkiye. She also highlighted the positive contributions to be achieved upon implementation of the Guidelines in support of the Regional Plans. After expressing the usual courtesies, the Chair declared the Meeting closed at 17:30 on Thursday 23 November 2022.

Annex I

List of Participants

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EUROPEAN BANK FOR RECONSTRUCTION AND DEVELOPMENT	**Ms. Hande Yükseler** Programme Manager

UNITED NATIONS ENVIRONMENT PROGRAMME – COORDINATING UNIT AND COMPONENTS OF THE MEDITERRANEAN ACTION PLAN
PROGRAMME DES NATIONS UNIES POUR L'ENVIRONNEMENT – UNITÉ DE COORDINATION ET COMPOSANTES DU PLAN D'ACTION POUR LA MÉDITERRANÉE

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Annex II

Agenda of the Meeting

Agenda

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Agenda Item 2: Organizational matters

Agenda Item 3: Treatment technologies for urban wastewater and sewage sludge

Agenda Item 4: Pre-treatment standards for industrial sectors

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Annex III

Conclusions and Recommendations

Conclusions and Recommendations

On 22-23 November 2022, the "Regional meeting to review guidelines on available treatment technologies for urban wastewater and sludge, industrial pre-treatment, and environmental standards and available desalination treatment technologies" was held at the kind invitation of the Ministry of Environment, Urbanization and Climate Change in Ankara, Türkiye.

The meeting thanked the Ministry of Environment, Urbanization and Climate Change of Türkiye for the hosting and support provided to ensure the successful completion of the meeting.

Further to its deliberations, the Meeting reached the following conclusions:

I. Agenda Item 3: Treatment technologies for urban wastewater and sewage sludge

1. The Meeting reviewed the draft **regional guideline on available treatment technologies for urban wastewater and sewage sludge and decision support systems (DSS) for their selection** (UNEP/MED WG.540/3). The Meeting provided a number of technical modifications and amendments. The version of the Working Document UNEP/MED WG.540/3 encompassing proposed changes in "track change mode" is included in Appendix 1to this report.

2. The Meeting requested the Secretariat to further elaborate on the following technical aspects of the Guideline:
    a) Best practices regarding to materials and energy recovery technologies in the Mediterranean.
    b) Potential Green technologies eco-friendly procedures based on biotechnology as well as potential use of nature-based solutions that can be applied for material recovery and water reclamation.
    c) Newly emerging treatment technologies which are currently under development regarding water reclamation.
    d) Updating information on the state of the art for the removal of contaminants of emerging concern as considered for proposal of revising the Urban Wastewater Treatment Directive.

II. Agenda Item 4: Pre-treatment standards for industrial sectors

3. The Meeting reviewed the draft **regional guideline on pre-treatment standards and applicable BATs for industrial sectors eligible to discharge to urban wastewater collection systems** (UNEP/MED WG.540/4). The Meeting provided a number of technical modifications and amendments. The version of the Working Document UNEP/MED WG.540/4 encompassing proposed changes in "track change mode" is included in Appendix 2 to this report.

4. The Meeting requested the Secretariat to further elaborate on the following technical aspects of the Guideline:
    a) A new definition for the term of "light industries" that takes into account the "eligibility" of relevant industries to discharge into the sewerage system; proposing the use of the term "eligible industries to discharge" instead of "light industries."

b) Reviewing Table 3 concerning the parameters to be monitored and establishing a minimum frequency for sampling for the proposed sectors; and

III. Agenda Item 5: Regional standards on desalination technologies

5. The Meeting reviewed the draft **Guideline on Reginal Standards for Discharge from Desalination Plants and Decision Support Systems for Sustainable Desalination Technologies in the Mediterranean** (UNEP/MED WG.540/5). The Meeting provided a number of technical modifications and amendments. The version of the Working Document UNEP/MED WG.540/5 encompassing proposed changes in “track change mode” is included in Appendix III to this report.

6. The Meeting requested the Secretariat to further elaborate on the following technical aspects of the Guideline:
   a) collect the ELVs for the desalination discharges taking into consideration, location of discharge and additional parameters discussed and agreed during the meeting from the Contracting Parties and suggest a consolidated table at regional level.
   b) propose sampling frequency (if applicable) for desalination operators for regular monitoring of a above mentioned parameters;
   c) include the “contingency planning”, “monitoring of discharges of brine” and “public consultation” for EIA process;

IV. <u>Follow up by the Secretariat</u>

7. Further to updating the three guidelines, the Secretariat will:
   a) Prepare a revised version of the Regional Guideline reflecting amendments requested above in both the English and French languages. The document will be shared with the meeting participants for their “non-objection” for a period not exceeding one month from date of receipt. The revised version will be shared no later than mid-January 2023.
   b) Submit the revised version of the Regional Guideline for the approval of the Meeting of the MED POL Focal Points tentatively planned in May 2023.

Appendix 1

Regional guideline on available treatment technologies for urban wastewater and sewage sludge and decision support systems (DSS) for their selection

Table of Contents

Pages

List of Abbreviations / Acronyms

AC	Activated carbon
AD	Anaerobic digestion
AOP	Advanced oxidation processes
ASP	Activated sludge process
CAS	Conventional activated sludge
CEC	Contaminants of Emerging Concern
COD	Chemical Oxygen Demand
COP	Conference of the Parties
DSS	Decision Support System
ED	Electrodialysis
FAO	Food Agriculture Organization
GHG	Greenhouse Gases
H_2	Hydrogen
IDSS	Intelligent Decision Support System
K	Potassium
LBS	Land Based Sources
LCA	Life Cycle Assessment
MM	Mathematical Model
MED POL	Mediterranean Pollution Control and Assessment Programme
Mg	Magnesium
MCDM	Multi-Criteria Decision Making
MWWTP	Municipal Wastewater Treatment Plant
N	Nitrogen
OH	Hydroxyl radicals
O_3	Ozone
P	Phosphorus
PCP	Personal care products
PhAC	Pharmaceutically active compound
PF	Pulverized fuel
RRR	Resource Recovery Route
SCFL	Supervised Committee of Fuzzy Logic
SS	Suspended Solids
SSP	Sanitation Safety Planning
TDS	Total Dissolved Solids
TOC	Total organic carbon
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TS	Total Solids
UNEP/MAP	United Nations Environment Programme /Mediterranean Action Plan
UV	Ultraviolet radiation
WEFE	Water-Energy-Food-Ecosystems
WPO	Wet (catalytic) peroxidation
WWTP	Wastewater Treatment Plant

1. Introduction

1. This Guideline is developed under Article 7 of the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-Based Sources (LBS Protocol) of the Barcelona Convention, which stipulates that “the Parties shall progressively formulate and adopt, in cooperation with the competent international organizations, common guidelines.”

2. The Guideline is also prepared in line with Decision IG.25/8 adopted by COP22 (Antalya, Türkiye, 7-10 December 2021) on the Regional Plans on Urban Wastewater Treatment and Sewage Sludge Management (herein referred to as the Regional Plans) which entered into force on 26 July 2022. Pursuant to Article VI addressing Technical Assistance, Transfer of Technology and Capacity Building, the Regional Plans stipulate: “for the purpose of facilitating the effective implementation of Article V of the Regional Plans, the Contracting Parties collaborate to implement, exchange and share best practices directly or with the support of the Secretariat including resource efficiency, sustainable consumption and production, circular economy, resource efficiency, WEFE Nexus in the design, construction, operation and maintenance of the urban wastewater treatment plants.”

3. To this aim, the present Guideline is elaborated to address specific technical aspects, including best practices in the Mediterranean, of the adopted measures related to design and operation of wastewater treatment plants in order to assist the Contracting Parties in their implementation. These aspects include:

a) Potential for recovery of materials and substances from wastewater treatment plants including supply of water, energy and nutrients.
b) Resource recovery technologies for municipal wastewater treatment plants including water reclamation and reuse technologies, energy recovery technologies, and fertilizers (nutrients) reclamation and recovery technologies.
c) Treatment technologies for emerging contaminants in wastewater including sources, occurrence and fate/transport of emerging contaminants.
d) Occurrence, detection and removal of microplastics in wastewater treatment plants.
e) Decision Support Systems for selection of environmentally friendly technologies for wastewater treatment.

4. The Guideline is intended to assist wastewater engineers and treatment plants operators to select and implement the appropriate resource recovery technologies for water, energy and nutrients as well as assess available technologies for removal of emerging contaminants and microplastics based on Decision Support Systems for selection of environmentally friendly, economically viable and socially acceptable wastewater treatment technologies.

2. Potential for Recovery of Materials and Substances from Wastewater Treatment

5. In the past 10 years, the circular economy has grown rapidly as it supports the widely accepted sustainable development concepts and even goes beyond them. The water sector is well positioned to improve by this transition given its inherent circularity and the valuable and essential resources it manages, which are primarily found in wastewater (Panchal et al., 2021). Although the principal objective of WWTP design is the effective treatment of wastewater for safe and environmentally friendly discharges, WWTP’s performance can be sustainably improved by integrating innovative resource recovery technologies into the design of treatment processes.

6. There are various types of materials and substances that can be extracted in the form of resources from wastewater, including water, energy, biofuels, nutrients, and biopolymers. Some of these resources are becoming increasingly limited as the world's population and urbanization increase (Dagilienė et al., 2021; Kehrein et al., 2020). Resource recovery contributes to reducing the carbon footprint of wastewater treatment plants (Kehrein et al., 2020). In recent years, the water-energy-food nexus has been viewed as a more effective way to comprehend the intricate interactions across

resource systems (Fetanat et al., 2021). Ensuring the security of these three interconnected sources is crucial for the region.

2.1 Water Supply

7. Wastewater from household, industrial, and agricultural sources is produced daily in vast quantities. The global wastewater discharge is projected to be 400 billion cubic meters per year, contaminating about 5,500 billion cubic meters of water per year (Zhang & Shen, 2019). There is potential for reuse of wastewater mainly in agriculture. Currently, approximately 20% of all agricultural land is irrigated, supplying 40% of total agricultural production (FAO, 2020). While solving water scarcity, wastewater reuse, untreated or poorly treated wastewater for crop irrigation, can generate public health risks if treatment, storage, and piping are not adequate (Fuhrimann et al., 2016). The link between water security and climate security is becoming increasingly evident. Recovering lost wastewater and making water reuse safer are therefore priorities. The region needs to accelerate the expansion of financially sustainable treatment facilities. But these measures should be accompanied by the adoption of on-farm and post-harvest practices that ensure safe water reuse in food supply chains

8. In the Middle Eastern region, wastewater reuse potential remains largely untapped. Of the total 21.5 billion cubic meters (BCM) of municipal wastewater generated each year, only around 10% is treated and reused directly for irrigation, landscaping, industrial processes and so on. A further 36% is reused indirectly, for example by farmers drawing water from streams or rivers containing wastewater. Indirect use is often informal and unsafe because of the lack of treatment. The majority of municipal wastewater – 54% – is lost when it is discharged to the sea or evaporates (IWMI, 2022).[1] A notable exception is found in Israel where nearly 80% of wastewater was reclaimed for reuse as early as 2013 (Futran, 2013), and is currently estimated at 90% which is mainly used in Agriculture (Fluence, 2020).[2]

2.2 Energy Supply

9. The growing use of renewable energy sources to generate electricity, such as water for hydropower and biomass for bioenergy, has beneficial economic and mitigating effects, but can have a negative impact on water supplies that are already strained (Zarei, 2020). A typical wastewater treatment plant requires between 0.3 and 0.6 kWh/m^3 of energy to operate (He et al., 2019). Recovery of the chemical energy available in sewage is economically attractive since the thermal energy potential of digestion of the organic matter in wastewater is more than the energy requirement of a typical wastewater treatment plant (Fernández-Arévalo et al., 2017).

10. Energy recovery in the form of biogas, biodiesel, hydrogen, electrical power, and heat energy from wastewater treatment plants can be achieved using heat pumps, mechanical and thermal pre-treatment processes, and high-temperature streams by heat exchangers (Bertanza et al., 2018). The most feasible and widely practiced method to generate power and heat is by use of biogas produced by anaerobic digestion. For example, a recent study (Kehrein, et al. 2020) suggests that for a heat exchange or heat-pump system installed to recover heat energy of 5°C, 24 hours per day, for 365 days a year, the total recoverable heat from municipal WWTP effluents in the Netherlands would be 40% of all heat energy derived from gas, coal or biomass combustion processes.

11. When compared with aerobic treatment, anaerobic-based treatment processes offer the potential to considerably minimize energy consumption of wastewater treatment by avoiding aeration and achieving energy-neutral wastewater treatment through biogas production (Dai et al., 2015; McCarty et al., 2011; Seib et al., 2016; Sills et al., 2016). However, in order to be effective and energy positive, municipal wastewater requires pre-concentration of wastewater due to its medium to low organic matter content (Ozcan et al., 2022).

[1] https://www.iwmi.cgiar.org/
[2] https://www.fluencecorp.com/israel-leads-world-in-water-recycling/

2.3 Nutrient Recovery

12. Nutrient (fertilizers) recovery from wastewater has the potential to increase the sustainability of wastewater treatment, minimize the costs associated with nutrient removal, and supply additional nutrients for food production. However, the removal of nutrients from reclaimed water used in agriculture will ultimately result in increased inputs of nutrients for cultivation (Sun et al., 2016).

13. Many studies published in the recent decade contained thorough information on nutrient recovery from wastewater in terms of mechanisms, the effects of various significant elements, future directions, and so on (Ma et al., 2018; Yan et al., 2018); however, just a few applications concentrate on the financial issues. Economic feasibility is a more essential factor than technical feasibility in deciding whether the nutrient recovery system can be utilized at the plant scale.

3. Resource Recovery Technologies for Municipal Wastewater Treatment Plants

3.1 Water reclamation and reuse technologies

14. Considering that around 99% by weight of the matter contained in wastewater is water, reclaiming and reusing this source is a more sustainable option than, for example, desalination or long distance fresh-water transfers, particularly for addressing water scarcity problems and the global climate change-related water stress in the framework of circular economy.

15. In this context, the term "Resource Recovery Rout" (RRR) is defined as the route taken by a resource entering to a wastewater treatment plant; extracted and refined with the help of certain technology before finally being used (Kehrein et al. 2020). While resource extraction happens on site at the WWTP, refining and usage can be undertaken elsewhere. Selecting the appropriate technology for extraction/reclamation of water is critical depending on various factors.

16. Reclamation/recovery technologies can be classified as a function of their applicability and suitability for resource removal. They can be further categorized under the appropriate treatment phases as indicated in Table 1:

a. Primary reclamation/recovery technologies which fall under primary treatment processes for domestic wastewater. These are generally insufficient to be used alone.
b. Secondary reclamation/recovery technologies which constitute part of the secondary treatment processes. These are capable of obtaining water suitable for reuse; and
c. Tertiary reclamation/recovery technologies which are part of the tertiary treatment processes (excluding disinfection) with an end-product allowing reuse and full tertiary treatment, including pre-treatment for disinfection.

17. Primary treatment technologies such as screening, centrifugation, coagulation, and flotation are all included in this category, as they are all used in the basic stage of wastewater treatment. These technologies are typically employed in case of a significant water pollution. The main purpose of primary treatment is removal of solid and/or suspended particles using these technologies for ensuring the efficient functioning of the treatment plant.

18. Secondary treatment technologies comprise biological methods for bacteria to remove soluble and insoluble contaminants. There are many aerobic and anaerobic bacteria that can be utilized in different biological wastewater treatment processes to remove various water contaminants. These technologies vary based on their configuration and operation design, i.e., suspended growth, attached growth, etc.

19. Tertiary water treatment technologies are very important in wastewater treatment strategies. The techniques used for this purpose can be grouped in three main clusters such as: filtration, disinfection and advanced oxidations.

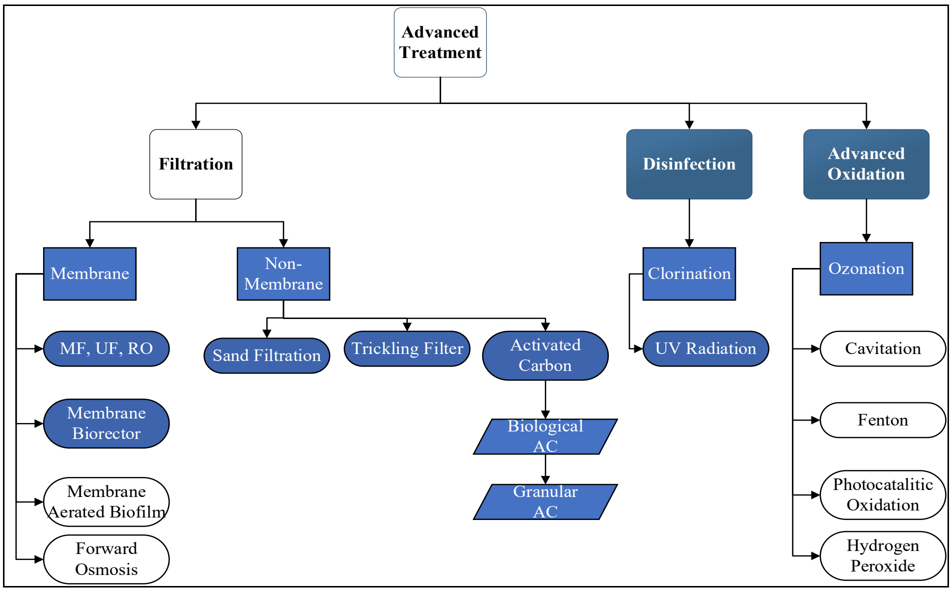
20. Main examples of advanced treatment technologies to reclaim water from municipal WWTPs are presented in Figure 1, classified under filtration, disinfection and advanced oxidation technologies.

Table 1: Wastewater treatment technologies for resource recovery from municipal wastewater

Reclamation/recovery technologies for	**Applicability of reclamation/ recovery technology removal of**	**Suitability of reclamation/recovery technology for**
Primary treatment		
Screening, configural separation	Suspended solids, Inorganic, organic biological	Reclamation, source reduction, treatment
Sedimentation and gravity separation	Suspended, inorganic, organic biological	Reclamation, source reduction, treatment
Coagulation	Suspended solids, Inorganic	Reclamation and treatment
Flotation (oil/water separation including DAF)	Suspended solids	Reclamation and treatment
Secondary treatment		
Aerobic	Soluble and suspended, organic	Reclamation and treatment
Anaerobic	Soluble and suspended, organic	Reclamation and treatment
Tertiary treatment[3]		
Distillation	Soluble, inorganic, organic and biological	Reclamation and treatment
Crystallization	Soluble, inorganic, organic	Reclamation, source reduction, treatment
Evaporation	Soluble, suspended solids, Inorganic, organic and biological	Reclamation, source reduction, treatment
Solvent extraction	Soluble, inorganic, organic and Volatiles	Reclamation, source reduction, treatment
Oxidation	Soluble, inorganic, organic	Reclamation, source reduction, treatment
Precipitation	Soluble, inorganic, organic	Reclamation, and treatment
Ion Exchange	Soluble, inorganic, organic	Reclamation, source reduction, treatment
Micro- and ultra-filtration	Soluble, inorganic, organic and biological	Reclamation, source reduction, treatment
Reverse osmosis	Soluble, inorganic, organic and biological	Reclamation, source reduction, treatment
Adsorption	Soluble, suspended, inorganic, organic and biological	Reclamation, source reduction, treatment
Electrolysis	Soluble, inorganic, organic	Reclamation, source reduction, treatment
Electrodialysis	Soluble, inorganic, organic	Reclamation, source reduction, treatment

[3] The level of treatment currently under revision by the EU Commission for the Urban Wastewater Treatment Directive will be considered when revisions are finalized.

Figure 1: Mainexam



21. The following notes provide further insights into the applicability of the aforementioned technologies for water reclamation and reuse:

a. Filtration by adsorption using activated carbon (AC) in conjunction with sand and gravel can improve effluent quality, making it suitable for water reuse. These carbonaceous compounds have the ability to reduce COD, total organic carbon (TOC), chlorine, and many other hydrophobic organic contaminants like pharmaceuticals after being activated by physical and/or chemical agents at high temperatures.

b. Several non-biodegradable organic pollutants, such as pharmaceuticals, dyes and pesticides, can be degraded by subjecting them to advanced oxidation processes (AOPs), which generate hydroxyl radicals (OH) as highly reactive oxidant agents. It is common practice to apply AOPs as a final stage of disinfection and cleaning after biological treatment, but they can also be employed as a pre-treatment step to promote further biological treatment.

c. Membrane technologies are considered the main and key technology for advanced wastewater reclamation and reuse strategies which allow reliable advanced treatment. Their advantages include the need for less space, being a physical barrier against particle material, and efficiency at retaining microorganisms without causing resistance or by-product formation. Unless membrane treatment in the form of reverse osmosis (RO) is already applied, an additional disinfection unit may be needed for safe wastewater reuse. Further details on membrane technologies are provided in Annex A.

d. Disinfection, which includes chlorination, UV radiation and ozonation, etc., is usually the final step to be applied to water reclamation in most of WWTPs, of course this depending on the final use of reclaimed water.

22. Selection of the appropriate treatment technology should consider the intended final use of reclaimed water (i.e., potable water, irrigation water, use in city parks, etc.) as well as the applicability of reclamation technologies for removal of pollutants and their suitability for reclamation and treatment as indicated in Table 1.

23. The main disinfection technologies for wastewater treatment and water reuse and their variations are presented in Table 2. Disinfection is applied in order to ensure that reclaimed water is in compliance with national/local standards and regulations. The Regional Plans on Urban Wastewater Treatment and Sewage Sludge Management adopted in Decision IG.25/8 (COP 22, 7-10 December 2021, Antalya, Türkiye) provide guidance on this aspect as part of their measures.

24. Finally, it is important to consider, for water reclamation purposes, the implementation of risk management systems such as the Sanitation Safety Planning (SSP)[4] system when public health is at stake. Predicted risks and their impacts should be considered as part of the inputs to be used in Decision Support Systems (DSS) which are explained later in this Guidance document.

[4] Sanitation Safety Planning (SSP) is a step-by-step risk-based approach developed by the World Health Organization (WHO) to assist in the implementation of local level risk assessment and management for the sanitation service chain - from containment, conveyance, treatment and end use of disposal.

Table 2: Main disinfection technologies for wastewater treatment and water reuse and their variations (Salgot and Folch, 2018)

Main disinfection technologies used for the reclamation/reuse systems		
Type	*Technology*	*Comments/Indications*
Physical	Ultraviolet radiation (UV) Membrane-based technologies	Multiple lamp systems are recommended for wastewater disinfection. The lamps should be changed after the end of their theoretical lifespan. Not useful with high turbidity. Several types. The pore diameter defines the disinfection capacity. Ultrafiltration and nanofiltration as well as reverse osmosis are the main technologies quoted.
Chemical	Chlorination	The most common technology. Residual action is its most important feature. Also used in combination with other technologies, mainly UV. By-products are generated while reacting with organic matter and other pollutants.
Other	Additional lagooning (maturation) systems Constructed wetlands, infiltration-percolation	The natural UV radiation disinfects. Other processes are natural die-off, predation. It is necessary to eliminate algae after this treatment. Use of soil/biofilms disinfection capacity as well as filtration capacity (organisms associated with the solids).
Mixed-combination	Ultraviolet (UV) chlorination. Also, membranes and chlorination	UV acts eliminating pathogens, and chlorine is used for final elimination and for maintaining a residual disinfection capacity.

3.2 Energy recovery technologies for wastewater treatment plants

25. The energy intensity of wastewater treatment plants can be decreased by designing treatment processes with a focus on energy efficiency and recovery. Energy recovery from wastewater is achievable through the application of different technologies.

26. The chemical energy in a typical municipal wastewater treatment plant can be estimated at 17.8 kJ g^{-1} of COD. This is about five times the electrical energy needed to operate a conventional activated sludge (CAS) process; although in the latter, a significant fraction of the energy stored in the COD is lost as heat during microbial metabolism. Current configurations hardly achieve energy self-sufficiency, which is usually in the range of 30% to 50%, depending on country concerned. Main examples of energy recovery technologies for municipal wastewater treatment plants are shown in Figure 2.

3.2.1 Energy recovery from wastewater treatment processes

27. Biogas is the most frequent form of energy produced in WWTPs further to the anaerobic digestion of sludge. Biogas consists of methane (50% to 70%), carbon dioxide (30% to 50%), and trace amounts of nitrogen, hydrogen, hydrogen sulfide, and water vapor (Manyuchi et al., 2018). Nevertheless, energy generated from the anaerobic digestion of wastewater sludge and combined heat and power technologies is still limited. Barriers to widespread implementation of anaerobic digestion and combined heat and power are primarily associated with costs, (e.g., infrastructure or equipment capital costs) (Pfluger et al., 2018).

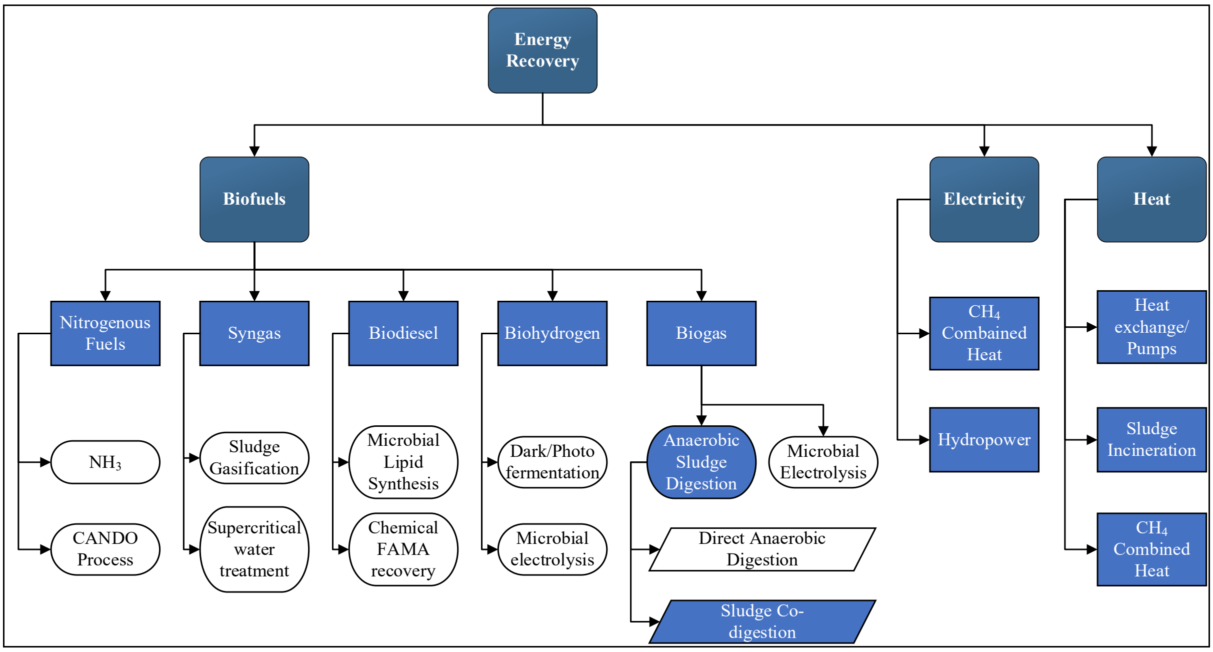


Figure 2: Main examples of energy recovery technologies for municipal wastewater treatment plants

28. Nitrogenous compounds can also be recovered from wastewater. One route for this is the CANDO process which involves three steps: (i) nitrification of $NH4^{+}$ to NO^{2-}, (ii) partial anoxic reduction of NO^{2-} to N_2O and (iii) chemical N_2O conversion to N_2 with energy recovery. Another route recovers NH_3 directly from concentrated side streams in wastewater treatment plants, for example by stripping. NH_3 can be burned to generate power or used as a transport fuel with the appropriate technology. A major issue with these routes is the nitrogen concentrations in municipal wastewater and whether this makes them feasible and economical to use (Kehrein, P. et al., 2020).

29. Syngas can also be obtained from municipal sewage sludge using supercritical water treatment processes. Syngas or synthesis gas is a mixture of hydrogen and carbon monoxide, in various ratios. It is formed by the decomposition of organic matters in sewage sludge which is hydrolyzed into syngas. The gas often contains some carbon dioxide and methane. It is combustible and can be used as a fuel. The advantage over other sludge-handling technologies is that the sludge is converted into an energy carrier in much shorter residence times of only a few minutes. Moreover, excess sludge from WWTPs does not need to be dewatered before being fed to supercritical water reactors. In this regard, supercritical water technology has proved to be a promising treatment method for contaminated wastewater and sludge from a wide variety of industries including pulp and paper, pharmaceutical, textile, pesticides, dairy, petrochemical, explosives, and distillery.

30. Biodiesel is another fuel that can be derived from sludge. Harvesting lipid-rich biomass by simply skimming the surface of wastewater treatment reactors could provide feedstock for high-yield biodiesel production. The use of phototrophic microalgae that treat the wastewater in high-rate ponds is a well-studied production route for biodiesel. However, the performance of phototrophic organisms depends on climatic conditions that are not available all year round in countries that have a winter season. In addition, land use for this type of biodiesel production is high, as are the costs of photo-bioreactors and algae harvesting (Kehrein *et al.* 2020).

31. Heat pumps are designed to use electricity to extract low-temperature thermal energy from the wastewater. They usually provide 3 to 4 units of heat energy per unit of electrical energy consumed. Considering that the temperature of the effluent shows relatively small seasonal variations by comparison with atmospheric temperatures, this can serve as a stable source of heat that is recoverable using heat pumps. Wastewater temperature can be used for heating or cooling buildings. Sludge temperature also offers a potentially interesting thermal energy resource for recovery on-site use during sludge drying (W. Mo and Q. Zhang, 2013).

3.2.2 Energy recovery from sewage sludge in energy plants

32. Treated sewage sludge can be co-incinerated in existing power plants. Co-incineration takes place mainly in coal-fired power plants, waste incineration plants and cement works.

33. Co-incineration in coal-fired power plants: Coal fired power plants are being replaced by gas powered plants. Nevertheless, sewage sludge can be co-incinerated in both lignite and hard coal fired power plants. Pulverized-fuel or circulating-fluidized bed are the main operating furnace systems.

34. Generally, only stabilized (i.e. digested) sewage sludge is burned. The use of raw sludge would cause great difficulties in handling and storage and is not suitable due to its high water content and especially due to its poor dewaterability and gas and odor generation. Technically, both the incineration of dried sewage sludge and that of simply dewatered sewage sludge is possible. Currently, dewatered sewage sludge having a dry substance content of about 25% to 35% dry mass is burnt in most co-incinerating power plants. Some power plants only use fully dried sewage sludge. In others, it is mixed with dewatered sewage sludge and added back to the incineration process.

35. When using dewatered sewage sludge, integrated drying of the sludge generally takes place prior to incineration. In power plants using pulverized fuel (PF) firing, the sewage sludge is usually introduced in the process via the coal mill and dried and crushed together with the coal. The drying capacity of the coal mills is often the limiting factor; reducing the use of dewatered sewage sludge to a low percentage. This is especially true for hard coal-fired power plants where only limited drying capacity is available due to the low water content of hard coal. In most coal-fired power plants, the proven sewage sludge content is up to 5% of the fuel mass.

36. Compared to coal, sewage sludge has a relatively high proportion of mineral components of about 40% to 50% (reference?). Correspondingly high is the ash content, which must be separated after incineration, while low is the calorific value related to the total solids content. The calorific value of sewage sludge is 9 to 12 MJ/kg in the fully dried condition. Lignite has a comparable calorific value at about 50% water content. Hard coal is extracted with a water content of 7% to 11% and has a calorific value of 27 to 30 MJ/kg in this condition.

37. Sewage sludge is a sink for a number of pollutants. When sewage sludge is co-incinerated in coal-fired power plants, the additional input of heavy metals – particularly highly volatile substances such as mercury – becomes noticeable in the emission values. This is one of the reasons why the sewage sludge amount co-incinerated in power plants remains limited to a small percentage. It is recommended to use risk-based assessments for assessing undesired impacts of air emissions stemming from co-incineration of sludge in coal-fired plants.

38. Co-incineration in waste incineration plants: Municipal sewage sludge is disposed of in different degrees of drying in a number of waste incineration plants; the procedural principle of which is mostly based on grate firing technology. The admixture rate should not exceed 20% and the moist sludge should be well mixed with the rest of the material to avoid lumping. This is often achieved by so-called strewers in the waste bunker or through centrifugal devices for feeding the combustion chamber. If dried sewage sludge is co-incinerated, there is a risk that the sludge will fall through the grate without being sufficiently burned out. When co-incineration takes place in waste incineration plants, it should be noted that the sewage sludge significantly affects the dust content of the exhaust gas and therefore the flue gas cleaning facilities must be designed for the required increased separation performance.

39. Co-incineration in cement works: Cement production is a very energy intensive process and has used surrogate fuels from waste for decades. For this purpose, dried sewage sludge (an average water content of 27% by weight) replace fossil fuels. In addition, the mineral content in sewage sludge can substitute the mineral raw materials such as sand or iron ore required in cement production.

40. The co-incineration of sewage sludge in cement works is advantageous in two respects. On the one hand, valuable raw materials and fuels can be saved and, on the other hand, the co-incineration of sewage sludge, which is considered to be largely climate-neutral, also contributes to CO_2 reduction. In

addition to dried sewage sludge, mechanically dewatered sewage sludge is also used to a small extent. In this case, only a very small contribution to meeting the energy demand can be expected; the substitution of raw materials is much more important.

41. The heavy metal limit values of waste incineration also apply to the co-incineration of sewage sludge in cement works. Heavy metal input limits for sewage sludge are also particularly important to limit the heavy metals content.

3.3 Nutrients reclamation and recovery technologies

42. Wastewater is a rich source of phosphorus (P), nitrogen (N), magnesium (Mg) and potassium (K). These substances provide the basis for the composition of a number of commercial fertilizers. Therefore, attempts have been made to properly recover these substances from wastewater even though their recovery is not fully economical despite their high potential.

43. There are many operational or partially deployed phosphorus recovery systems from wastewater such as wet chemical leaching, wet oxidative processes, metallurgical, bioleaching, thermochemical, and wet chemical extraction. It is common knowledge that P and NH_4-N naturally precipitate out of urine as struvite scale (Somathilake, 2009). Other technologies for nutrients recovery include chemical precipitation, membrane processes, enhanced biological phosphorus removal, adsorption processes, adsorption.

44. Recent efforts (Günther et al., 2018) to collect nutrients as struvite through various chemically based extraction techniques have been pioneered. Struvite which is a phosphate-rich organic substance containing high levels of Mg^{2+}, PO_4^{3-}, and NH_4^+ offers numerous advantages over commercially available chemical fertilizers. This includes slow-release characteristics, soil conditioning, preventing surface run-off, and limited consumption over an extended period of time (Krishnamoorthy et al., 2021).

45. Electrodialysis (ED) is another technology which is currently seen as a promising method for removing and recovering nutrients from wastewater. It is best described as an electromechanical separation technique that serves for the extraction of ions in solution, in addition to the extraction of hardness and organics from electrolytes, by using ion-exchange membranes within an electric field to encourage ionic separation (Lee et al., 2013). It should be noted that the electrodialysis process for nutrient recovery differs from the typical ED for desalination (Mohammadi et al., 2021).

46. As discussed in the previous section, incineration of sewage sludge is a wastewater treatment method that serves to decrease sludge volume, odor, and to eliminate organic pollutants like pharmaceuticals and pathogens. Significant quantities of phosphorus contained in sewage sludge can be reused in agricultural or urban land application provided sludge characteristics meet national standards and regulations. But the presence of heavy metals is still the main obstacle to direct application of sewage sludge incineration ash on crop fields (Vogel et al., 2013).

47. Examples of fertilizers/nutrient recovery technologies for municipal wastewater treatment is shown in Figure 3. It should be noted that sludge land applications and use of sludge as soil conditioner have been addressed in the Regional Plan for Sewage Sludge Management (Decision IG.25/8, COP22, Antalya, Türkiye).

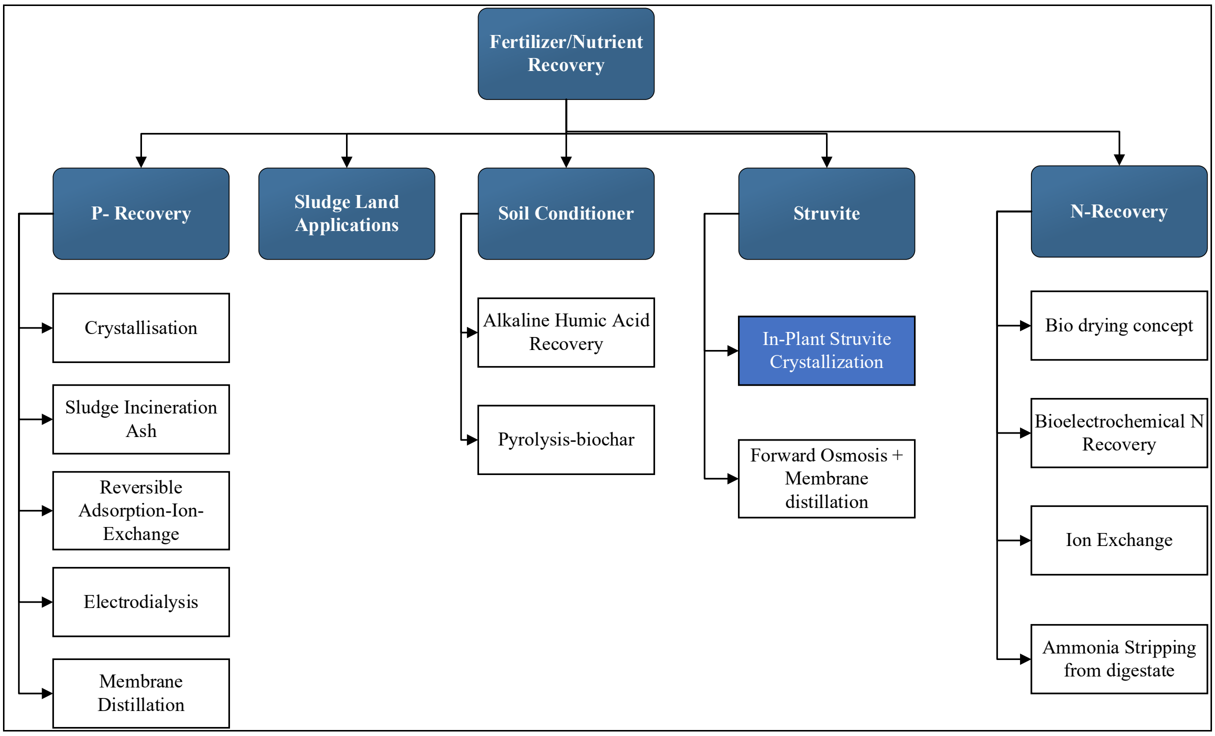


Figure 3: Main examples of fertilizers/nutrient recovery technologies for municipal wastewater treatment

3.4 <u>Economic, environmental, health and social considerations for resource recovery from wastewater treatment processes</u>

48. Before selecting a resource recovery route, the feasibility for water reclamation/recovery of materials and energy from wastewater treatment processes should be investigated beforehand to determine the associated economic costs in terms of extracting the required resource in feasible quantities and acceptable quality; their market value chain, competition and logistical aspects which impact cost; emissions and health risks; as well as social acceptance and availability legislations. These aspects should be considered as part of the inputs to be used in Decision Support Systems (DSS) which are explained later in this Guidance document.

49. The main economic, environmental, health and social considerations for recovery of water, energy and fertilizers (nutrients) from wastewater treatment processes are presented in Table 3. These aspects are considered the starting point for any design of wastewater treatment plants as well as selecting the appropriate technologies for resource recovery. Table 3 is clustered into three parts: (i) economy including value chain, (ii) pollution and health risks, and (iii) social acceptance and supporting policies.

50. The value chain is the key driving force for decision makers to select a certain technology to serve the purpose of material/energy recovery. Naturally it may vary based on the country needs and priorities. Comprehensive market research with a projection including logistical aspects should be prepared, especially for nutrient recovery.

51. Pollution and health-related considerations are directly related to the effect of discharges and production of unwanted harmful byproducts which are key elements for mitigating the risk of a selected resource recovery technology. For this reason, risk management systems should be considered in any scheme for materials recovery with the aim to alleviate any adverse impacts on human health.

52. Finally, social acceptance of recovered materials (e.g. reuse of reclaimed water) and related policies in place are crucial for the technologically successful and economically viable recovery of resources and materials from wastewater treatment processes.

Table 3: Main economic, environmental, health and social considerations for recovery of water, energy and fertilizers from wastewater treatment processes (adapted from Kehrein, P. et al. 2020)

ECONOMICS AND VALUE CHAIN			
	Issue	*Resource Recovery*	*Considerations*
Process costs	A resource recovery process is not cost effective due to excessive operational or investment costs	Water	High energy demand of membrane technologies. Per m^3 water reclaimed by secondary effluent treatment with ultrafiltration and reverse osmosis a benefit of 0.25 € has been calculated
			Fouling as an additional cost factor for membrane technologies. Costs vary greatly and depend on membrane characteristics, operating conditions, feedwater quality and applied cleaning techniques
			Disposal costs of membrane retentate depend on level of treatment, retentate characteristics and disposal method
			Advanced oxidation processes are energy intensive and require expensive reagents
		Energy	Microbial fuel cells: expensive equipment and operational cost
			NH_3 recovery for fuel is not cost effective because energy costs of removing NH_3 often exceed the energy and value of recovered gas
		Nutrients	Phosphorus recovery costs exceed conventional phosphorus ore costs. Assuming a load of 660 g phosphorus per capita per year, recovery costs would be 3,600–8,800 € per ton recovered phosphorus
			Struvite recovery processes may not be cost effective which depends strongly on profits from struvite sales. Market prices vary greatly and have been estimated for example between 180–330 € per ton
			Phosphorus recovery from sludge incineration ash requires specialized and expensive incinerators
Resource quantity	[Compared with conventional production methods, only small quantities of a resource can be recovered at a WWTP.] This may be due to low process yields, low resource concentrations or low overall resource quantities in the wastewater stream	Energy	Combined heat and power units for recovered CH_4 have high conversion losses of around 60%
			COD may be too diluted for effective direct anaerobic digestion of wastewater. 750 mg COD per litre is a medium concentration for municipal WWTP influents
			Dark fermentation of sludge shows very low H_2 yields of 17%
		Nutrients	Nutrient quantities recoverable from wastewater are low compared with industrial production rates. For example, in Flanders (Belgium) yearly mined P imports amount of 44.100 tonnes while combined WWTP influent-P amounts only of 3.350 tonnes
			Struvite: low phosphorus concentrations limit precipitation which requires at least 100 mg phosphorus per litre
			Struvite: only soluble phosphorus fraction of side streams is recovered
			Low nitrogen concentrations of only 30 mg per litre NH_4-N in average Dutch wastewater may make NH_4 recovery uneconomical

	Description of process	*Resource Recovery*	*Considerations*
Resource Quality	The quality of a recovered resource is not high enough to market easily. This may be due to contaminants or impurities in the resource	Nutrients	Field application of sewage sludge: high water content (70% to 90%) and low nutrient content (7 kg phosphorus per tonne)
			Possible contamination of struvite
Market value and competition	Conventional production methods potentially outcompete the RRR. This may be due to various factors, including higher product quality and quantities or lower production costs.	Energy	CH_4 has a low market value in 2019 of 0.046 € per kWh for household consumers. To note however, energy prices are volatile.
			Electricity has a low market value in 2019 of 0.22 € per kWh for household consumers. To note however, energy prices are volatile.
		Nutrients	Bulk nutrients from the fertilizer industry are available cheaply (phosphate rock: 110 US$ per tonne in 2014)
			In livestock intensive regions phosphorus-rich manure is often abundantly available as an alternative fertilizer
			The market value of struvite is hard to estimate in many countries due to a lack of knowledge and trust of farmers into its fertilizing potential
Logistics	If recovered resources are not used on site, distribution and transport have to be organized. This may be challenging due to geographical and temporal discrepancies between supply and demand, lack of infrastructure, or cost	Water	Temporal and geographical discrepancies between supply of and demand for water must be considered
			Topographical location of WWTP might require uphill pumping of reclaimed water. A 100 m vertical lift is as costly as a 100 km horizontal transport (0.05–0.06 US$ per m^3 in 2005)
			Possible need for new pipeline infrastructure for reclaimed water
		Energy	Temporal and geographical discrepancies between supply of and demand for thermal energy need to be balanced out
			Costs of pressurizing and transporting CH_4 if no connection to the natural-gas grid is present
		Nutrients	In-field sludge application: transport between WWTP and arable land might be too costly due to high water content
POLLUTION AND HEALTH RISKS			
	Description of process	*Resource Recovery*	*Considerations*
Emissions and health risks	The use of recovered resources or the recovery process may entail risks to human health due to contaminants or may cause emissions and environmental problems. This may be due to insufficient process control	Water	Potable water reuse has been evaluated as too great a health risk
			Incomplete removal of chemicals or pathogens during treatment may cause disease
			Disinfectants used in tertiary treatment can generate harmful by-products
			Plant or soil contamination as consequence of wastewater reuse for irrigation
		Energy	Unheated anaerobic digesters may promote emissions of solubilized CH_4

		Nutrients	Struvite may be contaminated with emerging pollutants and heavy metals
SOCIETY AND POLICY			
	Description of process	*Resource Recovery*	*Considerations*
Acceptance	User acceptance of resources recovered from wastewater may be low due to fears or misconceptions about the risks they pose	Water	Water reuse projects can rarely be implemented without social acceptance
			Direct potable water reuse raises psychological barriers
Policy	To be successful, RRRs need adequate policy and legal frameworks. A lack of legislation, political will or economic incentives may hinder successful implementation	Water	Government incentives are needed to make water reuse financially attractive e.g. for agriculture
			A lack of common regulations is a barrier to water reuse (in southern Europe)
			Regulations exist for agricultural use; however, there are still lacking on drinking water, etc.
		Energy	Anaerobic digestion may need to be subsidized to become competitive with natural gas
		Nutrients	Lack of legislation on in-field struvite application

4. Treatment Technologies for Emerging Contaminants in Wastewater Treatment Plants

53. Emerging contaminants (ECs) are natural or manmade chemicals and substances that can be found in water bodies. These contaminants have a high potential to be harmful to humans, aquatic life, and the environment. The presence of these contaminants becomes a significant cause for concern if they are not regulated. Emerging contaminants frequently result in the production of by-products whose physicochemical characteristics are unknown. Exposure to Emerging contaminants has the potential to cause a wide variety of diseases in humans. Some emerging contaminants can act as endocrine disruptors due to their structural similarity to naturally occurring hormones, while others can induce mutagenic and carcinogenic effects, such as an increased risk of breast and prostate cancer (Prangya R. Rout et al., 2021).

4.1 Classification of Contaminants of Emerging Concern and their sources, occurrence and fate/transport

54. In accordance with their chemical and physical features, ECs fall into one of three broad categories: Particulate matter, organic compounds, and inorganic compounds as depicted in Figure 4. Approximately [70%] of the ECs found in environmental samples are PhACs (pharmaceutically active compounds) and PCPs (personal care products), whereas the remaining [30%] are industrial and agricultural compounds (Ouda et al., 2021).

55. Domestic wastewater, industrial effluents, hospital discharges, livestock farming, and agricultural runoff are just some of the sources of ECs that make their way into the aquatic and subsurface environment. Major sources of ECs in the environment come from pharmaceutical, PCP, biocide, and other chemical industrial effluents. PhACs and PCPs can be introduced to the environment from a variety of sources, but household discharge is a significant contributor. Drug conjugates, antibiotic-resistant bacteria and genes, pharmaceutical metabolites, radioactive elements, and so on are all found in hospital effluents and contribute significantly to ECs. Other significant sources of ECs include the runoff from animal farming and agricultural activities, particularly in the form of steroid hormones and pesticides used to increase crop yields. The biocides and insecticides employed, the nature of the surface water bodies, and the weather all play a role in how much EC is contributed by these sources. Landfill leaching, irrigation with reclaimed water, aquaculture discharge, sewage treatment facility leaks, etc., are other sources of ECs in the environment. Figure 5 illustrates

the principal sources and routes of emerging contaminants (ECs) in aquatic and subsurface ecosystems.

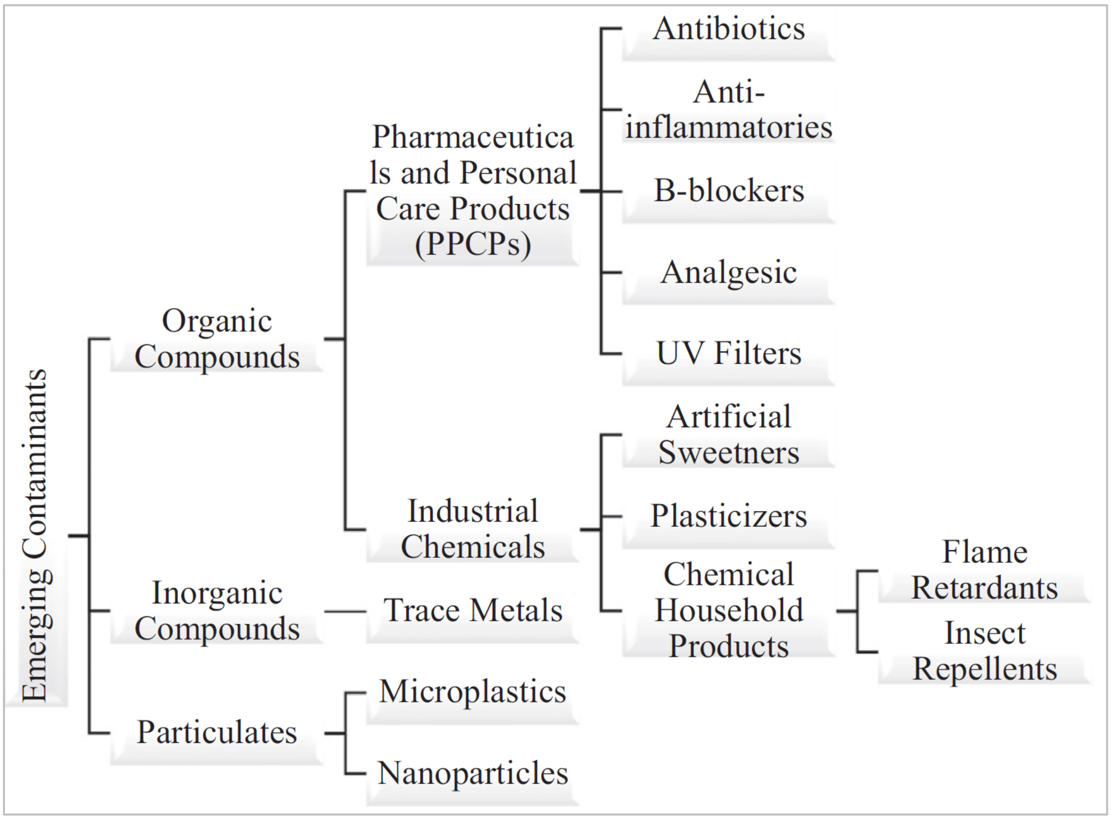


Figure 4: A streamlined classification method for EC (Adapted from Ouda et al., 2021)

56. Once ECs have entered the environment, they begin immediately to migrate to various aquatic environments by following a variety of distinct pathways; their concentrations varying greatly from one another in various aquatic environments. This is primarily the result of a number of factors, including, but not limited to, dilution, environmental persistency, treatment efficiency, and others (Luo et al., 2014). In most cases, the presence of ECs in aquatic environments was documented in a variety of distinct categories, including raw sewage, effluent treated wastewater from WWTPs, sewage sludge, surface water, groundwater, and drinking water.

4.2 Treatment of Contaminants of Emerging Concern in WWTPs

57. [The relatively low concentrations of ECs make them difficult to treat, which also suggests that detecting and monitoring ECs is a challenge. Although separation is a common method for concentrating samples in order to improve detection rates, this approach is not without its drawbacks. The most notable is the potential for loss of contaminants, damage to analytical instruments, and the difficulty of inline detection. CECs have highly variable physiochemical properties, which means that it is impossible to detect all types of CECs using the same analytical technique. As a result, there is a need for improved and advanced analytical and bioanalytical methods for the detection of ECs. Research is now being pursued for the creation of analytical methods for the detection and monitoring of ECs that are both straightforward and economical (Ouda et al., 2021).]

58. Conventional WWTPs are not specifically intended for the efficient removal of CECs. Depending on their persistence, the physicochemical features of CECs, applied treatment procedures, and the operational/environmental conditions, the removal effectiveness of CECs varies significantly. Generally, the basic primary treatment procedures applied in WWTPs are designed to remove

suspended and colloidal materials. It is found that CECs are also removed to some degree, primarily through sorption onto the primary sludge, as shown in Figure 6.

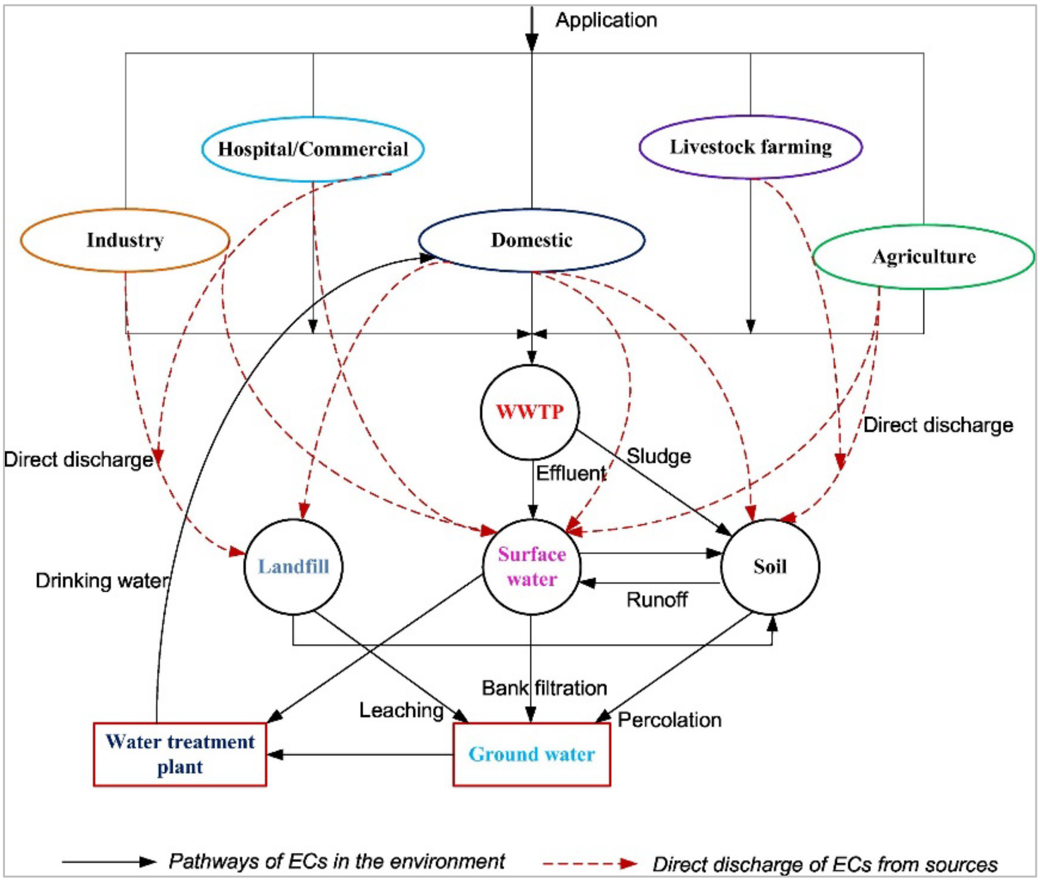


Figure 5: Principal sources and routes of contaminants of emerging concern (CECs) in aquatic and subsurface ecosystems (Adapted from Prangya R. Rout et al., 2021)

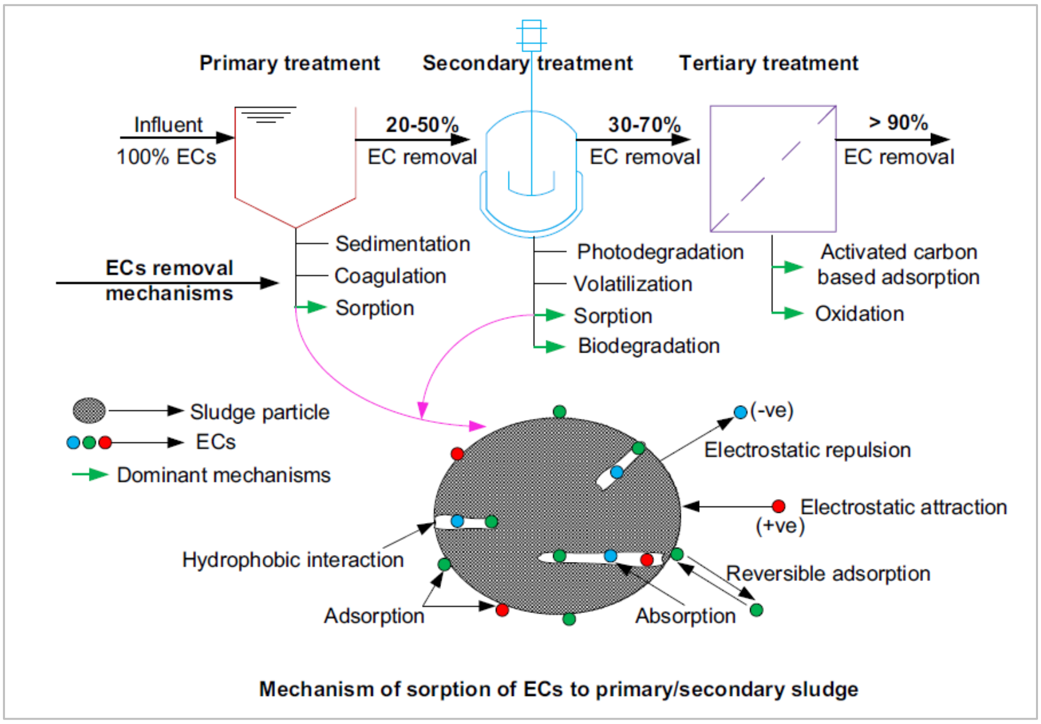


Figure 6: Mechanism of sorption of CECs to primary/secondary sludge

59. During the secondary treatment phase in a WWTP which aims to remove organics or nutrients by biological decomposition, the CECs are susceptible to different processes, such as biodegradation, sorption, dispersion, dilution, photodegradation, and volatilization. However, biotransformation or biodegradation and sorption are the predominant mechanisms of CEC removal.

60. Similarly, the tertiary treatment procedures in WWTPs intended for the removal of nutrients, suspended particles, and pathogens have been shown to have a considerable EC removal efficiency, particularly for the resistant CECs by traditional oxidation techniques comparable to ozonation.

61. Generally, CECs removal efficiency during primary treatment ranges from 20% to 50%, whereas the removal efficiency during the subsequent treatment processes ranges from 30% to 70%. On the other hand, there are instances of negative removal of CECs in WWTPs in which their effluent concentrations exceed their influent concentrations. This is because the majority of CECs are eliminated as a mixture of parent chemicals and conjugates via feces and urine. During biological treatment, conjugates can revert back to their parent compounds by enzymatic cleavage, leading to a rise in the concentration of the relevant CECs (Prangya R. Rout et al., 2021).

62. Effects of use of primary, secondary and tertiary treatment technologies on CEC removal are further elaborated in Annex B to this Guideline, including removal of CECs in the activated sludge process and membrane bioreactors under secondary treatment, as well as removal of CECs by means of ozonation, and activated carbon adsorption under tertiary treatment.

5. Microplastics in Wastewater Treatment Plants: Occurrence, Detection and Removal

63. Microplastics, also defined as plastic particles with a size smaller than 5 millimeters (Thompson, 2015) can either be generated directly (primary microplastics) or formed indirectly (secondary microplastics) by the erosion of large plastic debris as a result of exposure to environmental stressors such water, wind, and sunlight. Microplastics are found throughout the aquatic environment, from rivers and lakes to estuaries and coastlines to marine ecosystems, due to the widespread use of plastic items and the inadequate management of plastic waste disposal. There is growing concern about the threats that microplastics bring to aquatic life and human health. Microplastics' presence and deposition in the environment raise significant environmental and ecological problems (Sun et al., 2019). Their absorption can also contribute to the spread of micropollutants.

64. Controlling microplastics requires a thorough understanding of their occurrence and fate in WWTPs, as well as an efficient detection method (Sun et al., 2019). This section is aimed to provide guidance on microplastics removal in wastewater treatment plants with the aim to help facility operators to achieve sustainable operation of WWTPs.

5.1 <u>Occurrence of microplastic in wastewater treatment plants</u>

65. Microplastics originating from industrial and urban activities can be transported to WWTPs via the sewerage system. These include numerous personal care and cosmetic products such as lotions, soaps, facial and body scrubs and toothpaste. Even though these facilities are capable of removing more than 90% of microplastics from wastewater, millions of microplastics are still released into the environment each day via treated wastewater (Sol et al., 2020).

66. The concentration of microplastics typically ranges between 6.10×10^2 and 3.14×10^4 particles/L in influent and between 0.01 and 2.97×10^2 particles/L in the effluent, despite a wide range of reported data variability (Ali et al., 2021). Microplastic concentrations may vary from one treatment plant to another due to many factors, including catchment area, population served, land use in the near area, the presence or absence of a combined sewer system, the type of wastewater being treated (domestic, commercial, industrial), and so on. As the major proportion of microplastics in wastewater are derived from residential discharges, human activities in the served catchment, such as the

preference of residents for wearing synthetic clothing or using plastic products, may directly affect the concentration of microplastics in wastewater (Sun et al., 2019).

5.2 Techniques for microplastic detection in wastewater treatment plants

67. As depicted in Figure 7, the detection of microplastics in WWTPs typically involves three steps: sample collection; sample pretreatment; and microplastic characterization/quantification; yet, the methodologies utilized for each step are not yet standardized. Since microplastics can be found in both wastewater and sewage sludge, several approaches may be applied depending on sample properties (Sun et al., 2019). Microplastics in wastewater can be collected in a variety of ways, the most common of which are container collection, autosampler collection, separate pumping and filtration, and surface filtration. For the pretreatment of microplastics in WWTPs, various techniques are used to purify and remove microplastics from their original matrices, as samples obtained from WWTPs (especially sludge samples) may contain a high concentration of organic matter or inorganic particles. Wet (catalytic) peroxidation is a frequent technique for removing organic materials from WWTP samples (WPO). Enzymatic degradation is a relatively recent technique being explored for the purification of microplastics contaminated with organic material. Technical enzymes such as lipase, amylase, proteinase, chitinase, and cellulase are used in the degradation process by dissolving microplastic samples. Alkaline and acid treatment are alternate techniques for removing organic materials from wastewater and sludge samples. On the other hand, inorganic particles in wastewater and sludge samples are typically extracted using density separation and salt solution. As the last step of the detection of microplastics in WWTPs, microplastics analysis can be divided into two categories: physical characterization and chemical characterization. Characterizing the size distribution of microplastics as well as analyzing other physical parameters such as shape and color is the primary focus of physical characterization. Besides, chemical characterization is essentially used to investigate the microplastics' chemical composition (Sun et al., 2019).

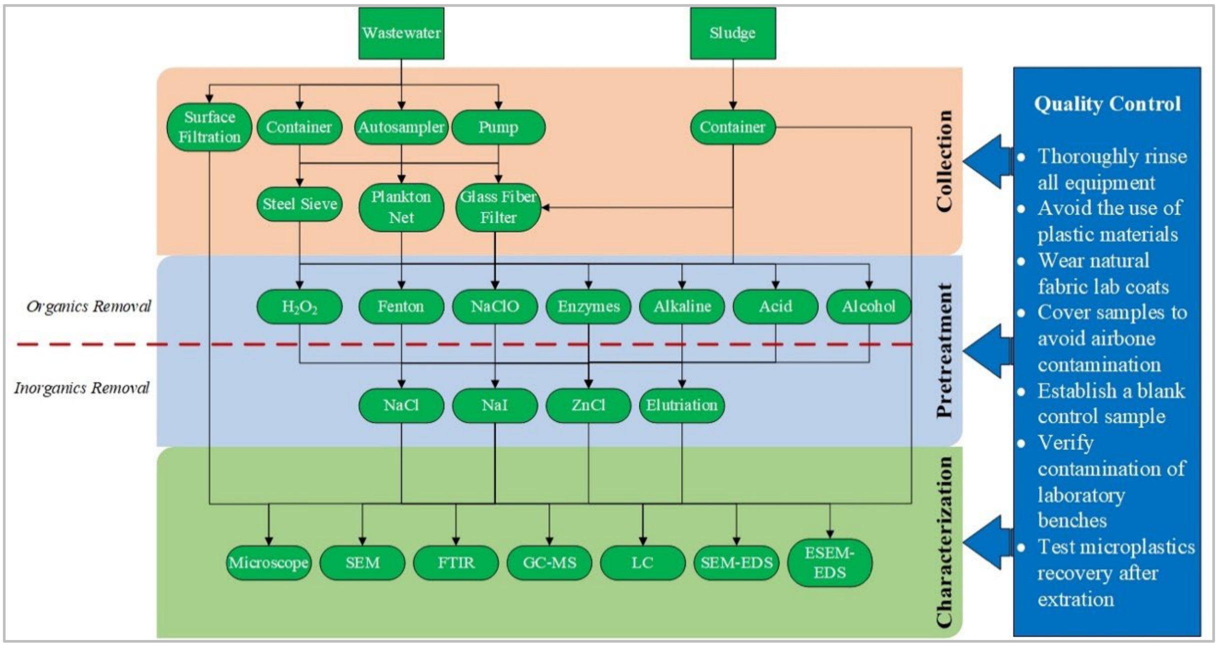


Figure 7: Process flow diagram for microplastic detection in wastewater treatment plants (Sun et al., 2019)

5.3 Removal of microplastic in wastewater treatment plants

68. The removal effectiveness of microplastics during preliminary, primary, secondary, and tertiary treatment is depicted in Figure 8 by the estimated particle flow of microplastics based on literature-reported value ranges. The majority of microplastics in wastewater can be efficiently removed by preliminary and primary treatment (pre-treatment). It is reported that between 35% and

59% of the microplastics could be eliminated during the preliminary treatment and between 50% and 98% of the microplastics could be eliminated during the primary treatment. As a result of its ability to efficiently remove microplastics of larger size, pre-treatment has the greatest effect on the size distribution of microplastics. Microplastics in wastewater were reduced to 0.2% to 14% with secondary treatment, which typically includes biological treatment and clarification.

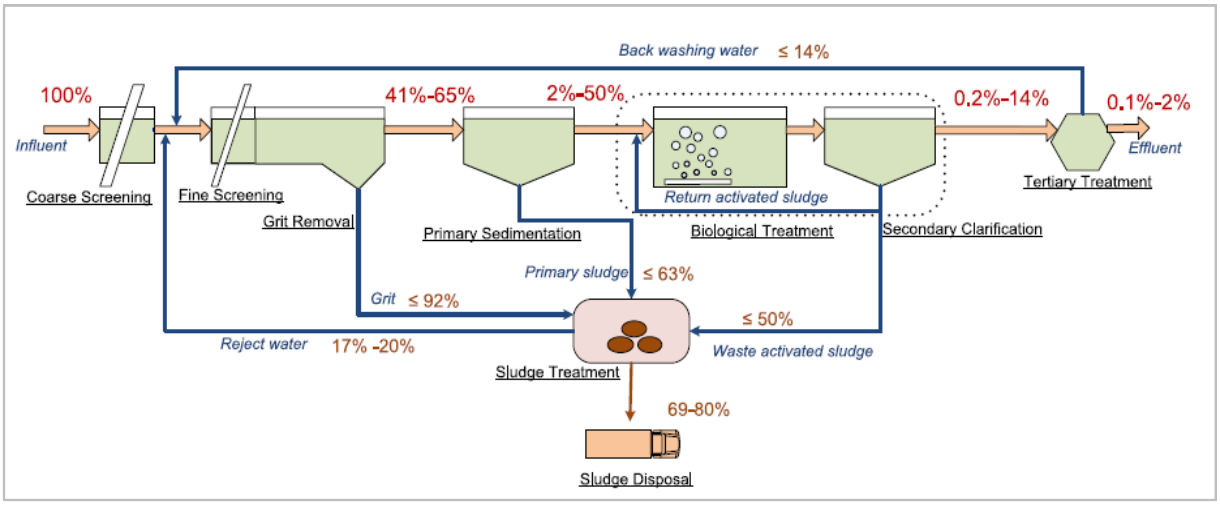


Figure 8: Estimated particle flow of microplastics in a WWTP with primary, secondary, and tertiary treatment processes (Sun et al., 2019)

69. As a result of the presence of sludge flocs or bacterial extracellular polymers in the aeration tank, the remaining plastic debris is likely to be accumulated and eventually deposited in the secondary clarification tank (Sun et al., 2019). In addition, chemicals used in secondary treatment, such as ferric sulfate or other flocculating agents, may have a beneficial effect on microplastic removal by causing the suspended particulate matter to aggregate together forming a "floc." (Murphy et al., 2016). On the other hand, potentially significant additional microplastic polishing may be provided by the tertiary treatment. After the tertiary treatment, the microplastic concentration in the effluent can be dropped to between 0.2 and 2% of the influent. The efficiency of microplastic removal depends on the applied treatment processes, with membrane-related technologies having the highest performance (Sun et al., 2019).

5.4 <u>Measures to reduce inputs of microplastics into sewage sludge</u>

70. Effective reduction of microplastics in sewage sludge can be achieved through enforcement of bans on single use of plastics and by prohibiting inputs of microplastics in personal care and cosmetic products. This action should be accompanied by a behavior change of the general public and campaigns to reduce the use of such products. Certain textile designs can be developed taking into consideration the need to reduce microfibre generation during washing. Household-based systems can be manufactured to prevent microplastics from being released into sewer lines or the environment.

71. Furthermore, the Amendments to the Regional Plan on Marine Litter Management in the Mediterranean which was adopted in Decision IG.25/9 by COP22 (7-10 December 2021, Antalya, Türkiye) provide a comprehensive legal framework for combatting microplastic with some robust measures to be implemented for reduction of the plastics reaching the Mediterranean environment.

6. Decision Support System for Selection of Wastewater Treatment Technologies

72. This section is aimed to provide guidelines on Decision Support Systems (DSS) to help policymakers/design engineers/facilities manager in implementing the best technology to achieve sustainable wastewater solutions in accordance with national/regional legal frameworks and regulations.

73. Wastewater treatment plants (WWTPs) are investigated globally in an effort to develop more environmentally friendly methods for their management. The design and operation of WWTPs are required to take into account a variety of complicated goals, such as reducing costs while successively developing installations that are both safe and operative and that offer entirely reliable wastewater treatment (Rodriguez-Roda et al., 2000).

74. To this aim, Decision Support Systems (DSS) have been employed as a helpful tool in solving complex and multi-scenario problems for WWTPs. They provide a systematic framework for the selection and design of water and wastewater treatment processes (M. A. Hamouda et al., 2009).

75. Decision Support Systems (DSS) allow not only for the integration of various aspects relevant to the sustainable operation of WWTPs, but also address external factors of economic, environmental, health and social nature. In this regard, risk-based management systems such as Sanitation Safety Planning (SSP) systems should be also considered. These systems provide a systematic analysis and prediction of risks and their impacts on human health which can be used as inputs in Decision Support Systems (DSS) for mitigating adverse impacts on public health.

6.1 Role of decision support systems for the selection of wastewater treatment technologies

76. A robust DSS should be (i) based on system analysis technique, (ii) capable of gathering, representing, and analyzing information relevant to the problem, (iii) adaptable and able to deal with insufficient data or uncertainty, (iv) user-friendly, (v) capable of producing results that are helpful. The decision-making process's complexity, the immediacy with which a solution is required, the presence of relevant knowledge during application, and the issue's specificity are all factors that should be taken into account when determining whether or not a DSS is necessary. General procedures for developing a DSS include: (i) problem analysis and interpretation, (ii) representation of knowledge and reasoning, (iii) progressive optimization of the design with the purpose of producing and assessing alternatives, and (iv) validation and confirmation of the DSS logic for better user engagement and usability (M. Hamouda et al., 2009).

6.2 Main types of DSS applied to WWTP issues

77. There are four approaches adopted by Decision Support Systems for implementation of wastewater treatment plants (G. Mannina et al., 2019) as illustrated in Figure 9. These are:

a. Life Cycle Assessment (LCA),
b. Mathematical Model (MM),
c. Multi-Criteria Decision Making (MCDM),
d. Intelligent DSS (IDSS)

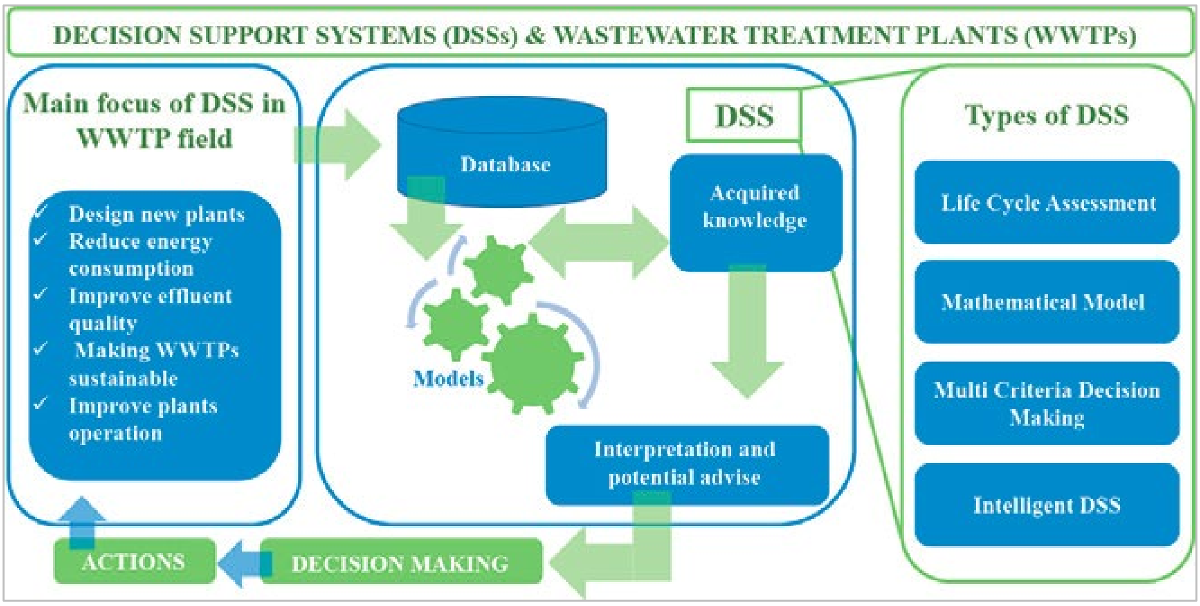


Figure 9: Main focuses and decision support systems for WWTP (G. Mannina et al., 2019)

6.2.1 Life Cycle Assessment (LCA)

78. In the field of wastewater treatment, LCA has been increasingly applied to assess the environmental trade-offs of current technologies (Fang et al., 2016). Additionally, the environmental impact of WWTPs, including the efficiency of the processes and the services, can be assessed with cradle to grave approaches by utilization of LCA (Pasqualino et al., 2009). The main objective of LCA applications for WWTPs is to develop and quantify indicators for evaluating the global environmental consequences of WWTPs. Energy use, wastewater discharge, sludge disposal/reuse, and land occupation are the primary factors that affect the WWTP's environmental profile (Hospido et al., 2004).

79. One of the challenges of LCA is defining the system boundary because it varies greatly, with some studies covering the whole urban water system and others focusing solely on the WWTP (Corominas et al., 2013). Although plant performance can be affected by influent composition, plant size, and local climate (Lorenzo-Toja et al., 2016), the environmental performance of WWTPs is mostly based on effluent discharge and sludge application on land (Hospido et al., 2004). In addition, the sludge and solids stream of wastewater treatment accumulates substances that are both useful and hazardous, such as phosphorus and heavy metals, and these compounds need to be included in LCA analyses (Yoshida et al., 2014). Thus, any environmental assessment of a novel wastewater technology must incorporate life cycle boundaries that include the end-use of water and nutrients (Fang et al., 2016). Instead of being a measuring tool, LCA can also be used to help make decisions. The decision-maker is provided with data from the DSS to help narrow down their alternatives (Pryshlakivsky & Searcy, 2021).

6.2.2 Mathematical Model (MM)

80. Mathematical models serve as the foundation for the earliest documented DSSs. Due to the low cost of implementation, mathematical model-based DSSs are a promising tool for gaining a detailed understanding of WWTP characteristics (Mannina et al., 2016). Mathematical models may vary based on their level of complexity and details. The quantification of both direct and indirect GHG emissions (Kyung et al., 2015), as well as economic and social indicators (Gemar et al., 2018), are common components of these simplified models. When a more precise depiction of reality is needed, a detailed model should be used. However, mechanistic mathematical models (such as the activated sludge model - ASM family) are rarely utilized because of their complexity and the need for extensive datasets (G. Mannina et al., 2019). Regarding this type of DSS, there are a number of advantages that

can be highlighted. For instance, it is possible that MMs can be used to validate lab data at a proportional rate and to offer reliable estimates for commercial-scale operations (Zuthi et al., 2012) by providing a variety of potential solutions for consideration during the decision-making process (Mannina & Cosenza, 2013). In brief, stakeholders may be able to save time and money by using DSSs based on mathematical modeling to test out several approaches to a problem before implementing them at the site (G. Mannina et al., 2019).

6.2.3 Multi-Criteria Decision Making (MCDM)

81. The Multi-Criteria Decision Making-based DSS is a combination of various criteria/methods designed with the goal of optimizing the behavior of a WWTP that employs multiple technologies and focuses attention on multiple optimization goals (Torregrossa et al., 2017). Application of MCDM-based DSS to the WWTP context is suggested when multi-objective solutions are required for more effective management of the entire facility (Jiang et al., 2018). When it comes to pursuing the optimization of WWTPs, the MCDM technique in particular is one of the most powerful DSS.

82. In addition, MCDM-based DSSs are frequently combined with other DSSs to provide a more holistic solution to treatment problems (de Faria et al., 2015). For instance, Mannina et al. (2019) optimized the behavior of a membrane bioreactor pilot plant by coupling an integrated mathematical model with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) technique (G. Mannina et al., 2019). In order to determine the best treatment method and the most robust solution under influent uncertainties and stricter effluent limits, Castillo et al. (2016) combined a multi-criteria analysis (MCA) with an integrated mathematical model. This was done to generate a ranked shortlist of feasible treatments for three different scenarios, each of which involved a unique method of wastewater treatment (Castillo et al., 2016).

6.2.4 Intelligent DSS (IDSS)

83. The IDSS is a tool that integrates multiple methodologies, some from the Artificial Intelligence (AI) discipline and others from the fields of Statistics and Control Theory, to enhance the complicated decisions made by the final users of a WWTP. For instance, in order to avoid the adoption of sophisticated physical, chemical, and biological models, Nadiri et al. (2018) developed an IDSS that utilized supervised committee of fuzzy logic (SCFL) models as alternatives for the WWTP modeling. The fuzzy logic (FL) model predicts water quality parameters based on measurements derived from influent quality data, including pH, temperature, chemical oxygen demand (COD), biochemical oxygen demand (BOD), and total suspended solids (TSS). The SCFL model combines the water quality forecasts of individual FL models by using an Artificial Neural Network (ANN) (Nadiri et al., 2018).

6.3 Advantages and limitations of DSS approaches

84. Decision Support Systems for implementation of wastewater treatment plants offer several advantages when compared with traditional strategies. Figure 10 provides a schematic comparison between the two approaches: conventional versus DSS solutions. In principle, conventional solutions exhibit several limitations including (Giorgio Mannina et al., 2019):

a. Challenges in managing the great complexity of WWTPs owing to the interaction of different components and elements (biological, chemical, physical, mechanical, etc.);
b. Inadequate control, automation, and instrumentation in WWTPs to accommodate their dynamic nature;
c. Lack of a thorough analysis of all possible alternatives;
d. No prediction capability for probable alternative decision assessment; and
e. Inability to undertake extensive application of data-based models.

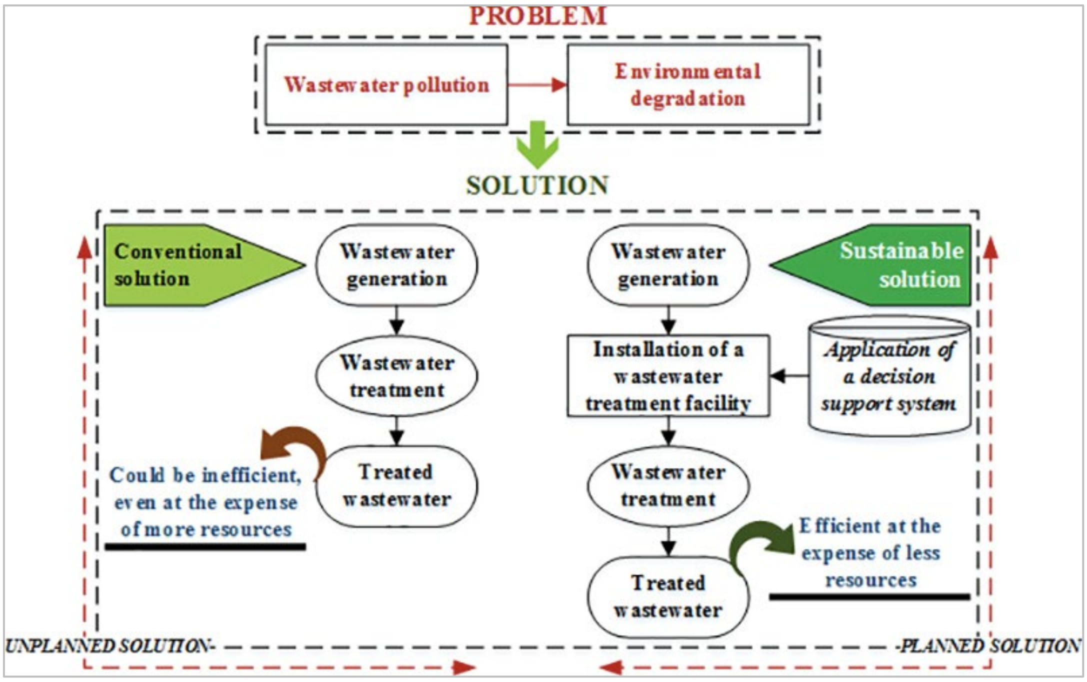


Figure 10: Decision support system for the selection of wastewater treatment technologies – conventional versus DSS solutions (Giorgio Mannina et al., 2019)

85. The four approaches adopted by the Decision Support Systems for implementation of wastewater treatment plants, namely life cycle assessment (LCA), mathematical model (MM), Multi-Criteria Decision Making (MCDM), and Intelligent DSS (IDSS) all have their own advantages and limitations which should be accounted for prior to selection for decision making. These aspects are manifested in the ability of these individual approaches to support decision-making in terms of quality, operational, design, energy, and sustainability issues. Specific advantages and limitations of each of the four approaches are illustrated in Table 4.

Table 4: Specific advantages for the various Decision Support Systems approaches for the selection of wastewater treatment technologies (Giorgio Mannina et al., 2019)

Aspects for consideration when selecting DSS approach	LCA	MM	MCDM	IDSS
Systematic development of alternatives	x	x	x	x
Alternative analysis forecasting capacities	x	x	x	x
Environmental impact assessment	x			
Making a comparison of plant layouts	x			
Cost and/or emission reductions		x		
Economic efficiency			x	
Laboratory-scale findings verification			x	
Application of data-driven methodologies				x
Application of model-driven methodologies				x
Integration of AI/statistical/control models				x

86. As can be inferred, DSS can be applied as a reliable tool for selecting appropriate treatment technologies in wastewater treatment plants. It can be equally employed in conjunction with the economic, environmental, health and social considerations for recovery of water, energy and fertilizers from wastewater treatment processes as tabulated in Table 3. All four DSS approaches provide for the systematic development of alternatives and support alternative analysis forecasting capacities. However, only the life cycle assessment approach allows the consideration of findings of environmental impact assessment and for making comparisons of plant layouts. On the other hand, intelligent decision support systems allow for application of data and model driven methodologies as well as artificial intelligence/statistical control methods.

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Annex I
Membrane treatment technologies

Introduction

1. Membrane technologies are considered the main and key technology for advanced wastewater reclamation and reuse strategies which allows reliable advanced treatment. Existing membranes can be classified as organic, inorganic, and inorganic-organic hybrid membranes based on the composition of the membrane materials. Examples of these organic, inorganic, and inorganic-organic hybrid membranes materials is presented in Figure A.1.

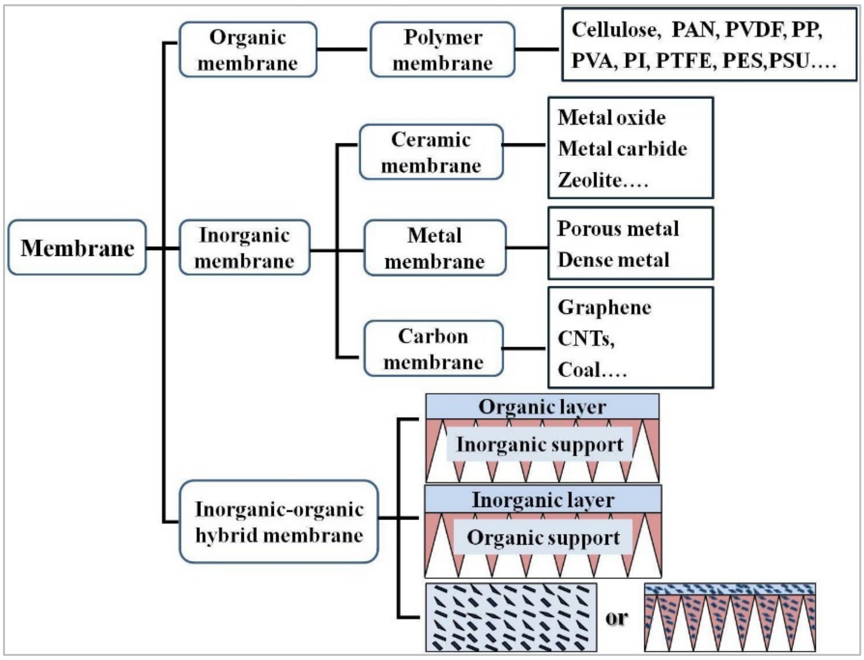

Figure A.1: Classification of membranes based on composition of membrane materials

2. Additionally, membranes could be also classified as isotropic and anisotropic membranes. Moreover, depending on the geometry of the membrane, it is possible to categorize the membranes as either flat sheet, tubular, capillary, or hollow fiber membranes. Each of these types of membranes is designed to be used for a specific engineering application.

3. Membrane technologies can be classified depending on their driving forces, which include osmotic pressure gradients, electrical potential, temperature, and hydraulic pressure. Wastewater is typically reclaimed and reused by the use of pressure-driven membrane separation technologies such microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) as explained below. Characteristics of pressure driven membrane processes are presented in Table A.1.

Table A.1: Characteristics of pressure driven membrane processes (Adapted from Singh & Hankins, 2016)

Membrane process	**MWCO (kPa)**	**Rejected size (µm)**	**Pressure requirement (bar)**	**Average permeability (L/m^2 h bar)**	**Rejected components**
MF	100-500	10^{-1}-10	0.5-3	500	Bacteria, fat, oil, grease, colloids, organics, microparticles
UF	20-150	10^{-3}-1	2-5	150	Proteins, pigments, oils, sugar, organics, microplastics
NF	2-20	10^{-3}-10^{-2}	5-15	10-20	Pigments, sulfates, divalent cations, divalent anions, lactose, sucrose, sodium chloride

Membrane process	MWCO (kPa)	Rejected size (µm)	Pressure requirement (bar)	Average permeability (L/m^2 h bar)	Rejected components
RO	0.2-2	10^{-4}-10^{-3}	15-75	5-10	All contaminants including monovalent ions

Microfiltration

4. MF membranes are of average pore radius 0.1-10 µm where transport in the process is driven by convective forces, and the target pollutants are separated by a sieving mechanism. Due to the large size of the pores, this membrane is used for rough separation of fine components with sizes between 0.025 and 10.0 µm. Therefore, in membrane-based separation and purification plants, MF is generally used as preliminary treatment stage. Although MF is frequently employed to decrease the load on UF, NF, or RO, the potential of fouling on this membrane is also quite significant. When an MF membrane module for wastewater treatment is implemented, residual macromolecules produce fouling through partial and total pore blockage (Pal, 2020).

5. The effect of membrane material on fouling is significant. Ceramic membranes are more susceptible to fouling than polymeric membranes. Again, the degree of fouling varies based on the polymer type among polymeric membranes. PES membranes are subject to more fouling than polyamide membranes. Ceramic MF membranes are superior to their polymeric equivalents when it comes to ease of cleaning, mechanical strength, disinfection, and service life. However, it is easier to fabricate polymeric membranes of various diameters for different modules than ceramic membranes. In cleaning and disinfection, ceramic membranes have a significant advantage over polymeric membranes because they are resistant to morphological change during chemical cleaning and thermal sterilization (Pal, 2020).

Ultrafiltration

6. Compared to MF, UF is utilized extensively in water treatment. Almost all kinds of water contaminants can be removed from water using UF, although to various degrees, if the pollutants' diameters fall within the range of 10-50 nm. This asymmetric membrane is characterized by a value known as the MWCO, which stands for the minimum molecular weight (in Dalton) of the molecules that are maintained by the membrane at a rate of 90%.

7. Concentration polarization is a significant challenge that arises when using UF membrane. In UF, the concentration polarization effect on flux demands the application of increasing pressure in order to maintain a constant flux. Manufacturers suggest acid-base cleaning cycles and back washing to help with membrane fouling. Even while ceramic UF membranes are simpler to clean and disinfect, polymeric UF membranes have fewer problems with fouling.

Nanofiltration

8. NF membranes are a fairly new technology that fills a gap between two well-known separation processes: reverse osmosis and ultrafiltration. One of the most interesting things about NF membranes is that they are capable of letting monovalent ions, like sodium chloride, pass through while preventing divalent and multivalent ions, like sodium sulfate. In order to reduce costs and enhance the environmental impact of wastewaters, NF could play a significant role in separating valuable compounds or removing a dangerous and undesired pollutant from liquid streams (Zhao et al., 2005). NF can be applied to the removal of dissolved minerals including hardness components, sulfates, nitrates, As, Ni, Cr, F, Fe, Mn, micro-inorganic and organic pollutants, pesticides, emerging contaminants, and disinfection by-products.

Reverse Osmosis

9. RO is well-known among pressure-driven membrane processes for its up to 99.5% separating small particles including microorganisms and monovalent ions such as sodium ions and chloride ions. RO has long been at the forefront of water reclamation through the treatment of wastewater. Pollution

of reused wastewater RO membrane is more challenging than RO membrane used for seawater desalination because of the dissolved organic matter in secondary effluent, which is made when biological wastewater is performed (Tang et al., 2014).

10. Tang et al. searched at the organic and inorganic forms of the deposits at different RO elements in full-scale municipal wastewater reclamation plants. On the surface of the RO membrane, the most commonly found elements were Fe, Ca, and Mg. Ca and Mg scaling could be prevented if the right antiscalants were injected. The reduction of certain specific fractions in the pre-treatment of the RO process may be beneficial in reducing membrane fouling (Tang et al., 2016).

Forward osmosis

11. Forward osmosis (FO) is a membrane separation technique that is neither pressure nor temperature driven. Under osmotic pressure, FO-based technology mimics the natural osmotic transport. When water contaminants cannot be easily removed from water due to their complicated nature, it is preferable to separate the water from the contaminants. Consideration has been given to the utilization of FO to reduce wastewater discharge for wastewater reuse and zero liquid discharge technologies. Furthermore, the utilization of FO to wastewater reclamation faces several key issues, including internal concentration polarization, reverse salt flux, concentration polarization, and membrane fouling (Jung et al., 2020).

Integrated Membrane Processes

12. Various combinations of these pressure-driven membrane technologies have been implemented in various wastewater treatment applications. This is applied to minimize fouling of the RO membrane and improve continuous flux maintenance. In addition, this functions as a multi-barrier treatment for removing pollutants from wastewater. In the majority of applications, MF, UF, and NF perform as RO pre-treatment phases. Rodriguez-Mozaz et al. studied on the performance of a pilot wastewater treatment system based on a MF–RO system that processed effluents of an urban wastewater treatment plant on-site (Rodriguez-Mozaz et al., 2015). The primary purpose of this work was to evaluate the viability of the MF–RO system for the removal efficiency of these contaminants, as well as to evaluate the suitability of the resulting water for numerous reuse applications.

Annex II

Effect of Wastewater Treatment Technologies on Removal of Contaminants of Emerging Concern

[Effect of primary treatment technologies on ECs removal

13. Because the efficiency of treating ECs using alternative physical processes, such as sedimentation and flocculation, has been reported to be less than 10%, the physicochemical process known as sorption has emerged as the major treatment technology of choice. The term "sorption" refers to the mechanisms of both the absorption of ECs onto the lipid fraction of the primary sludge through hydrophobic interactions and the adsorption of ECs onto the surface of sludge particles mostly via electrostatic interactions. Both of these mechanisms are included in the category of "sorption." Because sorption is a technology that changes phases, the ECs transfer from the liquid phase (wastewater) to the solid phase (sludge). As a result, it can only give a temporary reduction in risk, which is why it is crucial to remember that sorption is a phase changing technology. Because the ECs removal mechanisms are not entirely understood, these approaches need additional research. It is not known whether sorption comes before degradation or the other way around. On the one hand, sorption to biosolids may be a first stage in the biodegradation process; on the other hand, ECs may subsequently desorb upon achieving adsorption equilibrium and return to the liquid phase once biodegradation has begun.

14. The physicochemical properties of ECs, the features of the sorption medium, and the operating ambient conditions all play a role in how well ECs are absorbed by the sorption medium. The persistent ECs in sludge can leach out even more during sludge treatment and/or disposal, which is a big problem that requires a careful plan for sludge disposal. So, systems based on sorption can be combined with other treatment methods to get better results.

Effect of secondary treatment technologies on ECs removal

15. Biodegradation/biotransformation and sorption are the main mechanisms that ECs are removed by secondary treatment technologies. Other mechanisms, such as photodegradation and volatilization, don't have much of an effect on how well ECs are removed. Photodegradation-based EC removal isn't very important during secondary treatment because the amount of light is small compared to the amount of wastewater being treated, and highly concentrated particles in the wastewater block the sun. In the same way, the removal of ECs through volatilization during secondary treatment is not very important. Most places around the world use secondary biological treatment methods to get rid of ECs. Most conventional WWTPs use activated sludge processes (ASP), which are a type of secondary biological process. Other high-rate secondary biological processes include constructed wetlands, membrane bioreactors (MBRs), trickling filters, biological aerated filters (BAF), rotating biological contactors, moving bed biological reactors (MBBRs), fungal bioreactors, microalgal bioreactors, oxidation ditches, etc. In the sections, we'll talk briefly about the most common processes, like ASP and MBRs, which remove EC more effectively than other technologies.

Removal of ECs in Activated Sludge Process

16. The ability of the activated biomass that is already present in the sludge to biodegrade and bio-transform the ECs is essential to the functioning of the activated sludge process. The qualities of the ECs themselves (such as their structural complexity, bioavailability, and functional groups), the properties of the sludge (such as its age and biomass activity), and the operating circumstances all have a role in the biodegradation of ECs (redox potential, SRT, HRT). For instance, linear short chain unsaturated aliphatic compounds with electron-donating functional groups are more easily biodegradable than their counterparts, branched chain saturated polycyclic compounds with electron-withdrawing functional groups. This is because electrons are donated rather than withdrawn during the degradation process. In spite of the remarkable effectiveness with which ECs are removed by ASP, there are situations in which the toxicity of ECs toward microbes presents considerable obstacles, in particular when antibiotics are being administered. Since there is a knowledge gap in connection to the presence of ECs in the sludge due to the complex matrix and the lack of sensitive analytical techniques

to monitor ECs in sludge samples, the management of the secondary sludge that is produced during ASP (activated sludge process) is also another important issue to deal with. It is necessary to investigate the identification, measurement, and routine monitoring of reaction intermediates and transformation products of parent compounds. This is because transformation products can occasionally appear to be more harmful than the parent compounds and can revert back to them. In addition, the problems caused by the washout of biomass fraction in effluent, which leads to a low active biomass concentration and a relatively short SRT, need to be addressed in order to further improve the performance efficiency of the system. Therefore, the application of ASP in conjunction with various other treatment technologies may result in an improvement in the ECs removal efficiency.

Removal of ECs in membrane bioreactors

17. In recent years, membrane bioreactors have become increasingly popular for removing ECs from wastewater by combining the principles of biological degradation with membrane separation. The MBRs, which have evolved as an alternative treatment method to address the shortcomings of ASP, are highly effective at removing a wide variety of ECs that are notably challenging to remove using ASP or other secondary treatment technologies. Differential characteristics of MBRs, such as a longer SRT (15-80 days compared to 7-20 days in ASP), a higher biomass concentration mediated by membrane detainment, and a more significant separation between SRT and HRT with membrane retention of biomass/sludge, contribute to the system's superior EC removal efficiency. Physico-chemical parameters of ECs (size, concentration, func- tional group, charge, polarity), operating conditions, and membrane characteristics (surface roughness, surface charge, hydrophobicity, and membrane ma- terial) all play a role in the removal of ECs in MBRs (SRT, pH, temperature, and redox condition). Size exclusion, adsorption onto the membrane surface via electrostatic contact, sorption onto the biofilm layer/fouling layer generated on the membrane surface, followed by biodegradation, and hydrophobic interaction with the membrane are the primary methods by which ECs are removed in MBRs. However, biodegradation is the dominating method for removing polar ECs, while size exclusion, adsorption onto the membrane surface, or onto the biofilm layer (primarily ECs with a size smaller than membrane pore) are the primary mechanisms for removing nonpolar ECs. Additionally, UF MBRs are more effective at removing polar and hydrophilic ECs like estrone and ketoprofen than they are at removing non-polar hydrophilic ECs like phthalate.

18. There is a key drawback to MBR application in that it simply supports a separation process in which the ECs are just phase-changed but not actually removed from the environment. Permeate, a more dilute phase produced by the treatment process, and rejected effluent, a more concentrated phase produced by the ECs, are the two phases that result from the process. The concentrated phase must be processed further before being discarded. Alternative, sustainable methods of treating membrane concentrates are currently the subject of research. Sequential coupling of ASP with membrane filtration, which produced very high ECs removal efficiency, is one example. In this setup, the microorganisms in the activated sludge removed the ECs that were rejected by the membrane. Integration of membrane technology with bioelectrochemical systems (BES), also known as electrochemical membrane bioreactors, is another method (EMBR). By utilizing a three-pronged approach to treating wastewater (membrane filtration, biodegradation, and bioelectrogenesis; electricity generation by the microorganisms), EMBRs are said to be more efficient at removing ECs than MBRs and ASPs while using less energy. Most of these cutting-edge technologies, however, are still in the research and development (R&D) phase, at the pilot plant level. In addition, for future extensive usage at full scale, some constraints of MBRs such membrane fouling, high energy demand, and expensive membrane materials need to be addressed.

Effect of tertiary treatment technologies on ECs removal

19. In order to create high-quality discharge water for reuse, most WWTPs employ the tertiary or advanced treatment technologies as polishing techniques. The primary methods for EC removal during

tertiary treatment include oxidation (which can further mineralize ECs and their byproducts to CO2, H2O, and simple inorganic ions) and activated carbon (AC)-based sorption of a broad variety of ECs from secondary wastewater (de Oliveira et al., 2020). ECs can be oxidized using a variety of oxidation processes, including ozonation, ultraviolet (UV) treatment, chlorination, photocatalysis, etc. (Yang et al., 2017) Adsorption onto activated carbon, ozonation, and hybrids of these two processes are some of the most advanced methods for removing organic micropollutants (OMPs) from wastewater effluents (Guillossou et al., 2020).

Use of Ozonation for EC removal

20. Chemical oxidation of ECs using ozone (O3) gas is known as ozonation which is one of the most promising methods to significantly cut down on the ECs present in wastewater treatment plants (Hollender et al., 2009). It is possible for ozone to react with ECs in one of two ways: either directly, as a primary oxidant, or indirectly, via hydroxyl radicals (HO^-) generated as a by-product of ozone's reactivity with a subset of effluent organic matter (EfOM) such phenols and amines. Oxidation by-product formation is a major problem associated with ozonation. The mechanisms of ozonation, which inhibit the breakdown of ECs, are sensitive to pH, temperature, and ozone doses. Insufficient ozone dosages will result in the development of transformation products or oxidation by-products rather than full mineralization. In addition, it is necessary to consider drawbacks such as high energy consumption, the cost of the approach due to the short lifetime of ozone, and interference by HO• scavengers in wastewater (P. R. Rout et al., 2021).

Use of Activated Carbon Adsorption for EC Removal

21. Adsorption has also been widely explored for the removal of ECs due to its phase change mechanism, in which contaminants (adsorbates) transfer from the aqueous phase to the solid phase (adsorbent) (Rodriguez-Narvaez et al., 2017). Because of its high porosity, wide specific surface area, and, the high degree of surface contacts, active compounds (ACs) is the most commonly used adsorbent for a broad range ECs adsorption. Powder activated carbon (PAC) and granular activated carbon (GAC) are subcategories of AC based on particle size, whereas macroporous (50 nm), mesoporous (2-50 nm), and microporous (>2 nm) are subcategories based on pore size. Effective removal of ECs from wastewater may be achieved using both PAC and GAC, although mesoporous AC was determined to be the most appropriate due to lower interference from the organic components for the adsorption active sites. The adsorption efficiency is influenced by the characteristics of ECs (molecular size, polarity, functional group, KOW, Kd, pKa), AC (particle size, surface area, pore diameter, mineral content), and environmental conditions (pH, temperature, wastewater type). Compared to ozonation, the AC-mediated adsorption of ECs has the benefits of no by-product generation and reduced WWTP energy usage. However, there is a significant requirement for primary energy in the creation of AC. Therefore, the long-term viability of AC manufacturing is a major concern. For AC manufacturing, small-scale kilns are typically used, and these have a high energy input requirement because of their low efficiency. If AC is to be produced on a large scale, it is crucial to determine the most cost-effective and environmentally friendly methods of doing so, as well as to calculate the carbon footprint of the production process. Additionally, the primary difficulty in this process is providing proper treatment and disposal for the used adsorbents that have become saturated with ECs. In order to increase the efficiency with which ECs are removed, it has been suggested that AC adsorption be used in combination with other treatments such as ultrafiltration and coagulation (P. R. Rout et al., 2021).]

Appendix II
Regional guideline on pre-treatment standards and applicable BATs for industrial sectors eligible to discharge to urban wastewater collection system

Table of Contents

Pages

List of Abbreviations / Acronyms

BAT	Best Available Techniques
BEP	Best Environmental Practices
BOD5	Biochemical Oxygen Demand
BREF	BAT Reference Documents
COD	Chemical Oxygen Demand
COP	Conference of the Parties
EIPPCB	European IPPC (Integrated Pollution Prevention and Control) Bureau
ELV	Emission Limit Value
FAO	Food and Agriculture Organization
IPPC	Integrated Pollution Prevention and Control
LBS	Land Based Sources
MED POL	Mediterranean Pollution Control and Assessment Programme
N	Nitrogen
NBB	National Baseline Budget of Pollutants
OIZ	Organized Industrial Zones
P	Phosphorus
p.e.	Population Equivalent
PRTR	Pollutants Release and Transfer Register
SME	Small & Medium Enterprises
SS	Suspended Solids
TDS	Total Dissolved Solids
TS	Total Solids
UNEP/MAP	United Nations Environment Programme /Mediterranean Action Plan
UO	Unit Operation
UWWTP	Urban Wastewater Treatment Plant
WWTP	Wastewater Treatment Plant

7. Introduction

87. This guideline is prepared under Article 7 of the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-Based Sources (LBS Protocol), which stipulates that "the Parties shall progressively formulate and adopt, in cooperation with the competent international organizations, common guidelines and, as appropriate, standards or criteria dealing with (1.b) special requirements for effluents necessitating separate treatment; and (1.e) specific requirements concerning the quantities of the substances listed in annexes I and II discharged, their concentration in effluents and methods of discharging them."

88. In this context, in accordance with Article 15 of the LBS Protocol, the Regional Plan on Urban Wastewater Treatment (referred to hereafter as the Regional Plan) which was adopted by COP 22 (Antalya, Türkiye 7-10 December 2021) entered into force on 26 July 2022. In its Article V.III pertaining to measures on industrial wastewater discharge, Paragraphs 15 and 16, the Regional Plan stipulates:

> *By 2025 at the latest, the Contracting Parties shall ensure that the competent authority or appropriate body adopt emission limit values appropriate to the nature of industry discharging industrial effluents to collecting systems connected to urban WWTPs.*
>
> *By 2035 at the latest, the Contracting Parties shall ensure that industrial wastewater discharged into collecting systems and urban WWTPs shall meet, as a minimum, the emission limit values set in Appendix I.C.*

89. In Article VI of the Regional Plan, addressing aspects related to facilitating the effective implementation of the measures, Paragraph 18 stipulates that "the Contracting Parties collaborate in preparing and implementing common technical guidelines."

90. It is in the framework of Article 7 of the LBS Protocol, as well as Articles V and VI of the Regional Plan that the "Regional Guidelines on Pre-treatment Standards and Applicable BATs for Industrial Sectors Eligible to Discharge to Urban Wastewater Collection Systems" is prepared. Three key objectives are intended from this Guideline. These are iterated in Article IV of the Regional Plan under Paragraph 5, Clause (iv) which states:

> *Industrial wastewater entering collecting systems and WWTPs are subject to pre-treatment, if necessary, in order to:*
>
> *a) protect the collecting systems and the treatment plant;*
> *b) ensure that the operation of the WWTP and the treatment of the sludge are not impeded; and*
> *c) ensure that discharge effluents do not adversely affect the Mediterranean marine environment, particularly for priority substances, contaminants of emerging concern which are harmful to the receiving waters and cannot be treated in urban WWTPs.*

91. To achieve these objectives, the current Guideline aims to provide relevant information and knowledge on application of BAT and implementation of BEP to enable industrial facilities to meet the pre-treatment effluent standards which set the emission limit values (ELVs) for discharge of industrial wastewater into collecting systems and urban wastewater treatment plants as stipulated in the Regional Plan on Urban Wastewater Treatment (Appendix I.C) [reproduced in this guideline in Annex I].

92. The Guideline also supports the regulatory authorities on establishing monitoring programmes for industrial discharges and for setting permitting requirements for industrial facilities, as well as identifying "light industries" which are eligible to discharge safely to collecting systems without causing perturbance to the influent of Urban WWTPs. Moreover, the current Guideline provides the regulatory authorities information on managing Organized Industrial Zone (OIZs) which are discharging to collecting systems. OIZs have been introduced to the amended Annex I of the LBS Protocol, which was adopted by COP22 (Antalya, Türkiye, 7-10 December 2021).

93. This Guideline is organized in four sections:

a. Feasibility of pre-treatment of industrial effluents. This section is intended to assist operators of industrial facilities to assess the pre-treatment option which is most economically viable and technically feasible and affordable for meeting effluent standards for discharge of industrial wastewater into collecting systems and urban wastewater treatment plants.

b. Permitting requirements for industries to discharge pre-treated wastewater. This section provides information to both industry owners and operators of urban wastewater treatment plants on aspects related to applying, reviewing and granting permits to discharge further to pre-treatment of industrial effluents.

c. Monitoring of effluents from industrial facilities. This section provides the knowhow to industry operators for designing the monitoring programme to better assess the performance of industrial pre-treatment facilities prior to any discharge of hazardous and other pollutants into urban collecting systems that would result in the malfunctioning of the urban wastewater treatment plants.

d. Best Available Techniques (BAT)/Best Environmental Practices (BEP) for the pre-treatment of industrial effluents to be applied on-site as well as off-site (end-of-pipe techniques) taking into account the particular conditions in the Mediterranean Region in order to meet standards for discharge of industrial wastewater into collecting systems and urban wastewater treatment plants.

8. Feasibility for pre-treatment of industrial effluents

94. Although all industrial facilities can theoretically be connected to urban wastewater treatment plants, there are specific technical and economic constraints which make the installation of pre-treatment facilities economically unaffordable to meet the relevant requirements that prescribe a level of pre-treatment up to raw municipal wastewater composition. This is particularly relevant to the removal of hazardous substances that require the application of complex techniques associated with high investment/operational costs that cannot easily be covered especially by SMEs. Several factors come into play where pre-treatment can be feasible for a particular industrial process. These include effluent composition and related type of industrial process; pollution loads and related size of the industrial operation; and discharge of industrial effluents directly to a municipal sewage network or further to treatment in a centralized industrial wastewater treatment plant situated in an Organized Industrial Zone (OIZ).

8.1 Effluent composition and type of industrial process

95. In principle, industries which do not require extensive pre-treatment of their effluents are those which discharge pollutants which do not adversely affect the operation of urban wastewater treatment plants. The pollutants are mostly of organic nature like those discharged from human/urban activities. These include total solids (TS), suspended solids (SS), nitrogen (N), phosphorus (P), grease and BOD5. These industries do not discharge significant loads or high concentrations of harmful substances such as heavy metals, phenols, cyanides, etc.; therefore, they are best characterized as "light industries."

96. On the other hand, industries such as metal processing (e.g. electroplating, accumulators manufacture, copper smelting etc.), which are common in the Mediterranean Region, cannot discharge their effluents into urban wastewater treatment plants. A quick glance at the adopted emission limit values for discharge of industrial wastewater into collecting systems and urban wastewater treatment plants as stipulated in Appendix I.C of the Regional Plan for Urban Wastewater Treatment (reproduced in Annex I of this guideline) show that heavy metals standards (ELV) are stricter than those prescribed in most Mediterranean Countries. As a result, pre-treatment is not economically feasible, and consequently metal industries are not characterized as "light industries."

97. Typical examples of light industries from the Mediterranean can be inferred from the list of industrial sectors and subsectors listed under the National Baseline Budget (NBB) Classification System which applies to all Mediterranean Countries.[5] A correlation to this list can be also deduced for the sectors and subsectors under the European Pollution Release and Transfer Register (E-PRTR) Classification System.[6] A common list of light industries correlating both NBB and E-PRTR is presented in Table 1.

Table 1: Light industries according to correlation between NBB/E-PRTR Classification

NBB Classification		**E-PRTR Classification**	
Sector	Sub-sector	Sector	Sub-sector
4. Farming of animals	11. Farming of animals (cattle, sheep, swine, poultry) and slaughterhouses 12. Farming of special animals (rabbits, goats, horses, asses, mules and hinnies, other)	7. Intensive livestock production and aquaculture	(a) Installations for the intensive rearing of poultry or pigs (b) Intensive aquaculture
5. Food packing	13. Animal feeds 14. Animal raw materials, vegetable raw materials 15. Dairy industry 16. Manufacture of beer 17. Manufacture of non-alcoholic beverages 18. Manufacture of olive oil 19. Manufacture of other vegetable oils (other than olive oil) 20. Manufacture of sugar beet 21. Manufacture of wines and spirits 22. Other prepared foods 23. Preserving fruit and vegetables	8. Animal and vegetable products from the food and beverage sector	(a) Slaughterhouses (b) Treatment and processing intended for the production of food and beverage products from: (i) Animal raw materials (other than milk) (ii) Vegetable raw materials (c) Treatment and processing of milk
6. Port Services	76. Gasoline Loading 77. Port handling (cargo)		
21. Building and repairing of ships and boats	8. Drydocks 9. Shipyards		

[5] UNEP/MED WG.473/12: Introduction to Pollutant Release and Transfer Register (PRTR) and Guidelines for Reporting MEDPOL PRTR Implementation Guide - Appendix X (Istanbul 29-31.5.2019)
[6] EU Regulation No 166/2006 (establishment of E-PRTR)

NBB Classification		E-PRTR Classification	
Sector	Sub-sector	Sector	Sub-sector
8. Agriculture	1. Growing of cereals (wheat, rice, maize, soybeans, other) 2. Growing of fruit and vegetables 3. Horticultural specialties, nurseries 4. Industrial crops (cotton, tobacco, sugar cane, sugar beet, potatoes, other) 5. Manufacture of wines		
13. Aquaculture	6. Fish breeding 7. Fish processing		
14. Management of urban solid waste	24. Waste dumps	5. Waste and wastewater management	(b) Installations for the incineration of non-hazardous waste (c) Installations for the disposal of non-hazardous waste (e) Installations for the disposal or recycling of animal carcasses and animal waste
25. Waste incineration and management of its residues	97. Urban waste incineration plants		
26. Waste management activities	98. Refuse collection, depollution and similar activities		
31. Treatment of sewage sludge	94. Compost production		
18. Manufacture of other inorganic chemicals	48. Industrial gases 49. Manufacture of ceramic products 50. Manufacture of glass and glass products	3. Mineral industry	g) Installations for the manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain
20. Tourism	85. Hotel, food and beverage services 86. Recreational activities		

98. As can be seen, light industries may include food/drinks processing sectors (animal and vegetable products from the food and beverage sector, milk processing, beer/wine production etc.), farming of animals, agricultural activities etc. Infrastructural installations such as waste management and recreational activities (tourism) are sectors which can also be connected to urban wastewater treatment plants.

8.2 Pollution load and size of the industrial operation

99. Another factor enabling the connection to urban wastewater treatment plants is the production size of the industrial facility. In principle, industrial plants with moderate amounts of discharged wastewater that do not adversely affect the equilibrium of the biological/aerobic processes in urban wastewater treatment plant can be characterized as "light industries," and as such, they can discharge to collecting systems further to pre-treatment of their effluents.

100. Large industrial facilities discharging heavy loads of pollutants, even though they do not contain contaminants such as heavy metals in their wastewater effluent, are not considered "light industries," and hence may not be feasible from an economic perspective for pre-treatment.

101. Industrial facilities discharging small quantities of contaminants (e.g. manufacture of glass, ceramic products, etc.), regardless of their size, may be allowed to discharge their industrial effluents into urban wastewater treatment plants provided their effluents undergo pre-treatment meeting the local standards/regulations for discharging to public sewage system, and do not contain significant amounts of contaminants.

102. A "rule of thumb" about the size of industries allowed to discharge to urban wastewater treatment plants can be inferred from the EU Directive 91/271/EEC (the Wastewater Directive). Further to Article 13 of the Directive, a threshold value of 4,000 population equivalents (p.e.) for discharge of biodegradable effluents directly into water recipients i.e. sea, lake, river (and not to WWTP) is indicated. This limit value corresponds to a biochemical oxygen demand (BOD5) of 240 kg/day.[7] Consequently, it can be inferred that industries with less than 240 kg of daily discharge of BOD5 can be considered potentially suitable, size wise, to be connected to urban wastewater treatment plants.

103. In this regard, it should be noted that permissible loads and concentrations limits are defined by the operator of the urban wastewater treatment plant as prescribed in its relevant regulations. These regulations differ from one plant to another depending on the size and type of operation of the wastewater treatment plant as well as the environmental conditions of the final water recipient (sea, lake, river).

8.3 Organized Industrial Zones (OIZ)

104. In the Mediterranean Region, the concept of Organized Industrial Zones (OIZ) has been adopted in recent years where centralized treatment installations undertake the pre-treatment of effluents before their discharge to urban wastewater treatment plants; and in some cases, directly to water recipients further to full treatment of effluents. The OIZs have been included and agreed the updated LBS Annex I (A), Sector of Activity, which were adopted by COP 22 (Antalya, Türkiye 7-10 December 2021). Specialized OIZ have been also introduced for specific industrial sectors (e.g. tanneries) where the industrial wastewater treatment plant is developed to undertake a "tailor made" treatment of specific industrial effluents.

105. In both cases of specialized and general OIZ, the wastewater treatment plant operators ask for specific pre-treatment requirements from individual industries to be connected with the wastewater treatment plant, especially when new facilities want to join the OIZ. These requirements are typically stipulated in the permitting process (explained in the next section) and are necessary in order to safeguard the plant's efficient operation, particularly when a biological treatment unit is foreseen as the central treatment unit of the OIZ and there are fears of its malfunctioning due to overloads of pollutants such as heavy metals.

106. Pre-treatment standards for OIZ wastewater treatment plants have been averaged from several country standards in the Mediterranean. These are presented in Table 2 along with a comparison with the standards for connecting to urban wastewater treatment plants as stipulated in the Regional Plan (reproduced in Annex I). As can be seen, permissible concentrations of heavy metals are generally

[7] Calculated based on 60 g/day per p.e.

stricter if an industry discharges its effluents directly to an urban wastewater treatment plant. Therefore, it is advisable when decisions about the establishment of OIZ are taken to re-allocate metal processing industries to an OIZ where the relevant pre-treatment standards can be easily met.

107. Further to the data shown in Table 2, it can be inferred that pre-treatment of industrial effluents in Organized Industrial Zones is more feasible and easier to manage in comparison with individual pre-treatment facilities of industrial installations. Within an OIZ setting, meeting of effluents pre-treatment standards is much less complicated and less costly in comparison with individual pre-treatment units discharging industrial wastewater to municipal collecting system.

Table 2: Pre-treatment standards for discharge to wastewater treatment plants in OIZ in comparison to direct discharge to urban wastewater treatment plants

Parameter	**Pre-treatment standards from OIZ regulations** [8]	**Standards for discharge of industrial wastewater into collecting systems and urban wastewater treatment plants**
Aluminium – Al (mg/l)	10	25
Arsenic – As (mg/l)	0.5 - 3	0.1
Beryllium - Be (mg/l)	30	0.5
BOD5 (mg/l)	350 – 500	COD concentration not to exceed four times BOD concentration
Cadmium – Cd (mg/l)	0.5 - 2	0.1
Chromium – Cr^{3+} (mg/l)	2	-
Chromium – Cr^{6+} (mg/l)	0.5	0.5
Cobalt - Co (mg/l)	10	1
COD (mg/l)	1000 – 1200	2000
Copper – Cu (mg/l)	1 - 5	0.5 - 1
Cyanide (mg/l)	3 – 10	0.2 - 0.5
Detergents (mg/l)	50	-
Fluoride – F (mg/l)	6	-
Lead – Pb (mg/l)	5	0.5
Manganese – Mn (mg/l)	10 – 20	1
Mercury – Hg (mg/l)	0.01 – 0.2	0.05
Mineral Oil (mg/l)	15	20
Molybdenum – Mo (mg/l)	10	0.15
Nickel – Ni (mg/l)	5 – 10	0.5
Nitrite NO_2–N (mg/l)	4	-
Nitrates NO_3–N (mg/l)	20	-
Oil & Grease (mg/l)	40 - 100	-
pH	6 - 9	6 - 10
Phenols (mg/l)	5 – 10	3
Phosphates – P total (mg/l)	10	-
Sulfites SO_3 (mg/l)	1	-
Sulfates SO_4 (mg/l)	1,500 – 1700	-
Suspended solids (SS) (mg/l)	350 – 500	-
Temperature (°C)	35 – 50	40
Total dissolved solids (TDS) (mg/l)	3000	3500
Total N (mg/l)	100	15 - 30

108. In this regard, it must be noted that effluents from OIZ treatment plant have to meet the same pre-treatment standards as the individual industries when connected to urban wastewater treatment plants. And in case of direct discharge into a water recipient, the effluents from an OIZ treatment plant should be subject to full treatment.

[8] Examples from regulations of OIZ WWTP in Mediterranean countries

109. In conclusion, the pre-treatment or full treatment of industrial effluents within an OIZ provides clear advantages to individual treatment installations, namely:

a. Temperature and pH adjustment are facilitated due to mixing of various effluents which can also lower the concentration of pollution loads originating from similar industrial activities (dilution effect);
b. More effective use of equipment and chemicals; thus, allowing the decrease of the operating costs;
c. In case of biological treatment, the WWTP operations within an OIZ offer better balance, mixing of flows and aerobic conditions which can be more effectively controlled/monitored compared to individual facilities;
d. Sludge treatment can be better managed by centralized installations
e. It is more cost effective and easier to monitor the compliance;

9. Permitting requirements for industries to be connected to wastewater treatment plants

110. In principle, all industrial installations must possess an environmental permit issued by national or regional regulatory authorities where all details about their operation, effluents characteristics, pre-treatment/ treatment requirements and installations are clearly described. In this section, focus is provided on permitting for discharge of *pre-treated effluents* to urban sewer networks, urban wastewater treatment plants or industrial wastewater treatment plants within organized industrial zones.

9.1 Applying for a discharge permit by an industrial facility

111. In order to be allowed to discharge its effluents, an industry has to prove that it meets the pre-treatment requirements set by the relevant treatment plants operators. The fulfilment of these requirements can be part of the overall environmental permit of the industry or a “stand alone” document according to the regulations of the treatment plants operator.

112. An application for a permit to discharge can refer to a *new* facility which wishes to be connected or an existing industrial installation which must submit a *renewal/revision* application after a certain period of time, and/or if changes are made to the production process affecting the wastewater composition and/or quantity.

113. The application serves on the one hand to allow the treatment plant operator to become acquainted with the production process and the associated types/quantities of pollutants to be discharged. It also allows the industrial facility operator to design the subsequent monitoring programme with a focus on the crucial parameters to be monitored and reported on associated with the industry’s operation.

114. The application for a permit should be prepared by the industrial operator and submitted to the competent regulatory body before connection to the collection system leading to the urban wastewater treatment plant. It is recommended that the operator of the industrial facility provides as part of the permit application the following information:

a. The industry’s production process (raw materials, products, use of water/energy) – average production and peaks.
b. Detailed assessment of sources of wastewaters generation.
c. Types and quantities of wastewaters from each source.
d. Pre-treatment technologies to be applied to meet the pre-treatment standards for connection to the WWTP and fate of any solid wastes (e.g. sludge) resulting from pre-treatment.
e. Description of the effluent well (equipped with water meters for checking the effluent quantities) at the point of discharge into the wastewater treatment plant.
f. Contingency plan for emergency situations, where applicable.
g. Statements about:

i. Separation of the industrial from the municipal wastewaters generated in the facility (to be mixed after the effluent well).
ii. Frequency of measurements of the wastewater composition.
iii. Segregation of wastewater streams (except in cases of pre-treatment requirements, e.g. neutralization) before discharge to the treatment plant.
iv. Measures in place to prevent dilution of wastewaters.
v. Segregation of collected stormwaters and their diversion away from the treatment plant.
vi. Actions taken to ensure that substances such as radioactive materials, substances with autoignition potential and explosives are not contained in the effluent wastewater.

9.2 Reviewing and granting permits to discharge

115. In order to assess which industries can be connected to the treatment plant's collection network and associated risks, it is recommended that the urban wastewater treatment plant (or OIZ treatment plant) operator undertakes the following:

a. An inventory of industrial facilities connected/requesting permission to connect to the treatment plant. The inventory should focus on the types of expected effluents (i.e. which industrial processes discharge pollutants which can adversely affect the plant's operation); the size of the industries (i.e. with a focus on larger units); and associated risks on the operation of the treatment plant (i.e. focus on critical parameters). The inventory would give the treatment plant operator an insight into the overall situation of discharged effluent, providing a comprehensive overview of influent wastewater classification to be treated. This ensures the optimization of the working conditions of the treatment plant, as well as setting the upper limits of pollutants loads that the plant can safely treat.
b. Review of discharge permits with a focus on submitted/approved permits and the relevant registers (maintained by the authorities and the industries associations). This review would help to highlight "free riders" (i.e. industries which operate and/or are connected to the sewage network without the relevant permits).
c. Field visits to selected (high risk) industrial facilities to review records of samples taken by the industrial facility, and in their absence or in case of doubt of results, to undertake on the spot counter-samples. Sampling should focus on the crucial parameters to be emitted by the industry and which can affect the operation of the wastewater treatment plant. To avoid misunderstandings and controversies, sampling should be performed in the presence of representatives from the industrial facility. Sampling and analysis should be conducted by a certified independent chemical laboratory.

116. It must be noted that an urban wastewater treatment plant operator has a more difficult task to assess the industries to be connected to the plant than the operator of a treatment plant set in OIZ. In an OIZ setting, the number of industries connected to the treatment plant is limited. In case of urban wastewater treatment plants connected to public sewage systems of urban agglomerations, several industrial facilities and SMEs are also connected. These are typically spread over a large catchment area discharging their effluents to the treatment plant; sometimes without a prior notice.

117. An industrial facility may be denied connection by treatment plant operators if, in their opinion, the respective effluents can cause a deterioration of the environmental status of the receiving water body and/or, adversely affect the smooth operation of the wastewater treatment plant.

118. On the other hand, some industrial facilities including light industries, may be waived the requirement to apply for a permit to discharge or to undertake pre-treatment of their industrial effluents under the following conditions:

a. No harmful substances are contained in their effluents such as heavy metals, phenols, cyanides and the other substances listed in Table 1 (except BOD5, SS, TDS);
b. Wastewater generation from the industrial facility is in the range of 2 to 4 m^3/day.

c. Discharged wastewater is of similar characteristic to the urban wastewaters (i.e. small/medium BOD5/COD/SS loads).
d. Industries dealing with final finishing or packing of products (i.e. no generic production process).
e. Commercial activities such as car washing, clothes cleaning/dry-cleaning etc.

10. Monitoring of effluents from industrial facilities

119. A programme for monitoring of critical pollutants discharged in pre-treated effluents from industrial facilities should be established by the facility operator to safeguard in part the smooth operation of the wastewater treatment plants. The programme should include the parameters to be monitored and the frequency for sampling

120. The monitoring programme is one of the permitting requirements between the industrial facility and the regulatory authorities; as such, it is case specific. The key pollutants discharged further to pre-treatment of industrial effluents should be specified in the permit between the industrial facility and the treatment plant operator, as well as the frequency of their monitoring. In any case, industry specific parameters (e.g. $Cr^{3+/6+}$ from tanneries) should be part of the monitoring programme.

10.1 Parameters for monitoring

121. Appendix I.C of the Regional Plan for Urban Wastewater Treatment provides guidance on potential parameters for monitoring in industrial wastewater at the point of discharge to collecting systems and urban wastewater treatment plants.

122. With regards to light industries, for which pre-treatment is economically feasible, the following potential parameters presented in Table 3 should be monitored.

Table 3: Potential parameters for monitoring in industrial wastewater at the point of discharge to collecting systems leading to urban wastewater treatment plants[9]

Industrial Activity	Parameters for monitoring
Domestic and communal wastewater (function halls, restaurants, shopping malls, Hotels etc.);	BOD, COD, pH, TSS, Total Oil & Grease, Cl, Na, Boron, Detergents
Food Sector - Animal and vegetable products	COD, pH, TSS, Total Oil & Grease, [Heavy Metals], Cl, Na, Total N, Total P, Polyphenols, Phenols
Food Sector - Meat industry & Fish processing	BOD, COD, pH, TSS, Total Oil & Grease, Cl, Na, Total N, Total P, Polyphenols, Phenols
Laundry Facilities	COD, pH, VSS, TSS, Cl, Na, Boron, [Total Hydrocarbons], Detergents
Gas stations	COD, pH, Mineral Oil, BTEX, MTBE
Agriculture: chicken farms, pig farms, fish farms, etc.	[BOD,] COD, pH, TSS, Cl, Na, Total N, Total N, Boron
Waste and wastewater management	BOD, COD, pH, VSS, TSS, Mineral Oil, Total oil & Grease, Heavy Metals, Total N, Total P, Cl, BOD, Total Hydrocarbons, Toxicity to fish eggs (T_{egg})

[9] Data obtained from Appendix I.C of the Regional Plan for Urban Wastewater Treatment

123. The monitoring programme should ensure that sufficient data and information is generated to detect any malfunctioning in the pre-treatment installations in order to avoid any penalties imposed in the permit by the treatment plants operators.

124. It is the responsibility of the industrial facility to carry out the monitoring programme on the quality of the discharged effluents and to report back to the treatment plant authorities. Usually, industrial facilities are required to maintain a composite sampling register which covers the working period of the installation. The register should be made available to the controlling authorities (treatment plant operator and governmental inspection authorities) at request.

125. The industrial facility should maintain its own effluent well where samples can be taken. All wells have to be equipped with flow meters to check the compliance of the wastewater quantities with the issued permits.

10.2 Frequency of sampling

126. Appendix III of the Regional Plan for Urban Wastewater Treatment provides guidance on monitoring frequencies of pollutants discharged from industrial facilities to collecting systems.

127. In principle, monitoring frequencies need to be selected in a manner to characterize the effluent quality and to detect events of noncompliance, considering the need for data and, as appropriate, the potential cost.

128. Monitoring frequency should be determined on a case-by-case basis, considering the variability of the concentration of various parameters. A highly variable discharge should require more frequent monitoring than a discharge that is relatively consistent over time (particularly in terms of flow and pollutant concentration). Start-up/first year of operation and sudden increase of pollutants' concentrations in the treatment facility would warrant increased frequency.

129. Frequency requirements may be on the other hand reduced based on a demonstration of excellent performance. Facilities can demonstrate good performance by meeting a set of compliance and enforcement criteria and demonstrating their ability to discharge pollutants below the necessary levels consistently.

130. A minimum sampling frequency for the discharge effluents may be introduced in accordance with Table 4.

Table 4: Recommended sampling frequency per year for industrial wastewater at the point of discharge to the collection systems leading to urban WWTP[10]

Industrial Activities	Sampling frequency/year
[Domestic and communal wastewater (function halls, restaurants, shopping malls, hotels etc.)	4
Food Sector - Animal and vegetable products	4
Food Sector - Meat industry & Fish processing	4
Laundry Facilities	4
Gas stations	4
Agriculture: chicken farms, pig farms, fish farms, etc.	4
Waste and wastewater management	Waste – 4 Hazardous waste – 6]

131. All samples taken from the effluent well should be counter checked by the treatment plant operator and should be analyzed by accredited independent laboratories to avoid disputes over the results.

[10] Data obtained from Appendix III of the Regional Plan for Urban Wastewater Treatment

11. Best Available Techniques (BAT)/Best Environmental Practices (BEP) for the pre-treatment of industrial effluents

132. Best Available Techniques (BAT) and Best Environmental Practices (BEP) included in this section apply mainly for the particular conditions in the Mediterranean. They are developed based on experiences acquired and documented from other regions while taking into consideration the financial implications for investing in environmental protection.

133. There are two types of Best Available Techniques (BAT) and Best Environmental Practices (BEP) which can be considered for the efficient treatment of industrial wastewaters with the aim to meet pre-treatment standards set by WWTP operators:

a. On-site techniques.
b. End-of-pipe technologies.

11.1 <u>On-site techniques</u>

134. On-site techniques are meant mainly for simple methods to be applied within the industrial facility aiming at the reduction of water consumption in the production process and the rational use of raw materials and water. This would result in less generated wastewater quantities and smaller pollution loads; thus, easier and more cost-effective pre-treatment options (i.e. end-of-pipe techniques).

135. On-site techniques evolve from a detailed knowledge of the production process and can be defined further to analysis and assessment of each process Unit Operation (UO) through a mass balance sheet as shown in Figure 1. This analysis would allow the identification of those production steps in which extensive use of water and/or of raw materials and chemicals occurs and hence their reduction.

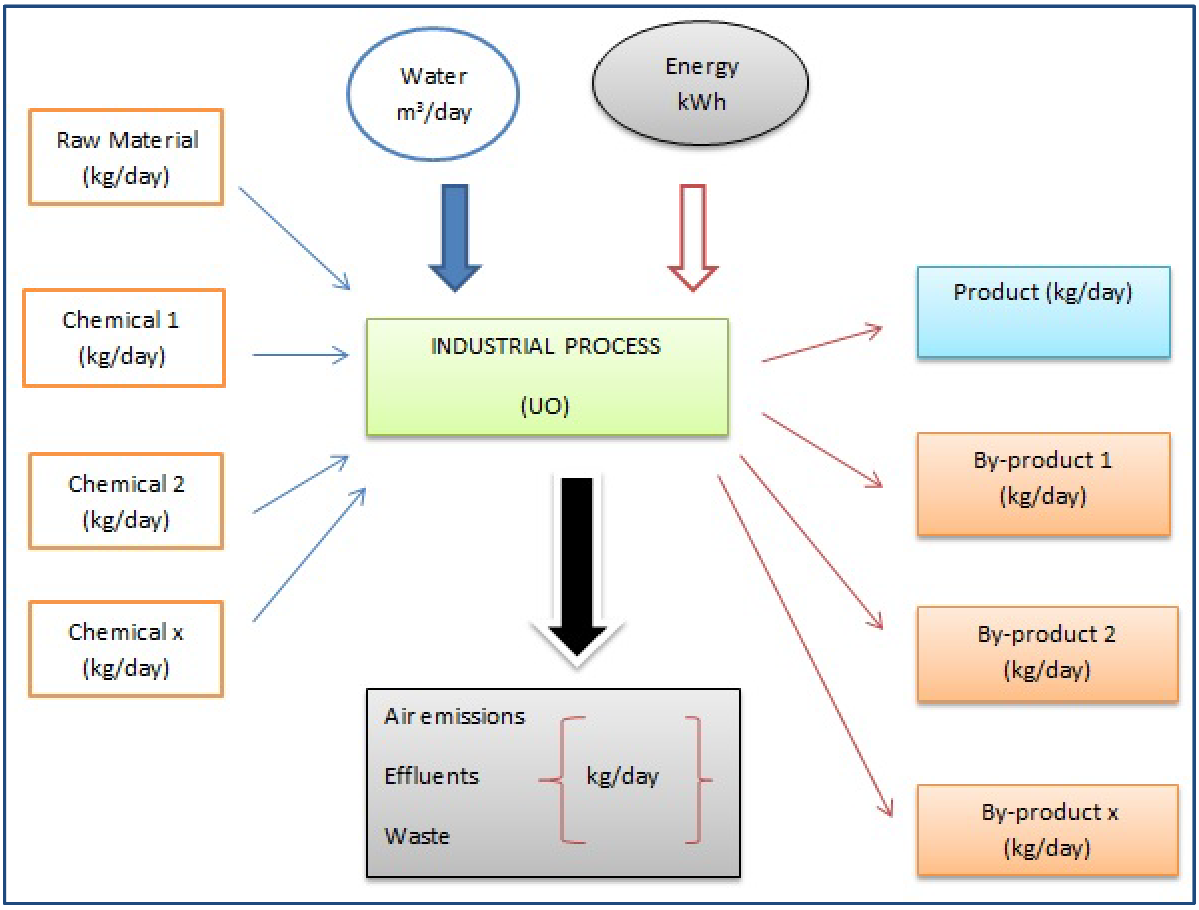

Figure 2: Mass balance sheet for a process unit operation

136. On-site techniques are sector specific, i.e. they refer to those UOs which are applicable in a specific sector (e.g. food processing industry); however, there are some general patterns which are universally applicable in industrial sectors; for example, re-use/recycling of process/cooling waters. These techniques are typically simple mostly focusing on good housekeeping practices.

137. The following list of BAT/BEP on-site techniques are mostly derived from the European experience as reflected in the BAT Reference Documents (BREF) prepared by the European Integrated Pollution and Prevention Control Bureau (EIPPCB). The IPPCB collects and evaluates BAT/BEP applicable not only in European countries but also worldwide.

11.1.1 Segregation of wastewater streams

138. A full segregation of the various wastewater streams originating from a single industrial facility has to be envisaged in order to allow a better performance of treatment interventions on case-by-case basis. The streams for which separate drainage systems are recommended to be installed are:

a. Stormwater;
b. Utility and support system water including cooling water;
c. Sanitary wastewater;
d. Wastewater containing organic (biodegradable) pollutants, where possible;
e. Wastewater containing inorganic pollutants (e.g. heavy metals), where possible; and
f. High salinity wastewater.

139. This segregation allows for a targeted treatment at the lowest possible cost whereas some streams such as sanitary wastewater and wastewater with biodegradable components can be directly discharged into the wastewater treatment plant.

140. Buffering facilities for the organic and inorganic wastewaters allow for the equalization of peak flows as well as of variations in flow and levels of concentrations on a daily/weekly basis.

11.1.2 Counter-current extraction/washing of raw materials and/or products

141. Multiple batch washings are usually applied in sectors such as food processing where the raw materials are repeatedly washed. A counter-current extraction (i.e. initial washing with waters from previous washings) allows the drainage of concentrated wastewaters which can be more effectively treated as depicted in Figure 2.

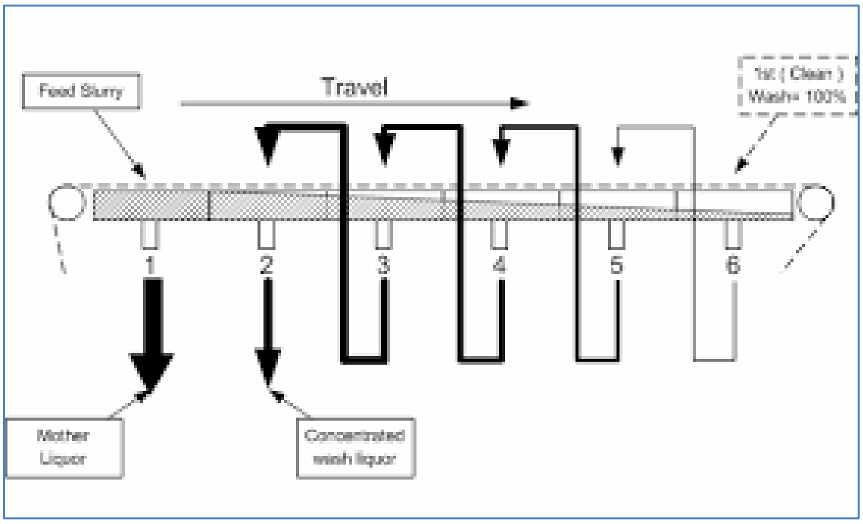

Figure 3: Counter-current washing[11]

[11] BREF Food, Drink, Milk industries (also Tables 6, 7, 8)

11.1.3 Multiple use/recirculation of water

142. Waters from equipment washing, distillates from the production, open circuit cooling waters, waters from air cleaning can be re-introduced in the production process provided that their composition does not negatively affect the production process. It is a simple good housekeeping technique; thus, allowing the reduction of the overall water consumption.

11.1.4 Dry transport of solid materials

143. The avoidance of the use of water for the transport of various solid materials especially in the food processing industry is a good housekeeping method for the reduction of wastewaters quantities. Some indicative examples are tabulated in Table 5.

Table 5: Good housekeeping methods (dry transport) for the reduction of wastewaters quantities from food industries

Industrial food process	Method for the reduction of wastewaters quantities
Meat processing	- Bones and fat from deboning and trimming meat materials by a conveyor belt
Slaughterhouses	By-products and waste from the slaughter and animal by-products treatment processes can be transported as dry as possible
Fish processing	- Skins are removed from drums by vacuum instead of water, - Fine mesh conveyor belts are used to collect wastes and separate them from the wastewater, - Removal of offal by vacuum or by using conveyors after filleting and eviscerating.
Fruit/vegetable processing	- Dry transport of peels and cutting residues

11.1.5 Installation of grates, fat traps, screens

144. Where high solids quantities are generated during the production process (e.g. in slaughterhouses, fruit/vegetables processing), the coverage of the floor drains with screens, fat traps and fine mesh grates allows the separation of considerable amounts of solid materials from the rinse waters; thus, preventing them to enter the wastewater collection system and consequently reducing BOD5, COD and suspended solids (SS) loads.

11.1.6 Segregation/re-use of secondary raw materials/by-products

145. Off-specification products, trimmings, fats and other products can be separately collected (and not flushed into the wastewater collection system) by installing some simple devices such as splash protectors, screens, pumps and troughs especially in the food processing sector. The collected materials can be re-used mostly as animal feeders but also for other purposes. Some indicative examples are tabulated in Table 6.

Table 6: Examples for segregation/re-use of secondary raw materials/by-products from food industries

Industry	Method for the reduction of wastewaters quantities
Dairy industry	- Draining of yoghurt and first rinses of buttermilk and residual fat in butter churning (stirring) operations, for use in other processes, e.g. for low fat spreads and whey, - Leaked and spilt materials for animal feeders.
Fruit/vegetable processing	- Peel, cores and cutting residues, apple and tomato pomace and citrus pulp pellets separated by screens/filters and used as animal feeders

11.1.7 Pressure cleaning

146. The use of pressure for cleaning floors and equipment results in considerable savings in water use and consequently to reduced quantities and pollution loads of the wastewaters.

11.1.8 Dry cleaning

147. Dry cleaning can be used to remove much residual material as possible from vessels, equipment and installations before they are wet cleaned. This can be applied both during and at the end of the working period. All spillages can be cleaned up for example by shoveling or vacuuming spilt material prior to wet cleaning.

11.1.9 Sector specific BAT/BEP

148. There are various techniques which are sector specific and can lead to beneficiary results concerning wastewater generation. Their main characteristics are the recovery of substances at source thus allowing reduced pollution loads in the wastewaters. Some examples of simple methods are given in Table 7.

Table 7: Various techniques for reduction of wastewater generation from various industries [12]

Sector	Process	Details
Dairy	Improved preliminary milk filtration and clarification	By improving the preliminary milk filtration and clarification processes, the deposits in the centrifugal separators are minimized, leading to a reduction of the frequency of cleaning
	Whey recovery	Sweet whey is collected and re-used in the process of cheese making or in other processes to make by-products, e.g. for protein recovery, as animal feed, as a food supplement and as baby food. Reduction of up to 50% of BOD5 and of approx. 80% of fat can be achieved
	Minimization of the production of acid whey	Wastewaters containing acid whey cause low pH levels in the wastewaters. Its separation after curd (yoghurt) formation by draining the acid whey from the top of the platforms of the salting vats leads to a minimization of the acid whey content of the wastewaters
	Continuous pasteurizers	The use of continuous pasteurizers instead of batch pasteurizers allows reduced wastewater generation
	Component filling	Milk products (e.g. with different fat content) can be diversified as late as possible, preferably immediately prior to filling by using different pipelines with skimmed milk and milk with standardized fat content. Component filling also reduces the need for in-line storage tanks and the corresponding cleaning requirements
Breweries	Recovery of yeast after fermentation	After fermentation, brewers' yeast is separated and stored in tanks to be used as animal feed, re-used in the fermentation process, used for pharmaceutical purposes, sent to anaerobic WWTPs for biogas production or disposed of as waste
Wineries	Recovery of filter material	The filter material (bentonite, diatomaceous earth) can be collected to prevent it from being washed into the wastewater drainage. It can be treated for re-use

[12] BREF Food, Drink, Milk industries, BREF Tanneries

Sector	Process	Details
Bottle cleaning in the drinks sector	Re-use of bottle cleaning solutions	To save caustic soda and fresh water and to avoid unnecessary wastewater loads, the contents of the bottle cleaning bath are settled and filtered at the end of the production period. The cleaning solution is pumped from the bottle cleaning equipment to a sedimentation tank. This tank also serves as a temporary storage unit. The settled particles are drawn off with a filtration unit. The water is then available again to be used for cleaning at the beginning of the next production period
Fruit/ vegetables processing	Dry caustic peeling	The material is dipped in a 10 % caustic solution heated to 80 to 120 oC to soften the skin, which is then removed by rubber discs or rollers. This reduces water consumption and produces a concentrated caustic paste for disposal
Oils/fats processing	Two-phase extraction of olive oil	In traditional olive processing, i.e. the three-phase production, the extraction of the olive seeds has resulted in three streams, i.e. oily, aqueous and solid. The wastewater is highly polluted. In the two-phase extraction, the decanter centrifuges are modified so that the crushed (mixed) olives are separated into two-phases, the oil phase and a solid phase. This technique does not require the addition of water to the olive mixture. Water is saved in the extraction part of the two-phase process. The amount of wastewater and its contaminant load is also reduced
Tanneries	Partial substitution of chromium	20 – 35 % of the fresh chrome input can be substituted by recovered chrome from the wastewater by re-dissolving chrome containing sediments with sulphuric acid and feeding again the chrome tanning process
	Partial substitution of ammonium	Ammonium salts can be partially substituted with CO2 and/or weak organic acids in the deliming/bating process
	Re-use of pickling liquors	In the pickling process liquors can be repeatedly recirculated before being flushed into the drainage system
	Reduction of water consumption during soaking	It is possible to re-use some process liquors such as the water at the end of the bating process, which is used to rinse and cool the pelts prior to the pickling operation. This water could be used for the dirt soak to reduce water consumption
	High exhaustion chrome tanning	In conventional tanning 2 – 5 kg/tonne raw bovine hides (8 - 12 kg/tonne dry goat- and sheepskins) of chrome salts are released via the spent liquors. With high-exhaustion chrome tanning this quantity can be reduced to 0.05 – 0.1 kg/tonne raw bovine hide. Leaching of chrome from the tanned leather can be reduced by ensuring good fixation, e.g. use of syntans at the end of the process

11.2 End-of-pipe techniques

149. End-of-pipe technologies consist of more complex treatment methods which can also be applied within the industrial facility as well as at centralized level, i.e. as central treatment units in an OIZ. They are common for any type of industrial wastewaters and can be used either for segregated streams as well as for combined wastewaters.

150. Usually a combination of on-site and end-of-pipe technologies is recommended to achieve the best possible results. On-site techniques allow the reduction of wastewater quantities at source and a more flexible adaptation to production changes whereas the centralized end-of-pipe installations allow the mixing of different waste streams (temperature and pH adjustment) and a better use of equipment and chemicals. It must however be noted that, if the relevant pre-treatment standards cannot be met by the on-site techniques (which is the usual case), some simple end-of-pipe techniques should also be applied on single facility level on top of the on-site techniques.

151. Concerning "light" industries i.e. those with mainly biodegradable pollutants, on-site techniques are more applicable by allowing the reduction of wastewater quantities and loads at source, whereas end-of-pipe methods aim mainly at the removal of heavy metals and other hazardous substances.

152. These are well known methods which can be installed either at the facilities' premises (for medium/large industries) or can form the pre-treatment stage in an OIZ treatment plant before the final biological treatment. These are described below.

11.2.1 Neutralization/ equalization

153. For small industries, neutralization/equalization followed by appropriate pre-treatment are more economically feasible before wastewater enters the treatment plan. Since effluent wastewater should be neither acidic nor alkaline (pH = 6.5 – 9), mixing of various wastewater streams and further addition of chemical agents achieve a neutral composition. In order to avoid oversizing of tanks, only acid and alkaline wastewater streams should be led to the neutralization tank whereas neutral streams can bypass this step. The neutralization tank also acts as an equalization step so that the consumption of neutralizing agents (sodium hydroxide, calcium hydroxide, sulphuric acid, hydrochloric acid) can be held to a minimum.

11.2.2 Coagulation/flocculation/sedimentation

154. If simple gravity sedimentation does not remove an adequate portion of the solids contained in industrial wastewater, then the addition of chemicals is an effective solution allowing the destabilization of colloidal and small suspended particles (dyes, organic solids, clay, heavy metals, phosphorous) and their agglomeration into flocs which easily settle as sludge at the bottom of the tank. At this stage, the settled sludge must be treated as hazardous waste. Inorganic coagulants (lime, ferric sulphate, polyaluminium chloride) and/or a polymer are commonly used.

11.2.3 Flotation

155. In this process, liquid-solid separation is induced by dissolving pressurized gas (air) into the treatment unit. The gas is released as micro-bubbles that rise to the surface, capturing the solids on the way. The sludge bed formed on the surface of the tank is withdrawn by scrapers or overflow and must be subsequently treated as hazardous waste. It helps to remove dissolved fats and grease.

11.2.4 Lamella separation

156. Settleable solids are separated from the liquid phase by a series of inclined plates. The advantage of lamella separation over traditional sedimentation is a reduced space requirement due to the increased effective settling area of the plates. Lamellas can also operate with high flow rates. Fine screening, grit and grease removal prior to this process might be needed.

11.2.5 Sludge management

157. Solids generated from various industries (e.g. meat processing, slaughterhouses, fruits/vegetables/oils processing). Sludge should be collected in separate containers. They can be disposed-off with municipal solid wastes if they do not contain hazardous substances.

158. When chemicals are used in end-of-pipe pre-treatment (e.g. coagulation/flocculation/ sedimentation), the settled sludge can be dried on-site (if space is available) and disposed-off together with the sludge from an OIZ treatment plant (if similar techniques are applied). This may require sludge drying and conditioning in order to reduce the moisture and the overall sludge volume for disposal in designated locations by local authorities.

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Annex I

Emission limit values for discharge of industrial wastewater into collecting systems leading to urban wastewater treatment plants[13]

[13] Appendix I.C of the Regional Plan on Urban Wastewater Treatment (Decision IG.25/8, COP22)

Emission limit values for discharge of industrial wastewater into collecting systems leading to urban wastewater treatment plants[14]

Parameter	Unit	Emission Limit Values (ELV)
Adsorbable organically bound halogens (AOX)	mg/l	1
Aluminium - Al	mg/l	25
Arsenic - As	mg/l	0.1
Benzene	mg/l	0.05
Beryllium - Be	mg/l	0.5
BOD5	mg/l	COD concentration not to exceed four times BOD concentration
Cadmium - Cd	mg/l	0.1
Chloride - Cl	mg/l	430
Chlorine	mg/l	0.5
Chromium – Cr^{6+}	mg/l	0.5
Cobalt - Co	mg/l	1
COD	mg/l	2000
Copper - Cu	mg/l	0.5 - 1
Cyanide	mg/l	0.2 - 0.5
Fluoride – F	mg/l	6
Lead - Pb	mg/l	0.5
Lithium - Li	mg/l	0.3
Manganese - Mn	mg/l	1
Mercury - Hg	mg/l	0.05
Mineral Oil	mg/l	20
Molybdenum - Mo	mg/l	0.15
Nickel - Ni	mg/l	0.5
Phenols	mg/l	3
pH		6 - 10
Polyphenols	mg/l	100
Selenium - Se	mg/l	0.05
Sodium - Na	mg/l	230
Total Dissolved Solids (TDS)	mg/l	3,500
Total Oil &Grease	mg/l	250
Total Phosphorous - (TP)	mg/l	30
Temperature	ºC	40
Tin - Sn	mg/l	2
Total Hydrocarbons	mg/l	20
Total Nitrogen - (TN)	mg/l	15 - 30
Total Suspended Solids (TSS)	mg/l	1,000

** The adoption and implementation of the ELVs shall respond to the respective industries. Different emission limit values, including for different parameters, may be adopted further to a risk-based assessment also in line with national regulations and procedures in collaboration with the operators of treatment plants. ELVs may be increased for small industries discharging to the collecting system when (i) the plant uses BAT and (ii) the effects of the discharged effluent on the collecting system and the WWTP are negligible.*
*** Total nitrogen as the sum of ammonia nitrogen, nitrite nitrogen and nitrate nitrogen*
**** Volatile halogenated hydrocarbons - sum of trichloroethene, tetrachloroethene, 1,1,1-trichloroethane, dichloromethane - calculated as chlorine*

[14] Appendix I.C of the Regional Plan on Urban Wastewater Treatment (Decision IG.25/8, COP22)

Appendix 3

Guideline on Reginal Standards for Discharge from Desalination Plants and Decision Support Systems for Sustainable Desalination Technologies in the Mediterranean

Table of Contents

Pages

Abbreviations and Acronyms

AD	Adsorption desalination
BAT	Best Available Techniques
BEP	Best Environmental Practices
BRO	Batch Reverse Osmosis
CDI	Capacitive Deionization
CHD	Clathrate Hydrate Desalination
COP	Conference of the Parties
DSS	Decision Support Systems
ED	Electrodialysis
EEA	European Environmental Agency
EIA	Environmental Impact Assessment
EMPs	Environmental Monitoring Plans
EU	European Union
FD	Freeze Desalination
FEI	Freshwater Ecosystem Impact
FO	Forward Osmosis
FWI	Freshwater Withdrawal Impact
GES	Good Environmental Status
GHG	Emissions Greenhouse Gas Emissions
GWI	Global Water Intelligence
HDH	Humidification Dehumidification
IDA	International Desalination Association
IMAP	Integrated Monitoring and Assessment Programme
LBS	Land Based Sources Protocol
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainable Assessment
LCC	Life Cycle Costing
MCA	Multi Criteria Analysis
MD	Membrane distillation
MED	Multiple Effect Distillation
MSF	Multi-Stage Flash Distillation
MED POL	Mediterranean Pollution Control and Assessment Programme
PRO	Pressure retarded osmosis
RO	Reverse Osmosis
RED	Reverse Electrodialysis
SCWD	Supercritical Water Desalination
SED	Solvent Extraction Desalination
SLCA	Social Life Cycle Assessment
STD	Solar Thermal Desalination
SW	Seawater
UNEP/MAP	United Nations Environment Programme /Mediterranean Action Plan
WFD	Water Framework Directive
ZLD	Zero Liquid Discharge

12. Introduction

159. In their 20th Ordinary Meeting to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean and its Protocols (Tirana, Albania, 17-20 December 2017), the Contracting Parties adopted in their Decision IG.23/13 the "Updated Guidelines on the Management of Desalination Activities."

160. The aim of the 2017 Updated Guideline was to better describe the desalination efforts around the Mediterranean and to assess their impacts on the coastal and marine environment. The Updated Guideline also served to provide information to the Contracting Parties on conducting Environmental Impact Assessments (EIA) for the implementation of desalination projects including environmental monitoring requirements.

161. Complementing the 2017 guidelines, in this Guideline, the reginal standards for discharge from desalination plants and decision support systems for sustainable desalination technologies in the Mediterranean are presented. This guideline which complements the 2017 Guidelines is built upon the following three pillars:

a. Available state of the art desalination technologies and their possible implementation in the context of sustainable desalination solutions. In this section, designers and operators of desalination plants are provided with information on emerging seawater desalination technologies, factors contributing to sustainable seawater desalination, pillars of sustainable seawater desalination, as well as the technological tools for sustainable desalination of seawater;
b. Regulatory aspects for seawater desalination including compliance with the amendments to the Annexes of the LBS Protocol; recommended emission limit values based on prevailing regional standards for seawater desalination; as well as guidance for implementation of regular monitoring programmes for discharges from desalination plants; and
c. Recommendations on Decision Support Systems (DSS) based on multi criteria analysis (MCA) and life cycle assessment (LCA) with the aim to assist policy makers/facilities' operators in applying best technologies which are appropriate to achieve sustainable desalination in compliance with national/regional legal frameworks and regulations.

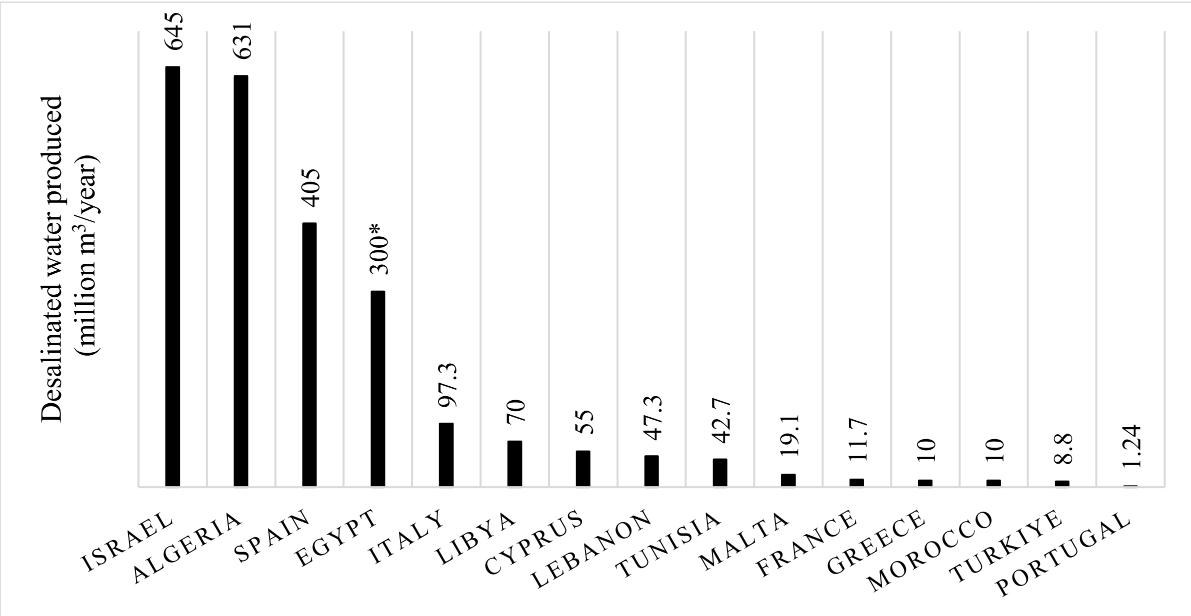
13. Seawater Desalination – Facts and Figures

162. Desalination can be divided into two categories depending on the feedwater source: seawater desalination and brackish water desalination. There are 15,906 working desalination plants worldwide with a total desalination capacity of approximately 95.37 million m^3/day (34.81 billion m^3/year), constituting 81% and 93% of the total number and capacity of desalination plants ever built respectively (Jones et al., 2019). Seawater desalination makes up roughly 61% of the 5328 desalination plants when it comes to capacity and plant count. Brackish and hard river waters account for 8% of 1825 plants, whereas brackish water desalination accounts for 21% of 5960 plants (Elsaid, Kamil, et al., 2020). This document serves as a comprehensive guide to the process of seawater desalination.

163. While brackish water, river water, wastewater, and brine water desalination each produced more than 15.4 million, 6.5 million, 4.4 million, and 110,501 m^3/y of freshwater, respectively, seawater desalination is still the most common method used worldwide, producing over 43.2 million m^3/y in 2018 (GWI, 2018). Since 2010, the global installed desalination capacity has been continuously expanding at a rate of roughly 7% per year through the end of 2019, which is equivalent to an average annual addition of roughly 4.6 million m^3/day of production capacity. In total, 155 new desalination plants were contracted and put into service worldwide from January 2019 to February 2020 alone, adding 5.2 million m^3/day to installed capacity (Eke et al., 2020).

164. Beginning in July 2016, 18,983 plants and projects around the world have a cumulative desalination capacity for freshwater production of 95.6 million m^3/day. By the end of 2017, the overall operating capacity of installed plants was estimated at 93% of the installed capacity, with a cumulative desalination capacity of 99.8 million m^3/day (considering facilities completed since 1965). Global installed and cumulative desalination capabilities for freshwater production as of mid-February 2020 were provided by 20,971 projects, and they were 97.2 million m^3/day and 114.9 million m^3/day, respectively. There were 16,876 installed plants among these 20,971 projects (Eke et al., 2020).

165. The United Nation's Food and Agriculture Organization (FAO 2019) provides the most up-to-date and thorough survey of desalination capacity in the Mediterranean region as depicted in Figure 1 (with the exception of Egypt where the amount of desalinated water is obtained from a study by Elsaie et al. 2022).



** Data for Egypt is obtained from a study by Elsaie et al. 2022*

Figure 1. Production of desalinated water in the Mediterranean (FAO, 2019)

166. A quick glance of the state of desalination in the region shows that Israel, Algeria, Spain and Egypt are the major producers of desalinated water in the Mediterranean region. Israel's annual desalination capacity is about 80% of the total urban water consumption (Miller et al., 2015). In Algeria and Morocco, 85% and 60% of desalination plants use seawater as their source of feed water, respectively (Dhakal et al., 2022). Spain has the most important desalination plants in Europe, located in Torrevieja in the province of Alicante, in the Region of Valencia and El Prat located in the Metropolitan area of Barcelona, which is one of the most heavily populated areas in Spain (Morote et al., 2017). In Libya, desalination technology has been used since the early 1960s, although few desalination plants have been established since then. In total, Libya currently has about 21 operating desalination plants in which thermal processes represent about 95% of production capacity while reverse osmosis membrane technology represents 5% (Brika, 2018). In Egypt, over 90 seawater desalination plants are operational (Elsaie et al., 2022). In Malta, desalinated water constitutes up to 60% of the drinking water supply.

14. Desalination technologies and their possible implementation in the context of sustainable desalination solutions

167. In this section, available state of the art desalination technologies, particularly novel and emerging seawater desalination, is presented with the aim to explore their possible implementation in the context of sustainable desalination. To this aim, factors contributing to sustainable seawater desalination, the three pillars of sustainable seawater desalination; sustainability indicators for sweater desalination, as well as the technological tools for sustainable desalination of seawater are discussed.

14.1 Common desalination technologies

168. The "Updated Guideline on the Management of Desalination Activities" (2017) provides an overview of the most common thermal and membrane process desalination technologies including Multistage Flash Distillation (MSF), Multiple Effect Distillation (MED); as well as Reverse Osmosis (RO) and Electrodialysis (ED).

169. Reverse Osmosis (RO) is by far the most dominant desalination technology, accounting worldwide for 84% of the total number of operational desalination plants and producing 69% (65.5 million m^3/day) of total global desalinated water. Despite their small number, the two major thermal technologies, Multi-Stage Flash Distillation (MSF) and Multi-Effect Distillation (MED), produce the majority of the remaining desalinated water, with market shares of 18% and 7%, respectively (Jones et al., 2019).

170. It should be noted that hybrid technologies like MSF-MED, MED-adsorption (MED-AD), and RO-MSF are currently being considered to improve the efficiency of desalination plants by combining the advantages of each technology to compensate for the weaknesses of the others.

14.2 Novel and emerging seawater desalination technologies

171. The interest in emerging technologies has increased due to the increasing demand for desalination and the high energy consumption, fouling and brine discharge issues in existing technologies. To overcome the current challenges in RO, MED and MSF technologies, there has been an increased focus on developing processes with low energy requirements. Emerging desalination technologies have the potential to compete with conventional technologies for seawater desalination, or to outperform these technologies in niche areas; however, their transition to full-scale employment depends on further scientific advances to achieve threshold performance and energy efficiency (Ahmed et al., 2021).

172. Membrane Distillation (MD), Forward Osmosis (FO), Adsorption Desalination (AD), Capacitive Deionization (CDI), Freeze Desalination (FD), Humidification Dehumidification (HDH), Clathrate Hydrate Desalination (CHD), and Batch Reverse Osmosis (BRO), Solar Thermal Desalination (STD) , Solvent Extraction Desalination (SED), Supercritical Water Desalination (SCWD) are several emerging desalination technologies that are still largely in the research and development stages. A detailed description of the aforementioned emerging technologies is presented in the Appendix I.

173. Pretreatment technologies, such as ultrafiltration (UF), nanofiltration (NF), ionic filtration (IF) and Zero Liquid Discharge (ZLD) have been also explored to increase the efficiency of desalination plants (Eke et al., 2020; Park et al., 2022).

174. Moreover, hybrid systems that combine various energy sources and desalination technologies seem to offer the most promising solutions. Innovative hybrid solar (or wind) energy driven systems coupled with highly effective desalination processes show promise in places with rising water scarcity and high solar radiation. Additionally, research is being done all over the world to increase the effectiveness of currently commonly used desalination processes (such as RO) as well as to find new solutions, such as metal-air desalination batteries and desalination via gas hydrate, as well as new materials, such as 3D printing for membrane separation, carbon nanotubes, Janus composite hollow fiber membrane-based direct contact distillation, single-layer graphene membranes, and nanofibrous membranes (Bundschuh et al., 2021).

175. Brine disposal in seawater desalination is a very important issue due to negative environmental impacts. As a result, an alternative and more sustainable approach to mitigating the effects of brine discharge has been considered. This method is referred to as zero liquid discharge (ZLD). More detailed information about the ZLD approach is given also in Appendix I.

14.3 Factors contributing to sustainable seawater desalination

14.3.1 Reducing environmental impacts

176. The majority of the environmental impacts of seawater desalination are attributed to brine discharges, which can degrade coastal water quality and harm marine life (Heck et al., 2018; Panagopoulos et al., 2019). However, the impingement and entrainment during seawater intake, the effects of brine and chemical discharge, changes in seawater quality, negative effects on fish resources, the degradation of marine habitats as a result of toxic brine concentrations, air pollutant emissions attributed to the energy demand of the processes are the main environmental impacts of seawater desalination processes (Elsaid, Kamil, et al., 2020). In addition to creating a number of environmental concerns, the seawater desalination industry offers a great deal of potential for using brine to produce some precious resources as a byproduct (Mavukkandy et al., 2019). In light of the desalination industry's expected, rapid growth, chemical composition of brine suggests that it may have both economic and ecological benefits (Ayaz et al., 2022). The construction of a seawater desalination facility requires laying underwater infrastructure such as pipelines, outlets and intakes. The manner in which these are constructed may include potentially harmful techniques such as dredging, cofferdams, and excavation of sensitive habitats. These can be mitigated using underground pipeline technologies such as horizontal directional drilling (HDD) and micro-tunneling.

177. Significant environmental impacts of seawater desalination are associated with the intake of seawater; brine discharge as well as for emerging contaminants released during the desalination process. These impacts are addressed in the “Updated Guidelines on the Management of Desalination Activities” (2017). In the current guideline, recommendations are provided for reducing impacts of the aforenoted aspects with the aim to achieving sustainable seawater desalination:

178. With regards to the intake of seawater (Kress 2019), and taking into consideration the nature of the local environment at the intake area, intake capacity, intake type, and structure, the following recommendations can be considered:

a. Install intake structure in zones of deep waters and/or with less significant biological productivity and sensitivity.
b. Install bypass mechanisms to enable the returning of organisms that have been impinged on in the intake site.
c. Decrease the effluent flow velocity; 0.15 m/s is suggested so that fish can resist impingement depending on the site.
d. Install behavioral barriers, such as horizontal velocity-caps that provide less impingement than vertical velocity-caps, and sound and light-generating equipment to keep organisms outside.
e. Locate the intake at a hydrologically active region with strong currents and waves.
f. Minimize over drafting and draining freshwater from the subsurface reservoir.
g. Appropriate planning and positioning of intake.
h. Use of high quality, corrosion/erosion-resistant material.
i. Apply appropriate and periodic maintenance.
j. Consider replacing the protruding intake with a subsurface intake, such as “seabed infiltration galleries”, “radial collector wells” and “HDD wells”.

179. Concerning brine management (Elsaid, Sayed, et al., 2020), and taking into consideration the various chemicals and different coagulants in use, as well as thermal desalination processes, the following recommendations can be considered taking also into account site location:

a. Use iron salts instead of aluminum salt as it is less toxic.
b. Optimize coagulant and flocculant dosage.
c. Use biodegradable green chemicals.
d. Apply predilution with wastewater and cooling water for brine from thermal desalination processes.
e. Performance of brine treatment for removal of toxic components.
f. Conduct appropriate planning and positioning of outfall basin including minimizing the effect of salinity/optimal dilution through proper planning of diffusers and setting level of salinity requirement using "near field models" taking into account synergistic effects.
g. Perform upstream treatment for removal of suspended solids (TSS), residual of coagulant and flocculant (e.g., iron (Fe), anthracite, etc., also minimize color contamination), and reduce turbidity (e.g. backwash of ultrafiltration) and limestone washes before discharge.
h. Apply antiscalant with zero phosphate (P) or polyphosphate and reduced phosphorus content.
i. Ensure quality control of additive contents and minimize inputs of pollutants (e.g., heavy metals, P, N).
j. Prevent scouring of seabed.

180. It should be noted that proper plant design may significantly reduce the entrapment of marine organisms at the intake and provide for the rapid dilution of brine released at the outfall; hence, reducing the environmental impacts of a single desalination plant on the local marine ecosystem. However, several desalination plants that discharge to a single body of water with limited circulation will increase the salinity of the water body because of the cumulative effect of multiple desalination plants; thus, increasing the susceptibility of semi-enclosed seas, such as the Mediterranean Sea, to increased salt levels (Gies, 2019).

14.3.2 Sustainable brine management: water, energy and mineral recovery

181. It is currently essential to use a different brine management strategy since disposal of brine strategies, which were once widely used in brine management, have recently been considered unsustainable (Alvarado-Revilla, 2015). It is necessary, in particular, to develop a strategy to decrease the volume of brine while recovering precious resources including water, minerals, salts, metals, and even energy.

182. The methods for recovering minerals can be broadly categorized into four groups based on the driving force that is used: (1) pressure-driven processes like NF and RO, (2) thermal processes like evaporation and membrane distillation (MD), (3) electrochemical potential-driven processes, and (4) physico-chemical processes like adsorption, ion exchange, etc. Currently, extraction of the four metals with the highest concentrations (Na, Mg, Ca, and K) in brine takes the form of Cl- and SO_4^{2-}. Additionally, minor elements including Li, U, Sr, Ru, and Rb among others were specifically isolated from seawater desalination concentrate.

183. Energy recovery (also known as 'blue energy' and 'salinity gradient power') has also gained attention recently in addition to the recovery of water, metals, and minerals from the brine flow of seawater desalination processes. The interest in energy recovering technologies based on salinity gradient from SWRO concentrate by an energy recovery system has risen steadily in recent years as a means of minimizing energy usage and maximizing the benefits of seawater desalination brine. The total energy consumption of the approximately 308 million kWh/day SWRO plants, which are widely used technique around the world, is estimated to be recoverable up to 40.7 million kWh/day (Wan & Chung, 2016).

14.3.3 Improving energy efficiency

184. Improving energy efficiency of current desalination technologies and development of new approaches for seawater desalination is crucial for the sustainability of the desalination sector. One of

the most essential strategies to reduce energy consumption is to improve the efficiency of the process itself. Additionally, seawater desalination has a significant potential to significantly decrease its contribution to pollution by minimizing its dependency on conventional fossil fuels (Ayaz et al., 2022). It is estimated that using renewable energy sources could prevent up to 99% of the carbon dioxide produced by desalination procedures (Elmaadawy et al., 2020). On the global scale, numerous small- to medium-sized desalination facilities have been constructed that are entirely powered by renewable energy sources. However, the capacity of these desalination plants is insignificant when compared to total global production. Although the Global Clean Water Desalination Alliance (GCWDA) has set a target of 20% for all new desalination plants constructed between 2020 and 2025 to be powered by renewable sources, the overall current share of renewable energy used for desalination operations is less than 1% (Ayaz et al., 2022). Currently, solar photovoltaic contributes 43% of the major renewable sources utilized for desalination, followed by solar thermal with 27% and wind with 20% (Khan et al., 2018).

14.3.4 Applying Best Available Technology (BAT) and Implementing Best Environmental Practice (BEP)

185. The criteria for defining Best Available Techniques (BAT) and Best Environmental Practice (BEP) are specified in Annex III of the LBS Protocol as amended in 2021. The priority of the industries and groups of substances listed in Annex I for the broad preventive measures relating to the use of BAT and the implementation of BEP is also emphasized in Annex III of LBS Protocol as amended in 2021.

186. The LBS Protocol as amended in 2021 emphasizes preventing or minimizing environmental impacts throughout all stages of a product's life cycle, maximizing the value of products, materials, and resources within the economy, and minimizing waste generation. This aspect is equally applicable for desalination plants. With regards to determining the BATs, in general or individual cases, the 2021 amended LBS Protocol makes note of the following special considerations which are equally applicable for desalination plants:

a. the commissioning dates for new or existing installations;
b. the consumption and nature of raw materials used in the process and its energy efficiency;
c. the need to prevent or reduce the overall impact of the releases to the environment and the risks to it;
d. the need to prevent accidents and to minimize their consequences for the environment;
e. the need to ensure occupational health and safety at workplaces;
f. the need to use non-toxic substances in view of facilitating non-toxic waste streams to facilitate recovery and recycling; and
g. the need to keep material and products in use as long as possible.

187. Regarding the selection of BEPs for individual cases, the 2021 amended LBS Protocol promotes the use of eco-labels, eco-design, and eco-innovation to identify environmentally sound products and the establishment of collaboration along the value chain to ensure that the origin and value of raw materials remain traceable when closing the loop are added as aspects. Implementation of the aforementioned BEPs is critical for the sustainable operation of desalination plants.

14.3.5 Meeting the sustainable development goals

188. Desalination directly contributes to the fulfillment of SDG 6 (access to safe drinking water) as well as climate change adaptation (SDG 13). Desalination offers safe drinking water in water-stressed areas, which is a prerequisite for socioeconomic development, industrial activity, and agricultural production. Furthermore, the construction of new desalination capacity can decrease demand on conventional water sources such as underground aquifers, lakes, and rivers. Additionally, desalination can also help to climate change adaptation for the reasons mentioned above (NATIXIS, 2020).

189. Moreover, desalination provides various co-benefits, indirectly contributing to the achievement of several other SDGs. Desalination facilities can be constructed to have an adjacent

wind farm or solar power plant, which will help increase the use of clean energy (SDG 7). Desalination, when powered by clean energy, can lead to more sustainable cities and communities (SDG 11) in such areas by providing a reliable supply of drinking water. In addition, long-term policy support for desalination can also encourage innovation and help create local industrial players, which will help with economic growth (SDG 8), as well as industrial development, technological innovation, and infrastructure building (SDG 9) (NATIXIS, 2020).

14.4 Pillars of sustainable seawater desalination

190. The three pillars of sustainable development are addressed in this section with the aim of providing guidance on the achievement of sustainable desalination solutions. These consist of: (i) environmental sustainability; (ii) techno-economic sustainability; and (iii) social sustainability.

14.4.1 Environmental sustainability

191. In recent years, seawater desalination has gained more importance due to the increase in global environmental problems such as climate change and drought. In contrast, traditional desalination techniques increase greenhouse gas (GHG) emissions since they depend heavily on fossil fuels (in some cases, heavy fuel oil) in many countries, which release carbon dioxide. The average amount of fossil fuel needed to produce 1000 m^3 (or 1 million liters) of water per day using thermal desalination is roughly 10,000 tons per year (Tal, 2018). Even with energy-efficient RO, the desalination of each 1000 m^3 of saltwater results in the potential release of 0.4 to 6.7 tons of CO_2, depending on the size of the plant and other operational processes (Cornejo et al., 2014). In 2020, global CO_2 emissions from desalination facilities driven by fossil fuels were predicted to be 76 million tons. Additionally, assuming operations continue under the current conditions, the amount of CO_2 can reach 218 million tons by 2040 (Ayaz et al., 2022). Hence, seawater desalination facilities must use renewable energy sources or low emission fuels such as natural gas to reduce their environmental impacts. In the absence renewable energy sources or low emission fuels air emissions treatment facilities must be installed.

192. As a result, the main sustainability issues for desalination, such as GHG emissions and energy consumption must be taken into account within appropriate temporal and spatial bounds. Planning, design, construction, commissioning, operation, and decommissioning are all directly related activities that must be considered, as well as indirect ones like the effects of the utilities and service systems that were used, the associated materials' embodied energy, emissions, and impacts.

14.4.2 Techno-economic sustainability of seawater desalination

193. The main concerns of techno-economic sustainability of seawater desalination are the overall unsubsidized cost of the desalted water, covering the rising cost of permitting (which can account for 60% of a major project) and of permitted chemicals (Lior, 2017). A variety of contractual, managerial, and technological factors that affect water production costs with seawater desalination. Besides from technical knowledge, the success of desalination projects requires the optimal selection of funding, risk-sharing, and contractual arrangements for the project's operational lifetime. Due to the high energy requirements of desalination and the complexity of designing, financing, building, and operating desalination infrastructure, the costs of desalinated water remain higher than those of conventional potable water sources. However, desalination must be employed strategically when conventional solutions to water constraint are insufficient (NATIXIS, 2020).

14.4.3 Social sustainability of seawater desalination

194. The social pillar of seawater desalination mainly covers impacts on health, developments, local growth and visual amenity (Lior, 2017). Desalination must be approved by the community; meet their water needs; and is operated and managed within their capacity to be socially sustainable (Werner & Schäfer, 2007). However, the public perceptions about desalination plants are not stable, and statistically proven predictors may change overtime. Furthermore, public support may shift between periods of adequate water supply and drought. Public support may reduce after the perceived

threat to the local water supply begins to fade, as it appears to be a substantial predictor of support (Haddad et al., 2018).

14.4.4 Sustainability indicators for seawater desalination

195. For a comprehensive assessment of environmental, techno-economic and social sustainability of seawater desalination, the following aspects for formulating indicators listed in Table 1 are recommended.

Table 1: Recommended environmental, techno-economic and social sustainability aspects for formulating indicators for assessing seawater desalination (Lior 2017)

Environmental sustainability aspects	Techno-economic sustainability aspects	Social sustainability aspects
a) Water conservation. b) Water resources planning and use, water supply alternatives. c) Water resources impact indices: Water Impact Index, Freshwater Ecosystem Impact (FEI) index, Freshwater Withdrawal Impact (FWI) index, Water Footprint. d) The Carbon Footprint. e) Impacts of construction wastes and excess soil. f) Soil and groundwater pollution (fuels, oils, etc.) g) Air pollution (fugitive combustion emissions). h) Noise emission. i) Damage to antiquities and heritage. j) Alteration of the seabed. k) Sediment resuspension (impacts on marine water quality and ecology). l) Alteration of the coastal zone and obstruction of passage along the seashore. m) Chemical and other discharges.	a) Cost of water. b) Affordability. c) Pricing policy. d) Capital investment cost (including possible financial incentives). e) Operating cost (including taxes, insurance, warranties). f) Impact on economy; economic growth and development. g) Commercial conflicts (e.g., immediate and surrounding land use and values, water navigation, access to harbors, commercial fishing, Aquaculture). h) Pre-treatment and post-treatment requirements. i) Production reliability. j) Water distribution. k) Water supply alternatives. l) Water conservation. m) Impact on energy use and security. n) Construction materials consumption. o) Consumption of fuel, chemicals. p) Corrosion cost and prevention. q) Embodied energy. r) Research and development (R&D) cost.	a) Health and sanitation, e.g., indices of the populations at risk of being affected by the project; product water quality must ensure that unhealthy ingredient levels are kept to a minimum. b) Life quality. c) Effective and equitable employment, local and regional. d) Impact on food (cost, availability, quality). e) Education and training. f) Land footprint. g) Present land-use and planned development activities. h) Visual amenity. i) Equitable water security for all. j) Poverty. k) Trans-border relations. l) Gender effects. m) Demographic development. n) Community structure. o) Recreation. p) Cultural aspects incl. tribal and indigenous people. q) Characteristic landscape and natural scenery. r) National water security.

14.5 Technological tools for sustainable desalination of seawater

196. Table 2 provides a list of technological tools that can be utilized for achieving sustainable solutions for seawater desalination (Ayaz et al., 2022). These include technology to be used, the process to which this technology can be applied, the aim and advantages to be accomplished.

Table 2: Comparison of technological tools for achieving sustainable solutions for seawater desalination (Ayaz et al., 2022)

Technology/ Technique	Target Process	Aim	Advantages
Sensors	Through all processes, including intake and outfall	Monitor a range of parameters (pH, conductivity, turbidity, etc.)	- Providing early detection of any malfunction - Keep the production and efficiency at peak - Expanding the system's life cycle - Decreasing safety risks and resource wastage
AUVs and gliders	Intake and outfall	- Identify and help to obtain proper water quality data for intake - Influences of concentration discharge and plume detection - Observe and map the plumes	- Contributing to the reduction of chronic impacts on marine ecosystems - Facilitating accurate navigation - Capable of carrying out week-to-month monitoring tasks
Satellites	- To determine proper location for plant and - Proper intake water quality - Point of discharge of the brine	- Observing the presence of HABs and other biofouling-causing factors - Ocean color measurement - Tracking the dispersion of effluent - Analyzing ocean salinity	- Providing long-term monitoring, both before and after the installation - Providing spectral and spatial resolution
Models and mapping	- The effects of brine discharge, particularly in the far-field - Diffuser planning based on "near field models" for dilution optimization	- Analyzing the impact of brine on a large scale - Investigating the impact of wind mixing and tidal currents - Investigating the impact of oscillating tidal flow in both near- and far-field	- Reduce the overall cost of outfall design - Minimize and control negative impact of brine discharge on the marine environment - Offer forecasts of the region associated with discharge plumes
Statistical observation	- Typically used for outfall - Design and operation performance of desalination membranes	- Characterization of the environment in which the discharge occurs - Keep track of measurements over time - Providing a precise characterization between data and models	- Analyzing the presence of the discharge along with the impacts of the discharge plume - Facilitating to analysis of various factors when designing the operational performance of a TFC desalination membrane

15. Regulatory aspects for seawater desalination

197. The Contracting Parties to the Barcelona Convention adopted in COP22 (Antalya, Türkiye, 7-10 December 2021) Decision IG.25/5 "Amendments to Annexes I, II, and IV to the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-Based Sources and Activities."

198. The “desalination of seawater” sector was added to the “Sectors of Activity” under Annex I of the LBS Protocol. With the updated amendment, desalination of seawater is currently primarily considered when setting priorities for the preparation of action plans, programmes and measures for the elimination of the pollution from land-based sources and activities.

199. Furthermore, “brine” was added as a new substance to the “Characteristics of Substances in the Environment” under Annex I of the LBS Protocol. With this updated amendment, the Parties are requested to take into account when preparing action plans, programmes and measures, the characteristics of “brine.”

200. In this context, and in line with the requirements of the amendments of Annex I of the LBS Protocol, policy officers regulating the desalination sector are recommended to consider implementation of the following measures:

a. Setting emission limit values (ELVs) for brine, also known as "effluent standards" or "discharge quality standards," which refer to numerical values for the constituents of effluent at the site of release with the aim to administer, monitor and enforce.
b. [Setting annual emission limit loads for constituents (e.g. iron, total phosphorus, total nitrogen, and total organic carbon) of additives for brine.]
c. Adopting regulatory measures aiming to avoid spatial conflicts between desalination plants and other activities and the environment. To this aim, the regulations should also enforce procedures to select activities’ site on the basis of the Ecosystem Approach, as well as, where applicable, the Maritime Spatial Planning (MSP).
d. Establish permitting requirements for desalination plants that define the essential conditions for installation and management of activities that ensure good environmental protection. This includes mandatory Environmental Monitoring of biodiversity and non-indigenous species, pollution and marine litter, coast and hydrography, to be based on related IMAP Ecological Objectives and Indicators.

15.1 Emission Limit Values (ELVs) for brine disposal

201. Environmental regulations for brine disposal vary greatly from region to another. In the majority of countries operating seawater desalination plants, the mixing zone concept is employed for brine disposal. The size of the permitted mixing zone ranges from 0 to 500 meters. The ability of mixing zones to regulate the discharge of brine is limited, particularly in environmentally sensitive areas. Recently, a simple-to-implement and -monitor Minimum Return Point Dilution method was proposed to regulate the discharge of brine in sensitive areas (Ahmad & Baddour, 2014).

202. Worldwide, brine discharges have a lack of actual regulations, standards, and guidelines. Though the regulations differ greatly in their specifics, they all include a salinity limit and a point of compliance expressed as a distance from the discharge. Increases in salinity of 1 to 4 parts per thousand above ambient level are typically cited as the upper limit. However, absolute salinity or a minimum dilution level are also typically used to define boundary limits. The salinity compliance point is typically specified as a fixed distance from the discharge, somewhere between 50 and 300 meters, and this boundary is the mixing zone.

203. Further to prevailing standards in the region, the following ELVs for salinity limits, temperature limits and compliance point for temperature listed in Table 3 are recommended.

Table 3: Recommended ELVs for salinity limits, temperature limits and compliance point for temperature for brine (Jenkins et al., 2012)

Parameter	Recommended ELV
[Salinity limit	Increment ≤ 4 ppt
Salinity limit % increase above ambient	Increment ≤ 5%

Compliance point for salinity (relative to discharge and main current)	50-300 m
Temperature limit (°C), above ambient	<3-10
Compliance point for temperature (relative to discharge)	300 m]

15.2 Environmental monitoring

204. Environmental monitoring programs in the case of desalination are primarily focused on determining potential negative impacts associated with brine discharges on the marine environment and implementing appropriate mitigation measures when such impacts are identified. The monitoring and control measures that should be used depend on a variety of factors, including the size of the desalination plant and the quality of the source water, but also the objectives and targets of good environmental status (GES) of marine environment monitoring.

205. A routine environmental monitoring program should be implemented by the operator of the desalination facility following the start of plant's operation on a regular basis and in compliance with applicable legislative requirements (e.g. the permit for marine discharge of the concentrate).

206. Major tools for monitoring of seawater desalination processes, including compliance and trend monitoring, as well as monitoring plans are presented in Appendix II. The monitoring program involves both maritime environmental monitoring that is Integrated Monitoring and Assessment Programme (IMAP) in the framework of the Barcelona Convention, and in-plant pollution monitoring of the intake water and concentrate streams (seawater, sediments and biota).

5. Decision Support System for Selection of Technologies for Desalination Plants

207. This section is intended to provide recommendations on Decision Support Systems (DSS) to assist policy makers/facilities' operators in applying best technologies which are appropriate to achieve sustainable desalination in compliance with national/regional legal frameworks and regulations.

208. The starting point for selection of the appropriate desalination technologies is the Environmental Impact Assessment (EIA). It is of utmost importance to conduct an EIA prior to initiation of any desalination project in order to evaluate the potential environmental impacts of desalination and to advocate for the adoption of appropriate countermeasures to prevent or mitigate these impacts (Ihsanullah et al., 2021). A recommended EIA process is presented in Appendix III. In principle, it is necessary to collect and analyze data on the terrestrial and marine ecosystems at the proposed location for the desalination plant, including the intake and discharge zones. Once operations officially start, the collected and/or new data will also serve as a major reference (baseline) for environmental monitoring.

209. The EIA is a method for assessing and analyzing the environmental impacts of seawater desalination projects, proposing mitigation or prevention measures, and monitoring sites after their construction and operation. It frequently produces massive amounts of complex information, often more than the capacities of decision-makers to process and integrate it. The decision-making process in an EIA can be characterized as a conflict analysis between various value judgments because different decision-makers and stakeholders frequently have differing preferences regarding a project. A formalized decision support tool that allows for the integration of numerous quantitative and qualitative criteria as well as various value judgments, such as multi criteria analysis (MCA) and life cycle assessment (LCA), can help with the process. Use of MCA and LCA, in seawater desalination is presented below.

5.1 Multi-Criteria Analysis (MCA) in Seawater Desalination

5.1.1 Multi-criteria analysis

210. There are typically a number of technologies/processes available for desalination, including thermal-based technologies, membrane-based processes, and alternative technologies (Subramani & Jacangelo, 2015). When faced with numerous options, it can be difficult for decision makers to choose the best desalination technology. This is because decision makers must consider a variety of factors in the process of selecting desalination technologies, such as production cost, environmental impacts, water quality, energy consumption, and technology reliability, among others. Thus, selection of desalination technologies is a complicated decision-making problem (Wang et al., 2019). MCA is an effective tool in the field of complex decision making that offers solutions to problems involving a wide range of indicators and carefully evaluates several criteria (Yazdani et al., 2017). Additionally, MCA is such a methodology that can assist the EIA in various ways and at various stages (Linkov et al., 2006). Some significant MCA studies applied on desalination from the literature are presented in Appendix IV.

- *MCA methodology and procedure*

211. MCA methodology mainly consists of three stages as shown in Figure 2. The decision problem is identified, input data is obtained, and the alternatives can be ranked based on the input data by using a graphical evaluation in the first stage. Information on all criteria and alternatives, as well as details on individual preferences among specified stakeholder groups, are all included in the input data for an MCA. The alternatives are ranked using MCA in the second stage, which includes selecting an MCA model and standardizing functions, giving weight to the criteria that represent value judgments, and performing sensitivity analysis to determine robustness of ranking. Weighting is a significant technique of MCA and numerical weights can be assigned by using MCA models for each criterion to define the relative valuations of a shift between the top and bottom of the chosen scale. After analyzing the results critically and evaluating the strength of the evidence, an alternative must be selected in the final stage (Latteman, 2010).

5.1.2 MCA models

212. Various MCA models have been developed that synthesize the input data and rank the alternatives using various metrics, each with a different set of advantages and disadvantages (Linkov et al., 2006). Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), multi-attribute utility theory (MAUT), UTA, MACBETH, PROMETHEE, ELECTRE, TOPSIS and VIKOR are the mostly used MCA models for decision problems. MCA models are classified into two groups which are value or utility function-based methods and outranking methods (Linkov et al., 2006). Hybrid models can also be applied by combining two or more MCA models depending on types of decision problem (Communities, 2009).

5.1.3 Sensitivity analysis

213. Sensitivity analysis is a methodology to determine how much vagueness in the inputs or disagreements among individuals affect the final overall results. The selection of weights may be sensitive, particularly for the evaluation of plans or projects that attract public interest. Sensitivity analysis can be applied on the weights assigned to the scenario branches to assess how the scenarios affect the overall ordering of the alternatives. Sensitivity analysis also has the potential to be helpful in resolving disagreements between interest groups (Communities, 2009).

5.2 Life Cycle Assessment in Seawater Desalination

214. The importance of desalination technology is increasing rapidly, which raises concerns about sustainable freshwater supply. Land use change, effects on the marine environment, energy usage, and noise pollution are only a few of the potential environmental effects of desalination technology. Based on this, it is necessary to incorporate environmental impact measures into the desalination process using a practicable solution and a sensible methodology. In order to assess the environmental performance of products and systems, including desalination technology, the LCA methodology has been widely used and acquired importance to date. Although desalination technology has become one of the most significant sources of water, it also has a number of environmental drawbacks that prevent its broader implementation. Therefore, the LCA approach may be used to propose environmental

pollution prevention strategies and enhance the environmental performance of the technology (Aziz & Hanafiah, 2021).

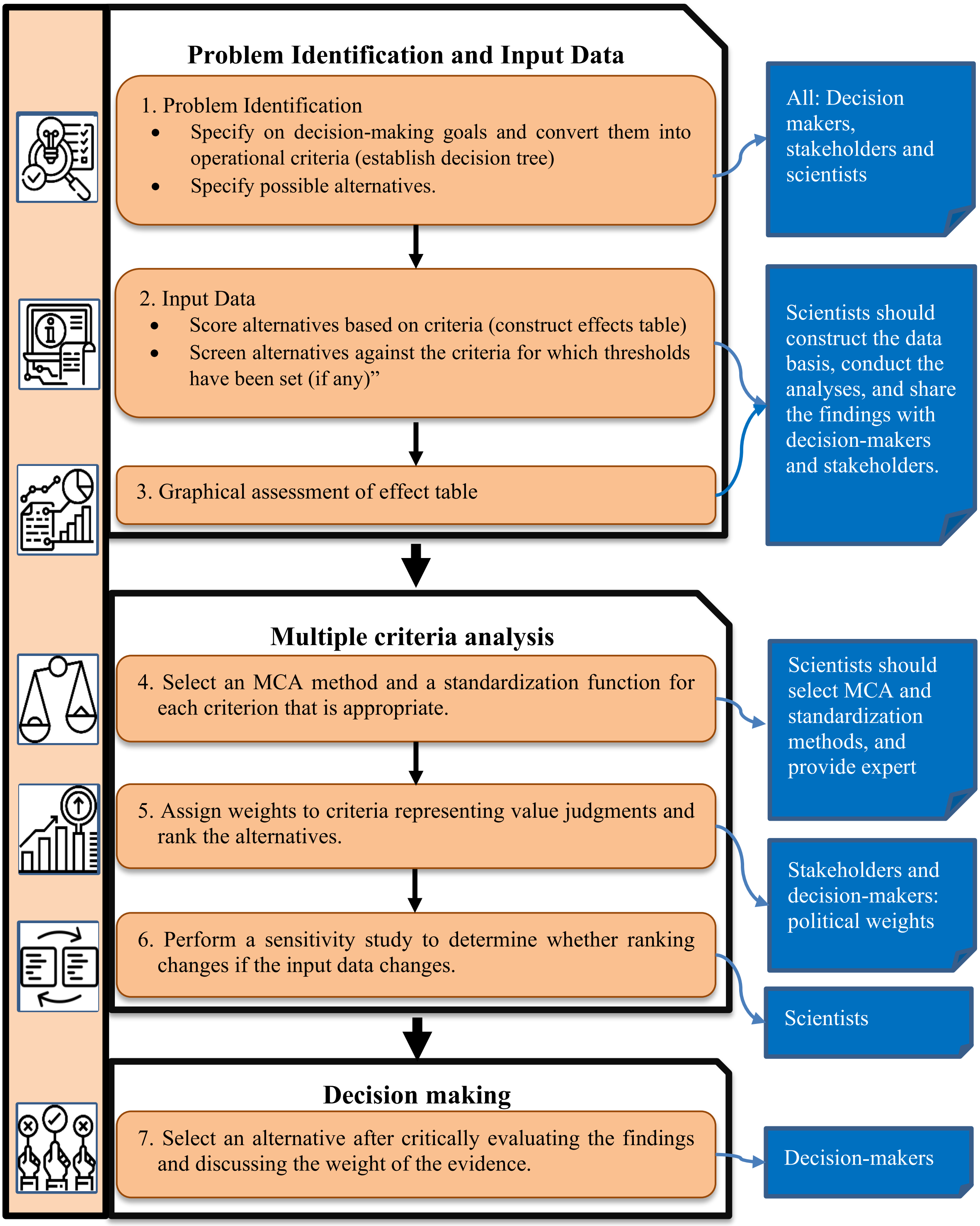


Figure 4. Methodology of MCA for decision making (adapted from Wang et al., 2019))

5.2.1 Life Cycle Assessment in the Context of Decision Making

215. LCA allows for the comprehensive inclusion and comparison of potential environmental impacts throughout the life cycle of a product or system. As a result, LCA enables decision-makers to

minimize or select different types of outcomes resulting from products or services that may have an impact on the environment or humans. The decision-making context in the LCA needs to be clarified to avoid using the results out of context (Pryshlakivsky & Searcy, 2021).

216. According to certain definitions, LCA is a decision support tool rather than a device for making scientific measurements. The person making a decision by choosing from a variety of possibilities is given information by the decision-support system. Decisions in LCA are typically presented as either/or choices when considering outcomes. Comparative studies in LCA draw conclusions based on measured differences in the same functional unit. The functional unit is a standardized unit—whether a product or a service—that is made explicit in the scope of the study and defines what is being studied in the LCA. The accuracy of the LCA study is determined by providing exact reference points for the functional unit's inputs and outputs. Despite the fact that the functional unit provides a standardized unit, comparative assertions in LCA are difficult to resolve for basic decisions. Decisions, for example, cannot always be reduced to a single variable, such as whether system A uses less energy than system B. Rather, users of LCA results must choose between options that are incompatible, such as whether waste reduction is preferential over air quality for the users of the results. Bias and preference are naturally introduced into the decision-making process as a result (Pryshlakivsky & Searcy, 2021).

217. LCA research employs scenarios in addition to prospective and retrospective studies. Scenario development tries to map out future situations or solutions. There are several approaches for developing scenarios in LCA, but the two most common are a) what-if scenarios and b) cornerstone scenarios (which use less resources). Because of the significant advancement in the related field, the use of standardized research plans, and the limited time frame in which implications are considered, what-if scenarios tend to be simpler than cornerstone scenarios. On the other hand, cornerstone scenarios, lack development and knowledge within the subject area, are complex, and are intended to broaden the subject area's depth of knowledge. Furthermore, cornerstone scenarios involve strategic planning, which has implications in terms of achieving desired results (Pryshlakivsky & Searcy, 2021). LCA has implications for decision making, but decision making also has consequences for LCA; that is, how the systems are modeled in LCA depends on the purpose of the study. In desalination systems, LCA is very important in decision making and especially in the evaluation and comparison of these systems.

5.2.1.1 LCA definition and principles

218. LCA method is a standardized framework that can enhance our understanding of the effects of a system or product throughout the stages of its manufacturing, utilization, and disposal. The LCA is a technique used to assess how desalination procedures change or effect environmental parameters. LCA is a tool for determining environmental aspects and potential effects throughout the whole life cycle of a product or system, from its raw materials through its disposal. Decision-makers can identify environmental hotspots and develop strategies to reduce harmful environmental impacts by using the LCA method (Lee & Jepson, 2021).

219. The four phases of the LCA, which is a standardized method guided by ISO 14040 and ISO 14044 standards, are goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The context of the LCA research is established in terms of defining the functional unit and system boundary during the goal and scope definition stage. The functional unit explains a system's main objective and makes it possible to treat various systems as functionally equivalent. In desalination LCA studies, the functional unit is often defined as 1 m3 of produced water. The aim of the study, the affected geographic area, the relevant time horizon, etc. all have an impact on how the system boundary is determined. LCI includes the compiling of relevant inputs, outputs, and the activities in the analyzed system. In the interpretation step, the results of the LCI and LCIA are evaluated in accordance with how the LCIA indicates the impacts of the environmental loads quantified in the LCI (Lee & Jepson, 2021; Zhou et al., 2014).

5.2.1.2 System boundary of desalination

220. In LCA studies, four different types of system boundaries are considered: cradle-to-cradle, cradle-to-gate, gate-to-gate, and cradle-to-grave. Only the process of extracting raw materials is covered under cradle-to-cradle. Cradle-to-gate describes the procedure from the extraction of raw materials to the phase of plant operation. Meanwhile, gate-to-gate refers to plant operation activity only. The desalination system's entire life cycle is covered by cradle-to-grave evaluation, which includes encompassing seawater extraction and processing, treatment, plant infrastructure, transportation, plant operation, distribution and use, dismantling, and final waste disposal. The system boundary of LCA's "cradle-to-grave" principle to desalination is shown in Figure 3. Building materials, equipment materials, and the transportation of construction materials to the plant site are all included in the construction phase. At the plant operation stage, the process consists of electricity generation, chemicals inputs, membranes production, and transportation. Building structure demolition, waste material (brine etc.), and membrane disposal are all included in the dismantling process.

221. Desalination's potential environmental burdens are attributed to the production of potable or non-potable water, which leads to the consumption of natural resources and discharge of pollutant emissions through infrastructure construction, energy generation, chemical production, membrane fabrication, and waste management (Aziz & Hanafiah, 2021; Zhou et al., 2014).

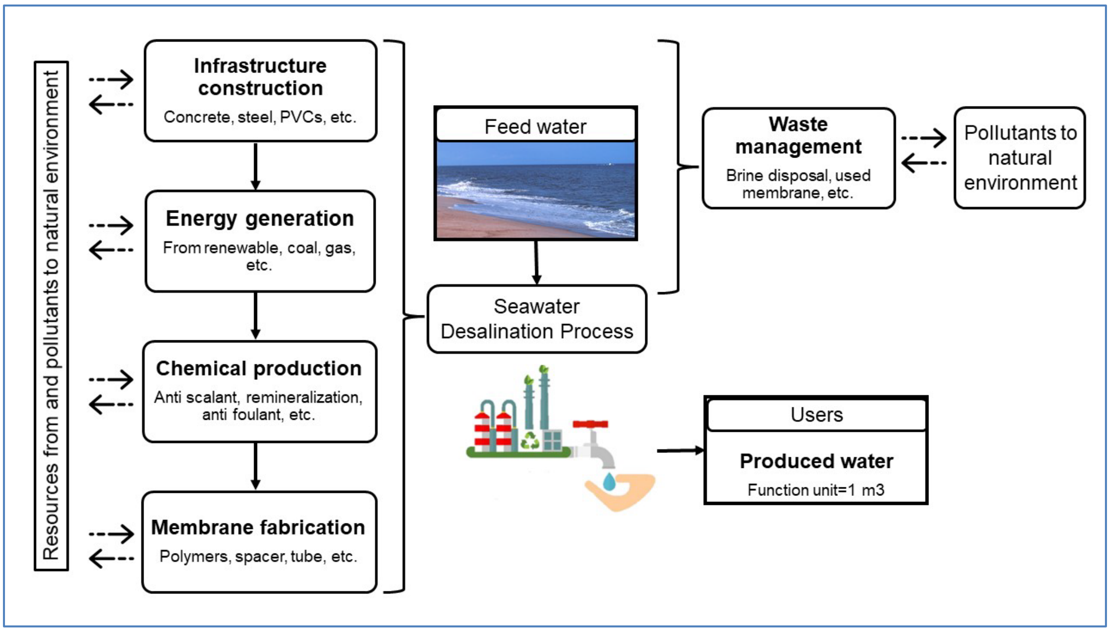


Figure 5. System boundary of LCA's "cradle-to-grave" principle to desalination (Adapted from Zhou et al., 2014)

5.2.1.3 Impact assessment of desalination

222. LCA can be conducted based on two approaches, namely midpoint (problem-oriented) and endpoint (damage-oriented). Midpoint indicators are located somewhere along the impact pathway between emissions and endpoints. A number of impact category indicators were combined into a damage category, also known as an area of protection, at the endpoint level. These indicators included human health, ecosystem quality, and resource availability (Aziz & Hanafiah, 2021).

223. The growth of desalination technology has demonstrated that it has turned into a significant supply of freshwater. This means that desalination must adhere to the principles of sustainable development. A holistic life cycle sustainable assessment (LCSA), as shown in Figure 4, can be completed by combining the well-established environmental life cycle analysis with life cycle costing (LCC) and social life cycle assessment (SLCA). The environmental LCA is performed using a functional unit that defines the product or process. The LCC method is used to calculate all costs associated with the product's or process's life cycle in terms of real monetary flows. In the case of

SLCA, the relative social impacts or benefits are evaluated using social criteria and indicators. The three pillars (environment, economy and social) complement each other to achieve the sustainability goal. As a result, desalination has had to be designed and operated in accordance with sustainability pillars in terms of environmental, economic, and social perspectives (Aziz & Hanafiah, 2021).

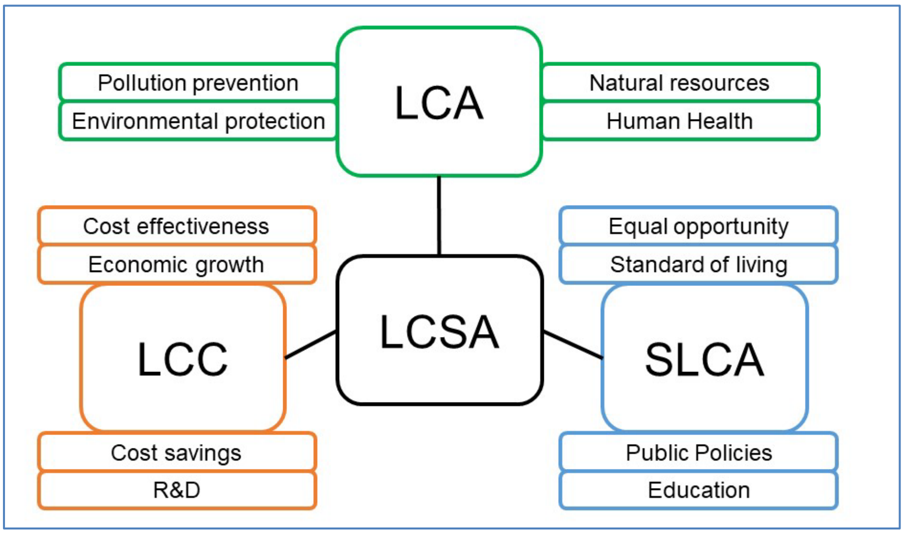


Figure 6. The three pillars of life cycle sustainability assessment (Adapted from Aziz & Hanafiah, 2021)

5.2.2 Feasibility of applying LCA to desalination

224. The approach used to make all acquired LCA knowledge easily accessible and usable for desalination studies is referred to as feasibility. Feasibility refers to three components: accounting methods, supporting databases, and approaches to LCIA. The approach used to make all acquired LCA knowledge easily accessible and usable for desalination studies is referred to as feasibility. Feasibility refers to three components: accounting methods, supporting databases, and approaches to life cycle impact assessment. Important considerations for the feasibility application in desalination are listed below (Zhou et al., 2014)

a. The process model is a better accounting method for desalination, whereas the Economic-input output LCA model can be used as a supplement depending on the availability of the economic-input output database and the scope of practitioners' research.
b. Desalination LCA studies, like other LCA efforts, are generally data intensive. To support background processes such as infrastructure construction, energy generation, chemical production, membrane fabrication, and waste management, LCA practitioners can use available databases. However, it is necessary to consider the representativeness of the chosen database.
c. The development of new knowledge can help to improve life cycle impact assessment. Two important features of a desalination system are brine disposal and freshwater savings. Unfortunately, the current assessment models used to translate those characteristics into corresponding impacts are still in development, potentially leading to significant underestimation of environmental impacts.

5.2.3 Reliability of LCA results for desalination

225. Another important factor to consider in desalination LCA is reliability. The concerns in this aspect are mainly on the incompleteness of the system boundary, the unrepresentativeness of database, and the omission of uncertainty analysis. Important considerations for the reliability of desalination are listed below (Zhou et al., 2014).

a. It is sometimes necessary to narrow the system boundary by ignoring a number of reference flows from background to foreground. From the perspective of practitioners, this approach is appealing because it can reduce the burdens of primary data collection. However, the exclusion of certain chemicals, construction materials, and membrane materials should be done with caution because they are highly dependent on the study's goal and the impact categories of interest.

b. The temporal and spatial representativeness of a database engaged in desalination LCA is important, as it is for other LCA efforts. Most current databases are based on European data from the late 1990s or early 2000s. To quantify the environmental impacts of newly constructed desalination plants in various geographic locations, regional and up-to-date data may be required to capture technological advancement and local context.
c. Uncertainty estimation can be improved by providing and tracking data quality metrics, such as how the data is acquired, how thoroughly the data is validated, and how well the data captures technological, spatial, and temporal variations. More efforts are needed to provide guidance and "best practices" in uncertainty analysis.

5.2.4 Sensitivity and Uncertainty analysis

226. LCA approach is used to evaluate the environmental impacts and resource consumption associated with the life cycles of products and services. LCA aims to support the development of low impact production systems and to inform decision-makers about the environmental impacts of various options. The results of an LCA study can be influenced by a variety of sources of uncertainty, mainly those related to methodological decisions, initial assumptions made about the allocation rules and system boundaries definition, and the quality of the available data. As a result, LCA supported decisions may be misleading. Uncertainty essentially results from a lack of knowledge regarding the precise value of a quantity. In detail, studies distinguish the following types of uncertainty.

a. Uncertainty in a parameter caused by inaccurate, incomplete, outdated, or missing values of data required for an impact analysis or an inventory analysis.
b. Uncertainty in models is frequently caused by the use of linear models to describe the connections between environmental events and by aggregate data on spatial and temporal aspects.
c. Uncertainty resulting from inescapable methodological decisions made in LCA, such as data collecting techniques, functional unit borders, and cut--off rules.

227. In the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) metrics, there is spatial variability between locations and temporal variability over short and long-time scales.

228. The two main analysis procedures for estimating the uncertainty of LCA results are sensitivity analysis- which assesses the influence of a parameter (the independent variable) on the value of another (the dependent variable) and uncertainty analysis-which determines range of possible results based on data uncertainty (Cellura et al., 2011).

229. Sensitivity analysis evaluates the results' robustness in response to potential changes in each research's underlying assumptions. Selected parameters were used in desalination LCA for sensitivity testing: electricity source and energy mix, energy usage, chemical usage, material life span, distances such as transportation distance, distribution distance, electricity transmission distance, material transportation distance, other variables including water hardness, environmental water requirements, feed water salinity and technology including membrane permeance, water flux, post-treatment process, pre-treatment system, and intake option (Lee & Jepson, 2021).

230. Uncertainty analysis in LCA allows us to calculate the overall uncertainty of the study results and estimate confidence intervals for the results, based on the uncertainties of all the parameters and model selection of the modeled product or system (Bamber et al., 2020).

231. Given the uncertainties that exist during the LCI and LCIA phases, sensitivity and uncertainty analysis should be used to evaluate the final results of an LCA in order to increase their transparency and robustness (Bamber et al., 2020).

5.2.5 Challenges and future perspectives of an LCA of desalination technology

232. Although the LCA is a scientific method for assessing a product's or service's potential environmental effects, it has its limitations and model uncertainties. An LCA requires a large amount of detailed data and information, and it is a time-consuming process. Additionally, a normalization reference, which represents the entire impact of a reference region for a particular impact category, drives the environmental analysis of LCA. The challenges and some recommendations regarding the application of LCA in desalination are given below (Aziz & Hanafiah, 2021):

a. A normalization reference, which represents the entire impact of a reference region for a particular impact category, drives the environmental analysis of LCA. To ensure that the outcomes of LCA analyses are accurate and practical, it is advised to use local databases.
b. Some of the challenges for LCA implementation will include a holistic consideration of stakeholders, time, and location. More LCI databases and parametric system models of process inventories and product life cycles should be developed urgently in order to overcome these obstacles.
c. Results from LCA should include an analysis of uncertainty, and LCA practitioners should be open and transparent about their limitations. Consequently, in order to implement this intricate and all-encompassing strategy, expert knowledge is required.

233. There are still several obstacles to the sustainable development of the desalination industry. Therefore, the necessary efforts should be contributed by designers, practitioners, utility managers and operators, water stakeholders, and policy or decision-makers. Additionally, education and awareness are crucial for implementing sustainable practices and including environmental performance metrics in decision-making (Aziz & Hanafiah, 2021).

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Appendix I

Description of Emerging and Pre-treatment Technologies

1. **Membrane distillation (MD):** MD is driven by an induced temperature difference between the hot seawater and the cold permeate water. As a result, seawater is heated to between 30–80°C before being transferred to the MD module, and the permeate is then cooled using the cool incoming seawater (< 20°C). An antiscalant is added to the stream prior to heating since the higher operating temperatures encourage scaling on the membrane surface. MD systems have advantages such as low temperature requirement, no pressure required, no limited feed water salinity, and high separation efficiency.

2. MD is now being researched as an alternative to RO and thermal-based desalination processes or as a supplementary technology at lab and pilot scales. Despite its advantages, MD is still not a widely used commercial technique. Pore wetting and low thermal efficiency are regarded as the two main problems for industrial-scale MD systems. The performance of the MD is also significantly impacted by fouling and low water flux (Ahmed et al., 2021; Skuse et al., 2021).

3. **Forward Osmosis (FO):** The natural osmosis phenomenon, by which a solvent moves from a low solute concentration to a high solute concentration, is the basis of osmotically driven processes. In FO, water is drawn into a concentrated draw solution on the permeate side of the membrane from the feed side. FO uses less energy than pressure-driven processes since it is a naturally occurring occurrence, and FO membranes also have a lower tendency to foul. However, FO desalination is a two-step process in which, the osmosis step must be followed by recovery of the draw solution. Desalination by FO depends on both the eventual recovery of the DS as well as the osmotic transport of water molecules through a FO membrane utilizing a concentrated draw solution. Despite being usually overlooked, the recovery step can have a substantial impact on overall energy usage, depending on the procedure used, the choice of draw solution, etc.

4. One of the most substantial FO barriers is the energy consumed during the recovery of the draw solution. Using a solution that does not require recovery, which essentially eliminates the recovery process, is a strategy to reduce the energy consumption of draw solution regeneration. However, this would lead to generation of additional waste through discarded draw solution. Investigating novel materials like ionic liquids (ILs) and magnetic nanoparticles (MNPs) are another strategy. MNPs have demonstrated important advantages over earlier DSs: they are capable of producing extremely high osmotic pressures and can be recovered using low energy magnetic separators. MNPs cannot operate under high enough flux to be commercially feasible, according to earlier studies. Recent studies show that this is being resolved, although long-term stability is still a problem. Since ILs may be recovered using solar energy or waste heat, they are also being looked into as a draw solution for FO desalination. Recent studies investigating ILs have shown improvements in flux and osmotic pressure, but incomplete recovery of the draw solution means that further separation (RO, MD) is needed.(Ahmed et al., 2021; Skuse et al., 2021)

5. **Adsorption Desalination (AD):** As an alternative to desalination methods, a low-temperature and yet low-cost thermal desalination method known as AD has emerged. The adsorption desalination cycle is a novel method that can produce water while using low-temperature waste heat. The two main processes that make up the AD cycle are adsorption-evaporation and desorption-condensation.

6. AD process can be used as hybrids by incorporating them into conventional systems such as MED or MSF, where the water production efficiency of the hybrids can be maximized. In laboratory-scale pilot trials, superior synergistic effects have been confirmed in the MED-AD hybrid system, increasing production up to two to three times over conventional MED (Gude, 2018; Ng et al., 2013).

7. **Freeze Desalination (FD):** The FD process represents a desalination technique involving a phase change from liquid to solid. Liquid, in this case, refers to seawater or saline water (i.e. brine) while solid refers to ice. Theoretically, a major part of ice crystals comprises pure water. Fresh water will be extracted in the form of ice during the freezing process, making the liquid that is left more concentrated. As a result, the FD process has a high separation factor. As it requires lower temperatures to operate, the FD process strongly depends on the use of refrigerants.

8. FD is an emerging technology to overcome limitations of membrane- and thermal-energy-based desalination processes. In contrast to the RO process, the FD method does not necessitate extensive pretreatment or chemical requirements. Additionally, the environment is harmed by the concentrated brine that is produced by RO. Contrarily, FD has the ability to process concentrated brine produced by the RO process with almost zero liquid discharge. When compared to the thermal desalination process, the FD process has minimum scaling and corrosion issues because of lower operating temperatures. Latent heat of ice fusion has a thermodynamically determined energy need of 333 kJ/kg, whereas water evaporation has a requirement of 2500 kJ/kg. As a result, the energy used for the FD process is approximately one-seventh of what is needed for thermal desalination.

9. In the FD process, large amounts of high-quality energy consumption are required to produce low temperature with the refrigeration cycle. Combining FD with liquefied natural gas regasification plant can solve the problem of energy consumption, thus reducing operating cost and making FD more attractive. Centrifugation, washing, and perspiration are the processes that are suggested to be used following crystallization to improve product quality (Kalista et al., 2018).

10. **Humidification Dehumidification (HDH):** In humidification dehumidification desalination (HDD) method, the saline water is heated, directly or indirectly, turning into water vapor and humidifying the ambient air. After that, it goes through a dehumidifier, producing freshwater condensate. During the humidification process, water diffuses into the air after coming into touch with unsaturated air. The driving force for this diffusion process is the concentration difference between the water–air interface and the water vapour in air.

11. Humidification-dehumidification is one of the most effective desalination procedures to consider for remote regions with a moderate freshwater demand. This is mostly due to the fact that it just needs minor operational and maintenance considerations. Since the heating process, which is an important step in this process, is an energy-intensive process, using sustainable energy sources is a necessity for today's world. The key advantages of HDD, such as its capacity to provide water to remote places, its small-scale rate, and its simplicity in integrating solar energy, make it a potential substitute for conventional desalination systems. When large-scale thermal desalination systems, such as MSF and MED desalination, are unsuitable options because of their cost and size, or when there is insufficient electric power supply to operate RO, HDD technology can be seen as a potential alternative. One of the major disadvantages of HDD systems is the high investment cost (Gude, 2018; Kasaeian et al., 2019; Srithar & Rajaseenivasan, 2018).

12. **Clathrate hydrate desalination (CHD):** In clathrate hydration desalination (CHD), a saline feed is mixed with clathrate-forming gases at low temperatures and high pressures to form clathrate hydrates: networks of hydrogen-bonded frozen water molecules surrounding the gas molecules. Clathrate hydrates, like ice, have a structure that excludes dissolved solids. To recover freshwater and liberate the gas, the solid hydrates can be separated from the remaining liquid and melted. Clathrate hydrates can form above the freezing point of the saline feed stream at sufficiently high pressures. Salts, like FD, adhere to clathrates, necessitating posttreatment (washing, pressing, or gentle melting) to produce low-salinity product water. CHD primarily consumes electricity for refrigeration and pressurization. CHD, like freeze desalination, has been proposed to be co-located with liquefied natural gas regasification, but any integration of LNG with desalination would need to justify that the economic benefits outweigh the opportunity costs of using LNG for other applications.

13. Corrosion, scale formation, and biofouling, which impair conventional desalination methods, are significantly reduced at CHD operating temperatures. CHD, like FD, has poor salt rejection, but it also has extremely slow kinetics and more complex operations, particularly the requirement to recapture clathrate-forming gas. As a result, the technology is unlikely to outperform FD (Shah et al., 2022).

14. **Batch Reverse Osmosis (BRO):** BRO is a transitory process in which the brine that exits the RO module is returned to the feed side without being mixed with fresh feed. The desalination process is extended in time rather than space with a small recovery ratio per pass. Regarding the problems of energy consumption and CO_2 emissions, numerous studies have published new processes and systems

to reduce the current level of energy consumption. In order to reduce the RO desalination process' thermodynamically irreversible energy losses, BRO has recently been developed. The irreversible energy loss is significantly decreased in the BRO system because the applied pressure gradually rises as concentration increases. BRO uses less energy than traditional continuous RO as a consequence, especially at high recovery. Despite the advantage in energy recovery with the BRO system, it cannot easily increase the recovery to a very high value as required for minimal brine disposal because the maximum operating pressure of the RO membrane is limited. For this reason, hybrid systems can be created by integrating BRO systems with systems such as AD, and minimal or zero liquid discharge can be achieved (Cordoba et al., 2021; Park et al., 2022; Wei et al., 2020).

d. Solar thermal desalination (STD): Sunlight is converted into heat in solar thermal desalination (STD) to evaporate saltwater. Solar evaporation ponds in conventional desalination, are used to concentrate saline streams but do not produce freshwater. Solar stills are STD devices that also condense the vapor to recover distilled water. Solar stills directly use solar energy, so the technology has the benefits of easy setup and operation, minimal equipment needs, and suitability for deployment in remote areas. Because STD is based on evaporation, it is not constrained by feed salinity and can, in theory, handle hypersaline salt concentrations. Where suitable low-cost land is available, STD can potentially serve as a simple ZLD solution.

e. Despite advances in solar absorption, heat localization, and salt buildup mitigation, STD remains an energy-intensive process. The SEC is, at best, the enthalpy of water vaporization unless the latent heat released by the condensing vapor is recovered (≈667 kWhth/m^3). Furthermore, the water productivity of STD is limited by solar irradiance. A considerable land area would therefore be needed for an operationally viable water production output (Shah et al., 2022).

f. **Solvent extraction desalination (SED):** SED is a thermally driven technique that does not involve the phase-change of water. At extraction temperature, the saline feed is mixed with a low-polarity solvent, where the two liquids are immiscible and thus form a biphasic mixture. However, because the solvent contains hydrophilic functional groups, it draws some water from the feed stream into the solvent phase, whereas salts do not prefer partitioning into the solvent's low dielectric constant environment and remain in the aqueous phase. The water-laden solvent phase is then decanted from the concentrated aqueous phase and brought to disengagement temperature, lowering the solubility limit of water. As a result, the previously extracted water separates from the solvent, yielding a desalinated product stream. Physical separation of the product water occurs, and the regenerated solvent is recycled back into the process. Since 2011, there has been renewed interest in this technology for hypersaline stream desalination and dewatering.

g. SED avoids many of the limitations associated with traditional high-salinity desalination technologies because it is both membrane-free and non-evaporative. Process top temperatures are typically <80 °C, so corrosion is lessened compared to conventional distillation methods.

h. Despite the fact that the solvents used in SED are low polarity, they are not completely insoluble in water. Therefore, a fraction of solvent is lost to both the dewatered raffinate and product water. Additional costs are incurred in recovering the solvent, and any leaked solvent that is not reclaimed must be replenished. Furthermore, residual solvent in the concentrate and product streams may necessitate posttreatment, especially if the solvent is toxic. The identification of solvents that minimize loss while being safe for the environment and human health is critical for technological advancement. Simultaneously, research on new solvents with high water production capabilities will reduce SED's energy consumption (Shah et al., 2022).

i. **Supercritical water desalination (SCWD):** SCWD uses the switch in solvent polarity from polar to nonpolar at supercritical conditions. Water behaves as a nonpolar solvent when it is subjected to supercritical conditions, which are defined as temperatures and pressures greater than 374 °C and 221 bar (≈3200 psi). Salts precipitate out of solution as their solubility in supercritical water decreases significantly, allowing for the easy separation of solid minerals from the fluid product water stream. SCWD is always a ZLD technology because no concentrate waste stream is produced.

j. Different feed stream compositions can be handled and treated with SCWD across the entire salinity range. Additionally, since the method precipitates out even sparingly soluble salts, extensive pretreatment is frequently not needed. The extreme pressures and temperatures required to produce supercritical water result in extremely high energy consumption and initial investment requirements for SCWD. SCWD materials must be thermally, mechanically, and chemically robust in order to withstand the extremely high temperatures and pressures. Despite the use of long-lasting materials such as stainless steel and titanium, superheated and pressurized high-salt brine is known to cause significant corrosion in equipment.

k. The two main challenges of high material durability requirements and high energy costs to achieve the extreme temperatures and pressures must be resolved for SCWD to be competitive (Shah et al., 2022).

l. **Zero Liquid Discharge (ZLD):** ZLD is a water treatment engineering approach in which the plant does not discharge any liquid effluent into surface water. This results in the complete elimination of the pollution associated with desalination. The ZLD method also eliminates liquid waste, maximizes water usage effectiveness, and reduces potential water quality issues. It also contributes to water conservation by reducing freshwater consumption through wastewater recycling and reuse. The challenges and cost of water recovery are increasing with the rise in salinity, presence of scaling compounds and organics in the wastewater and hence, the need for Zero-Liquid Discharge target is growing. The challenges to consider in ZLD implementation are following.

a. The choice of an appropriate method based on the composition, features, associated corrosion and temperature issues, and target capacity.

b. ZLD's capital and operating costs, which include energy and chemical costs associated with the evaporation and treatment processes, are significantly higher than those of other disposal methods.

c. When considering the ZLD technique, the material compatibility factor is critical. It refers to the material's corrosion resistance, or how it rusts or stains when exposed to chemicals, salt, and other compounds (Soliman et al., 2021).

15. Table A.1 provides a summary on evaluated metrics of energy grade product water salinity (i.e., compatibility with fit-for-purpose applications), technology demonstration status, zero liquid discharge capability, and ability to precipitate solids in bulk aqueous phase for emerging technologies (Shah et al., 2022).

Table A.1: Summary of metrics of energy grade product water salinity, technology demonstration status, zero liquid discharge capability, and ability to precipitate solids in bulk aqueous phase for emerging technologies (Shah et al., 2022)

Criteria	ED	FO	MD	HDD	SED	SCWD	FD	CHD	STD
Primary Energy Input	EC	S/LGH	LGH	S/LGH	LGH	EC+S	EC	EC	LGH
Product Water Salinity	FFP	FFP	DW	DW	FFP	DW	FFP	FFP	DW
Industrial-Scale Demonstration	+[1]	+		+			+[2]		
ZLD demonstrated				+	+	+			+
Precipitation in bulk solid				+[3]	+	+			

EC: Electricity, S: Steam, LGH: Low Grade Heat, +: Demonstrated performance, FFP: Fit-for-purpose, DW: Drinking water
1 ED Demonstrated for brackish water desalination
2 FD Demonstrated for food and beverage industry
3 Precipitation occurs at solution-air interface, away from solid surface

Appendix II

Major tools for monitoring of seawater desalination processes

Introduction

1. Seawater quality is a particularly sensitive subject and has dynamic conditions because it is closely linked to so many environmental issues. Due to the growth of pollution sources, monitoring its quality, particularly during intake and outfall operations, is becoming more difficult. In addition, the operational problems with desalination are heavily linked to the corrosive characteristics of marine organisms and seawater. These characteristics, in turn, might have a detrimental impact on the system, resulting in a facility's partial or occasionally entire closure. Furthermore, any unsuitable occurrence or operation can result in safety risks and resource waste. Thus, the comprehensive monitoring and assessment, and the selection of a suitable location has a significant impact on the entire production process and its efficiency, as well as the plant's overall operating life.

Compliance monitoring (indicator approach)

2. Compliance monitoring usually involves periodic or continuously monitoring of a certain parameter to ensure that legal requirements and environmental quality standards are being maintained. While it is ideal to look at as much as possible in an EIA, it is indeed practically impossible to constantly investigate every organism throughout every environment. Therefore, an indicator strategy is indirectly used in an EIA most often. Salinity and dissolved oxygen concentrations (or temperature for distillation plants) are appropriate physical indicators of desalination plants with the goal of ensuring compliance with regulatory requirements.

Trend monitoring (indicator approach)

3. Trend monitoring of the concentration of pollutants discharging into coastal waters through the effluents of the operations of desalinization needs to be established in order to contribute to the achievement of the targets of the Good Environmental Status (GES) of marine environment as defined in IMAP. Pollution reduction targets of inputs of pollutants should be agreed further to the outcomes of the trend monitoring.

4. Trend monitoring of pollutants discharging into coastal waters needs to include the pollutants emitted through the operations of desalinization by considering the analytical procedures for the sampling, sample preparation and analytical determination of the pollutants as recommended in UNEP/MAP Monitoring Guidelines for IMAP Common Indicators 13. 14 and 17.

5. The maximum permitted level of concentrations of pollutants measured in effluents discharging into coastal waters through the effluents of the operations of desalinization should be set further to a trend analysis of the concentrations of pollutants measured during a period that is not shorter than 5 years in order to guide the appropriate response measures in case of excessive discharges of pollutants.

Environmental monitoring plans

6. Although there is no scarcity of seawater, it is crucial to comprehend, constantly monitor, and take the appropriate steps to reduce the negative effects of seawater desalination, especially raising the prospect of its rapid expansion in the near future. Comprehensive environmental monitoring plans (EMPs) are developed to prevent, predict, and monitor impacts in feasibility, planning, design, construction, and operations of seawater desalination plants. These plans are implemented worldwide to comply with discharge water quality standards and environmental regulations with the aim of protecting the aquatic environment.

7. An environmental monitoring plan is developed to: (i) collect information on the environment during plant construction, installation, and operation as necessary; (ii) monitor the outfalls related to every project stage, including the operation stage; (iii) monitor any substantial changes in the area associated with the plant that may be caused by its activities, such as those that affect the physical,

chemical, or biological properties; and (iv) start mitigating actions before these changes affect the natural processes and become them irreversible.

8. The monitoring plan specifications should include water quality limitations at the sample locations, required dilution of brine discharges (including volume of discharge and salinity), controls for discharge dispersing, controls for local plant and animal species, and mitigation methods to reduce excessive salt concentration.

Appendix III

Process for conducting the Environmental Impact Assessments

Introduction

1. EIA is commonly defined as an assessment of the environmental impact of planned activities, including impacts on biodiversity, vegetation and ecology, water, and air. An EIA is a process for identifying, predicting, and evaluating the likely environmental, socioeconomic, cultural, and other impacts of a proposed project or development to define mitigation actions—not only to lessen negative impacts but also to provide benefits to the natural environment and well-being. A project's potential risks to the environment and human well-being are essentially identified in an EIA, along with steps that can be taken to eliminate and/or at least reduce such risks. This can be done by replacing and/or modifying planned activities to reduce impacts. In this context, an EIA can be seen as an information-gathering activity by the project proponent to outline (and if possible quantify) the risks, impacts and mitigation actions built into the project's whole lifecycle from design to closure so that decision makers are fully informed when approving the project. The most crucial factor in determining whether an EIA is necessary is the degree to which the project would have an adverse impact on both human and environmental health (IISD, 2016).

2. The EIA of projects is a key instrument of European Union environmental policy. It is currently governed by the terms of European Union Directive 2011/92/EU, as amended by Directive 2014/52/EU on the assessment of the effects of certain public and private Projects on the environment (EIA Directive). Since the adoption of the first EIA Directive in 1985 (Directive 85/337/EEC), both the law and EIA practices have evolved. The EIA Directive was amended by Directives 97/11/EC, 2003/35/EC, and 2009/31/EC. The Directive and its three amendments were codified in 2011 by Directive 2011/92/EU. The codified Directive was subsequently amended by Directive 2014/52/EU.

3. The three main stages of the EIA process are project screening and scoping, environmental impact assessment, and decision-making and EIA review. It should be noted that in practice, deviations from the outlined process may occur. Single steps may not necessarily have a defined limit; some may overlap or be used in place of others. Thus, the EIA process should be seen as a continuous and flexible process.

4. In order to assist project designers, consultants, regulators, and decision makers anticipate and address all relevant environmental, socioeconomic, and public health concerns that may arise when undertaking a desalination project for obtaining the highest possible level of beneficial use of the desalinated water in terms of quality, safety, and environmental protection, the United Nations Environment Programme (UNEP) and the World Health Organization (WHO) developed and released a guidance document on desalination. The objective of the guidance document is to identify a wide range of potentially significant challenges that may help in anticipating the pertinent issues of each desalination project individually. EIA process covering three main phases, scoping, screening, impact mitigation and reporting main EIA phases and were subdivided into 10 steps is shown in the following diagram (Figure A.1). UNEP (2008) Desalination Resource and Guidance Manual for Environmental Impact Assessments. United Nations Environment Programme, Regional Office for West Asia, Manama, and World Health Organization, Regional Office for the Eastern Mediterranean, Cairo.

Screening of the project

5. The process of screening determines whether or not an EIA is necessary for a certain project. Thus, screening involves making a quick assessment of the relative importance and anticipated environmental impact of a proposed project. A certain level of basic information about the proposal and its location is required for this purpose (UNEP, 2008).

6. The screening processes can be broadly categorized into two approaches: a standardized approach, where projects are subject to or exempt from EIA as defined by legislation and regulations; and a customized approach, where projects are screened on a case-by-case basis utilizing indicative advice (Lattemann & El-Habr, 2009).

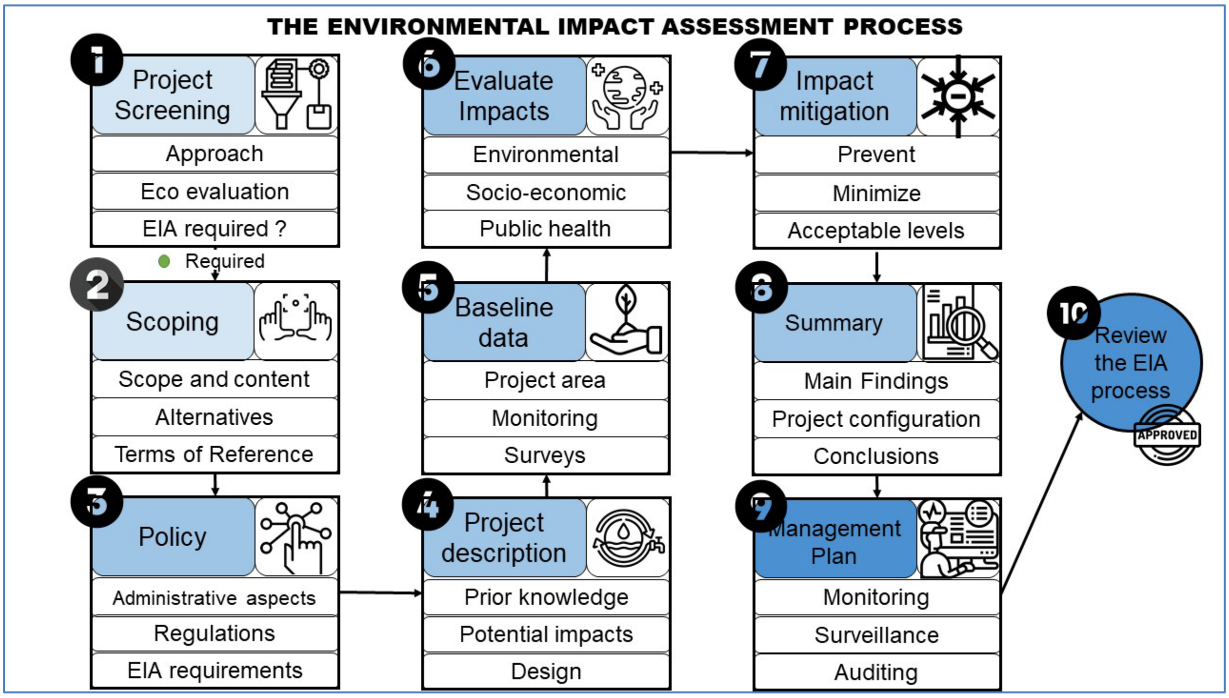

Figure A.1. The Environment Impact Assessment Process
(Adapted from (Lattemann & El-Habr, 2009))

<u>**Scoping of the project**</u>

7. Scoping is an important step in the preparation of an EIA because it identifies the issues that are likely to be most important during the EIA and eliminates those that are of little concern. Scoping is a systematic process that determines the parameters of your EIA and defines the framework for the studies you will perform at each stage. A quality scoping study reduces the risk of including inappropriate components or excluding components that should be addressed (UNEP, 2008).

8. The scoping procedure follow four basic steps; i) preparation of a scoping document for public dissemination, including project details and a preliminary environmental analysis, ii) organisation of scoping meetings inviting collaborating agencies, stakeholder groups, NGOs, experts and advisers, and announcement of the scoping meeting in public, iii)compilation of a complete list of issues during scoping consultations, which are then evaluated in terms of their relative importance and significance, iv) preparation of the terms of reference for EIA, defining the scope and information requirements of the EIA, study guidelines and methodologies (Lattemann & El-Habr, 2009).

9. The preparation of Terms of Reference (ToR) for an EIA is an important task in concluding the scoping process. The project proponent is given specific instructions for the information that must be submitted to the appropriate authorities for an EIA as well as the studies that must be conducted to gather that information in the Terms of Reference (ToR), which are developed throughout the process (Lattemann & El-Habr, 2009).

a) **Selection of the project site:** Environmental, socio-economic and public health impacts resulting from the construction and operation of a desalination plant are largely dictated by the location of the facility and its associated infrastructure. Therefore, proper site selection for a desalination plant during the planning process is essential for minimizing these impacts. Site selection typically takes place in the early stages of a desalination project and leads to the identification of a preferred site and possibly one or two alternatives.

b) **Project description:** A general description of the purpose and need of the project should be given at the beginning of the EIA document. It should include the following information:
   i. Proposed location of the desalination plant.
   ii. Co-location with other industries (such as power plants).
   iii. The onshore and offshore components of the plant (buildings, pumps, pipelines, brine outfall), planned construction activities and timeline.
   iv. Connection to the water supply grid.

c) **Technology selection and characterization of discharges** A detailed technological description of the chosen desalination process should be part of the EIA, including the rational for the choice. It should include the following information:
   i. The desalination technology chosen and engineering specifications
   ii. Desalination capacity of the plant and future expansion plans
   iii. Energy usage and source
   iv. Area and method of source water intake (open intake, well intake)
   v. The treatment steps of the source water during the desalination process (among others the pre- treatment, biocide application, anti-scaling measures, cleaning stages, desalinated water treatment)
   vi. Type of discharges and emissions (marine, terrestrial and atmospheric)
   vii. Total volume of discharges and emissions (daily, yearly)
   viii. Area and method of brine discharge (open discharge, co-discharge, marine outfall with or without diffusers)
   ix. Brine discharge pattern (continuous, intermittent, variable)
   x. Physio-chemical characteristics of the brine (salinity, temperature, etc...)
   xi. Concentrations and loads of discharged substances and their environmental characterization (such as persistent, toxicity, bioaccumulation).

Modeling

10. A model is a conceptual or mathematical simplification that is used to investigate a real natural system, a risk assessment problem, and/or a decision-making process, among other things. Modeling is a common requirement for an EIA process and a fundamental component of informed regulatory and decision-making processes. Modeling is a common requirement for an EIA process and a fundamental component of informed regulatory and decision-making processes (Kress, 2019).

Identification and description of policy and administrative aspects

11. An EIA typically takes place within the specific legal frameworks created by the nation in which the project will be located as well as those set by international organizations. As a result, it is advised to get a greater awareness of any national or international rules that might be relevant to the EIA process. Additionally, all thematically relevant laws and policies must be found, such as those pertaining to the preservation of the environment and biological diversity, the prevention and control of pollution, the management of water resources, or land-use and regional planning. To realize a desalination project, more than one permit will often be needed in several jurisdictions. The main approval process, which authorizes the construction and operation of a desalination plant, will not necessarily replace other existing statutory provisions, and permits. It is significant to identify the permits that must be secured early in the project planning process and to get in touch with the competent authorities. By designating a "lead" agency, which coordinates the process by involving other agencies and by notifying the project proponent about regulatory requirements, the permitting procedure may be made easier.

Investigation and description of the proposed desalination project

12. The many life-cycle stages of constructing, commissioning, operating, maintaining, and decommissioning the desalination plant should be covered in the project description. It should be brief,

include all the elements required for an impact evaluation, and not included any unnecessary or distracting material. It should include an estimate of every resource used during the various project operations, including the amount of land needed for building, the amount of chemicals used during plant upkeep, and the amount of energy used. It should furthermore include a characterization of all waste products in terms of quantity and composition, including emissions into air, water, and soils, as well as solid and liquid waste products transported to a landfill or discharged into the municipal sewer or stormwater system (Lattemann & El-Habr, 2009).

Investigation and evaluation of environmental baseline

13. It is possible to choose a reference region with comparable features, for which baseline data is established in the same manner as for the project site. This allows for a comparison between the reference site and the project site during project monitoring in order to detect any changes caused by construction and operation of the project. It is especially helpful to identify natural changes or other anthropogenic impacts unrelated to the desalination project using reference data from a site with similar environmental features (Lattemann & El-Habr, 2009). The environmental baseline must also include mapping of sensitive habitats in the area that will be potentially affected by the project and to plan the location of the marine infrastructure as that which will have the minimal effects. For example, to move the location of the outlet if the dispersion model shows that there is a sensitive habitat within the mixing zone.

Investigation and evaluation of potential impacts of the project

14. The prediction of impact in an EIA is typically based on conceptual models and tests, such as field and laboratory experimental methods (e.g. whole effluent toxicity tests), small-scale models to study effects in miniature (e.g. different outfall designs), analogue models which make predictions based on analogies to similar existing projects (e.g. other desalination plants) or mathematical models (e.g. hydrodynamic modelling of the discharges). Each of these models only covers a small portion of the range of impacts; therefore, they are frequently utilized in conjunction with one another, leading to a variety of studies being conducted by different experts. The relative importance of the anticipated impact should be assessed using factors like:

a) Is the impact direct or indirect, positive or negative?
b) What is its scope in terms of the impacted population's size or the geographic area?
c) How severe is the effect, how likely is it to happen, and is it reversible or can it be mitigated?

15. Identification of secondary effects, potential cumulative effects with other development initiatives on the project site, trans-boundary (far-distance) effects, and growth-inducing effects should be done whenever possible and suitable (Lattemann & El-Habr, 2009).

Mitigation of negative effects

In order to avoid, minimize, or correct major negative consequences to levels acceptable to the regulatory agencies and the affected community, impact mitigation step should identify the most feasible and cost-effective alternatives. According to various national, regional, or local standards, which depend on the social, ideological, and cultural values of a society or community, as well as on economic potential and politics, the definition of acceptable will change (Lattemann & El-Habr, 2009).

16. A hierarchy of actions is used to organize the mitigation components. Usually, impact prevention through appropriate actions and alternatives is given highest priority. Impacts should be reduced to the least extent practicable if prevention is impossible. All remaining major but unavoidable consequences that cannot be further minimized should be compensated for or remedied following the project's decommissioning (Latteman, 2009).

17. Mitigation can involve structural measures (e.g. design or location changes, technical modifications, waste treatment) and non-structural measures (e.g. economic incentives, policy instruments, provision of community services, capacity building).

18. Restoration of the impacted site during the project's lifespan or after demolition is complete is one option for remediation and compensation, as is the improvement of resource values elsewhere, such as through habitat improvement, reforestation, or restocking of a particular species (Lattemann & El-Habr, 2009).

Summary and conclusions

19. For this aim, a summary of the major implications (possibly in the form of a table) should be supplied, distinguishing between substantial impacts that can be avoided or mitigated and those that cannot. Both direct and indirect effects, positive and negative effects, and the potential of cumulative effects should be examined.

20. Whenever possible, choices to mitigation or avoid major effects should be provided. A systematic comparison of the original project proposal to different project configurations in terms of negative and positive impacts and the efficacy of mitigation strategies is essential. The final step is to identify the "best practicable environmental option," which is the ideal project design according to environmental, social, cultural, and public health criteria. It is important to make sure this choice is both financially and technologically viable. The decision should be transparent and supported by arguments (Lattemann & El-Habr, 2009).

Establishment of an environmental management plan

21. During the construction, commissioning, operation, maintenance, and decommissioning of the proposed desalination project, an environmental management plan should be developed to ensure the continual monitoring and review of the project's effects. Its purpose is to determine the actual consequences of the project and to confirm that the observed impacts are within the range indicated by the EIA. In addition, the goal of environmental management is to ensure that the mitigation measures or other requirements linked to the project permit are appropriately executed and effective. If not, or if unanticipated effects emerge, the measures and conditions must be modified in light of the new information. The management plan should outline any plans for planned monitoring, surveillance, and auditing activities, including methodology, timetables, and management processes for unanticipated occurrences (Lattemann & El-Habr, 2009).

Review of the EIA and decision-making process

22. The goal of review is to confirm the completeness and quality of the EIA data collected. This final phase ensures that the material supplied in the report conforms to the Terms of Reference as defined during scoping and is sufficient for decision making.

23. Review is a formal phase in the EIA procedure that serves as a final review of the EIA report before it is submitted for project approval. The review may be conducted by the relevant authority, another government agency, or an independent organization. Participation of collaborating and advising agencies in the review process is strongly advised, as is the participation of the public and important stakeholders in public hearings regarding the EIA's results.

24. The review should adhere to a systematic methodology. This will involve an appraisal and validation of the EIA methodology and technique, as well as a verification of the consistency, plausibility, and exhaustiveness of the discovered impacts, offered alternatives, and suggested mitigation actions.

25. The review process may adhere to specified norms and review criteria. If these are unavailable, the committee may rely on broad principles, objectives, and terms of reference, or use the questions below:

a) Does the EIA report address the Terms of Reference?
b) Is the requested information provided for each major component of the EIA report?
c) Is the information correct and technically sound?

d) Have the views and concerns of affected and interested parties been considered?
e) Is the statement of the key findings complete and satisfactory, e.g. for significant impacts, proposed mitigation measures, etc.?
f) Is the information clearly presented and understandable?
g) Is the information sufficient for the purpose of decision-making and condition setting?

26. The response to the last question is the most important and will essentially determine whether or not the EIA may be submitted to the competent authority as-is or with minor adjustments for decision-making.

27. On the basis of the EIA report, the analysis of stakeholder interests, and comments from collaborating agencies, the competent authority will make its own evaluation of the proposed project and decide on its approval or rejection. If the project is accepted, the competent authority will often impose conditions, such as mitigation measures, emission limitations, or environmental standards to be observed. (Lattemann & El-Habr, 2009).

Outline of an EIA report should incorporate

The outcome of the EIA process should include documented information pertaining to the following:

a) The goal and necessity of the project, including the accessibility and affordability of alternative water sources (water treatment and reuse, water conservation, water waste prevention).
b) Social sustainability: Impacts on human health (quality of desalinated water), land use, population growth, infrastructure, trust in the availability of desalinated water, impact on recreational activities, or other acceptable uses of the sea and shoreline.
c) Project description: The plant's onshore and offshore physical components (structures, pumps, pipelines, intake, and brine disposal systems), planned construction processes, and timeframe, as well as the intended location, co-located with other industries or marine applications.
d) Technology description: Engineering requirements, production capacity, energy source and use, intake and discharge systems, pretreatment of source water (coagulation, biocide application, anti-scaling measures, cleaning stages, desalinated water treatment), and type, volume, and composition of water discharge and emission levels (marine, terrestrial and atmospheric) are all factors in the desalination process.
e) Environmental baseline description: Compilation and analysis of current information on the terrestrial and aquatic environments nearby, as well as baseline monitoring assessments conducted before the construction.
f) Modeling: Loss of organism entrainment, impingement, and entrapment at intake systems, regional (near and far field) hydrography and brine dispersion, transboundary transport, and effects on seawater quality and sea organisms are the issues that need to be addressed.
g) Screening for toxicity in discharges.
h) Assessment of potential impacts.
i) Decision between options: Tools for defining and selecting the best alternative and establishing mitigation measures include environmental risk assessment and multicriteria decision assessment.
j) Describe the steps that will be taken to minimize or reduce adverse effects both during the construction phase and throughout the operational phase of the desalination plant, taking the following factors into account:
k) Best Available Technique (BAT): A measure's practical suitability for reducing discharges, emissions, and waste is indicated by its most recent stage of development (state of the art) of its processes, facilities, or methods of operation.
l) Best Environmental Practice (BEP): The use of the best possible set of environmental control techniques and methods.

m) The precautionary principle: Even if there is merely suggestive evidence of an influence, action should be taken to avoid major negative effects. 146 Seawater Desalination's Marine Impacts: Science, Administration, and Policy Recently, it has been proposed to add a phase to the EIA to account for the impact of climate change. Increased freshwater demand, rising seawater temperatures and salinities, and rising phytoplankton blooms are all potential factors in desalination (Kress, 2019).

Appendix IV

Example MCA studies applied on desalination

1. García-Bartolomei et al. (2022) used a GIS-based Multi-Criteria Analysis (GIS-MCA) approach to investigate and evaluate probable locations fit for the development and operation of desalination facilities in Chile. Using the Analytic Hierarchy Process (AHP) methodology, various environmental, social, and technical criteria were evaluated and weighted. Only 4.54% of the territory analyzed (114,450 km^2) was classified as highly suitable, proving the scarcity of space available to meet the industry's growth expectations. These findings indicate that GIS-based analysis provides a practical solution for selecting optimal areas for developing desalination plants, emphasizing the importance of defining priority areas for the long-term development of the desalination industry (García-Bartolomei et al., 2022).

2. Do Thi et al. (2021) studied on desalination procedure of saltwater using several technologies, including RO, MED, and MSF, with several energy sources (fossil energy, solar energy, wind energy, nuclear energy). In this study, the three assessment methods, which are LCA, PESTLE, and multicriteria decision analysis (MCDA) were studied at individually with the purpose of comparing the efficiency of the various desalination systems with that of the energy sources as given in Table 4. In MCDA part of the study, Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) method was used to assess the desalination technologies. In this study, the environmental factors were found as the most important with highest weight followed by the social and economic factors. The results indicates that RO is the best technology while MSF-based technologies are worst (Do Thi et al., 2021) as can be inferred from Table A.2 below.

Table A.2: Comparison of desalination techniques from several aspects (Abdelkareem et al., 2018; Al-Karaghouli & Kazmerski, 2013; Al Washahi & Gopinath, 2017; Cherif & Belhadj, 2018)

Type of Technology	Thermal Technology				Membrane Technology	
	MSF	MED	MVC	TVC	ED	RO
Type of Water	Seawater, Brackish	Seawater, Brackish	Seawater, Brackish	Seawater, Brackish	Brackish	Seawater, Brackish
Operation temperature (°C)	90–110	70	70–100	63–70	Ambient	Ambient
Typical unit size (m^3/day)	50,000–70,000	5000–15,000	100–3000	10,000–30,000	2–145,000	24,000
Electrical energy consumption (kWh/m^3)	4–6	1.5–2.5	7–12	1.8–1.6	2.6–5.5	5–9
Thermal energy consumption (KJ/kg)	190–390	230–390	None	145–390	none	None
Electrical equivalent for thermal energy (kWh/m^3)	9.5–19.5	5–8.5	none	9.5–25.5	none	none
Total electric equivalent (kWh/m^3)	13.5–25.5	6.5–11	7–12	11–28	2.6–5.5	5–9
Maximum value of CO_2 emissions (kg CO_2/m^3)	24	19.2	11.5	21	5.3	8.6
Distillate quality TDS (ppm)	~10	~10	~10	~10	150–500	<500
Unit product cost (USD/m^3)	0.52–1.75	0.52–1.01	2–2.6	0.827	0.6–1.05	0.52–0.56

3. In order to rank desalination plant location criteria in the United Arab Emirates (UAE), Dweiri et al. (2018) created a multi-criteria decision support system (DSS) by taking into account social,

environmental, economic, technical, and operational factors. Their results show that the most significant aspects of desalination plant location criteria are technical (21.9%) and economical (20.9%). Additionally, the most important sub-criteria of environmental, social, economic, technical, and operational aspects are wastewater discharge (22.2%), life species (13.3%), real cost of water and government subsidy (18%), quality and quantity of fresh water (12.4%), and water supply network (9%) respectively (Dweiri et al., 2018).