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إطلاق إمكانات تحلية المياه لأغراض الزراعة في المنطقة العربية

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United Nations Economic and Social Commission for Western Asia

Unlocking the Potential of Desalination for Agriculture in the Arab Region

Draft for Discussion

During

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Acronyms

BW	Brackish water
BOO	Build Own Operate
BOOT	Build Own Operate Transfer
BOT	Build Operate Transfer
BMC	Business Models Canvas
CAPEX	Capital expenditures (cost)
DBO	Design-build-operate
ED	Electrodialysis
EIA	Environmental impact assessment requirements
EMP	Environmental monitoring plan
ER	Environmental requirements
ESCWA	Economic and Social Commission for Western Asia
FO	Forward Osmosis
FS	Financial support
FAO	Food and Agriculture Organization (United Nations)
KISR	Kuwait Institute of Scientific Research
KSA	Kingdom of Saudi Arabia
LC	legal certainty
MENA	Middle East and North Africa
MSF	Multi-Stage Flash Distillation
MED	Multi-Effect Desalination

OPEX	Operating expenses (cost)
OECD	Organization for Economic Co-operation and Development
O&M	Operation and maintenance
PPP	Public Private Partnership
PV	Photovoltaic
PI	Public involvement
RO	Reverse Osmosis
RE	Renewable Energies
R&D	Research & Development
SW	Seawater
SWRO	Seawater Reverse Osmosis
SEC	Specific Energy Consumption
SIDA	Swedish International Development Cooperation Agency
SA	Social acceptance
TDS	Total Dissolved Solids
TST	Tajo-Segura Transfer
UAE	United Arab Emirates
USD	United States Dollar
WHO	World Health Organization
WWC	World Water Council

Summary

This study on desalination for agriculture is meticulously structured to ensure a comprehensive and in-depth exploration of the subject. Each theme within the report has been carefully organized to build upon the previous sections, providing a logical flow of information that covers all critical aspects of desalination in the Arab region. As follows:

The first theme will address the pressing issue of water scarcity and its impact on agriculture. It will begin by discussing the extent of water scarcity concerns in the region and proceed to examine sectorial desalinated water uses, focusing on how desalinated water is utilized across different sectors, with particular emphasis on agriculture. Additionally, the agronomic opportunities and socio-economic externalities of desalination projects will also be explored, highlighting the benefits of desalination for agricultural productivity, social communities, and the broader deployment market. Furthermore, the section on limiting factors and socio-economic and environmental requirements for desalination projects development will identify the various challenges and conditions necessary for the successful implementation of desalination projects, including environmental considerations.

The next part of the document, second theme, will provide an overview of the current technologies used in desalination, particularly those applicable to agriculture. It will present an overview of desalination technologies and discuss the latest technological advancements (bat) and market dynamics, exploring how innovations and market forces influence the adoption and development of these technologies.

Moving forward, the third theme will delve into the opportunities for improving energy efficiency in desalination processes, especially within emerging agro-industrial companies, and will highlight the primary challenges these companies face.

In the fourth theme, the document will review the policies, regulations, and planning strategies that impact desalination projects, providing insights into the legal and administrative landscape that governs these initiatives.

The fifth theme will analyze the costs associated with desalination projects, evaluating their economic feasibility by considering various financial aspects that affect their viability.

The document will then explore, in the sixth theme, financing modalities & delivery models of contract, discussing different financing options and contractual models available for desalination projects. This part will include an examination of financing modalities and delivery models of contract, as well as an introduction to financial schemes: business models canvas (bmc), which will serve as a tool for planning and implementing financial strategies. it will also assess the desalination cost & crops economic viability, determining the cost-effectiveness of desalination in relation to the economic viability of various crops.

Further, the seventh theme will focus on the growth of the desalination market in the Arab region, emphasizing the capacity-building efforts needed and the significant challenges encountered during the construction of desalination facilities.

The document will then present good practices: case studies & replicability potentials, offering case studies of successful desalination projects in different regions. This section will showcase examples from North Africa and the Middle East, as well as a global perspective, particularly examining the contrasting attitudes between managers and farmers in Alicante and Murcia (Spain).

Finally, the report will conclude with recommendations and future perspectives, offering practical advice and suggestions for future desalination projects. this section will include environmental recommendations: emerging sustainable strategies, focusing on environmentally sustainable practices, and political and social recommendations, providing guidance on navigating the political and social aspects of desalination project implementation.

Introduction

Given the growing concerns about climate change, food security, globalization of food markets and prices, water scarcity, and rising energy costs, the agricultural sector is under significant pressure to enhance its water management strategies & practices. Including the optimization of existing water resources utilization, implementing & leveraging efficient irrigation techniques, reducing water waste and more importantly adopting innovative technologies. Moreover, the agricultural sector must explore all available possibilities to balance the supply and demand of water. (Beltrán & Koo-Oshima, 2004)

These possibilities may include the use of treated wastewater, rainwater harvesting, soil moisture management and the potential integration of desalinated water where feasible. Given that over the past decade conventional water production cost have been rising in many parts of the world, conversely costs for desalination have been declining, consequently desalination has become more economically attractive and competitive. (Lattemann, Kennedy, Schippers, & Amy, 2010) And as water demand increase, the number of desalination plants has also increased.

Desalination allows a widening in utilization of available water resources by producing cost-effective and potentially climate-independent freshwater of controlled quality from saline or brackish natural water sources for agriculture application. (Zarzo, 2012) Furthermore, by tapping into the vast reserves of seawater, desalination provides a reliable and consistent water supply which can mitigate the effects of droughts and water shortages ensuring continuous agricultural productivity, stabilizing food production and supply and contributing to food security. (El Kharraz , 2024)

Additionally, due to the lower water quality standards needed for agricultural use, the desalination process requires limited manpower, chemicals and membrane replacement leading to reduce operational costs. (Zarzo, 2012) Consequently, the simplicity of desalination plants for agriculture, with reduced requirements for civil works, automation, and safety measures, further underscores their cost-effectiveness and feasibility. (Zarzo, 2012)

As a result, the worldwide population relying on desalinated seawater is expected to increase from 7.5% of the world population in 2015, to a projected 18% in 2050. Furthermore, in the last six years, the world total water desalination capacity, including brackish water and seawater desalination, increased steadily with an annual rate of about 9%. Likewise, the global production capacity of desalinated seawater is expected to double by 2040. (FAO, 2024)

Eventually, this study aims to offer comprehensive insights into the current status of water desalination intricacies dedicated to agriculture applications. By, presenting the latest developments and innovations in desalination technologies, the study seeks to inform and guide stakeholders in the agricultural sector on how to effectively integrate desalinated water into their irrigation practices. Notably, it focuses on providing up-to-date information on the use of desalination for agriculture, shedding light on the potential benefits and impediments associated with such approach. Turning the current study a vital source for farmers, policymakers, public servants and researchers fostering decision-making and promoting management of water resources in agriculture through case studies, meticulous cost analysis, successful business models, and replication potential.

I. Desalination for Agriculture in the Arab Region

A. Water Scarcity Concerns

The Arab region is known more for its abundance of oil rather than for its shortage of water. It is the driest region in the world with renewable water resources of less than the critical level of 1 000 m3/person/year as defined by the World Health Organization (WHO). (Beltrán & Koo-Oshima, 2004)

With 6.3% of the world’s population having access to merely 1% of the world’s total water resources. Water scarcity in the Arab Region is one of the major and most critical development challenges. This challenge is expected to grow over time due to many pressing driving forces, including population and economic growth, tourism, food & energy demand, political and social conflicts and climate change. Most of the Arab countries are already living in conditions of absolute water scarcity. (El Kharraz, 2020)

The region is one of the most water-stressed areas of the world, with an average per capita of renewable water resources of 351 m3/y in 2014, whereas water availability per person in other geographical regions is about 7,000 m3/y. Twelve Arab countries are below the absolute water scarcity level of 500 m3/y per capita. It is also worth noting that renewable water resources are unequally distributed across the region as evidenced by the annual share per capita that varies between 5 m3/y in Kuwait and 2,802 m3/y in Mauritania. (El Kharraz, 2020)

Consequently, the concept of water security has gained traction in the global political agenda and garnered attention from national governments at the highest level, specifically as a result of its relation to all forms of security including peace and state security, but also for its implications for development issues.

Notably, Across the Arab region, desalination is increasingly being considered as a technical, supply-side solution that can meet current increasing water demands and buffer against the negative impacts of climate change on water resources. Despite being energy intensive technology, the Intergovernmental Panel on Climate Change (IPCC) lists desalination as an adaptation option which may be particularly important in arid and semiarid regions such as the Arab region. (El Kharraz, 2020)

B. Sectorial desalinated water uses in the Arab region

One of the main challenges in the Arab coastal agricultural areas is the growing salinity of groundwater, with water tables falling throughout the country because of seawater intrusion and the overexploitation of aquifers. (El Kharraz, 2020) resulting in an intensive use for irrigated water estimated at 70% of total usage, followed by industrial utilization, around 21%, and domestic use around 9%. (Suwaileh, Johnson, & Hilal, 2020) As shown in **Fig.1**.

Initially, desalinated water as a resource was restricted to use on islands, military bases, industrial sites and hotels (1950 - 1970). Between 1970 and 1995, it became the main resource for cities in the Arabian Peninsula and it has now become an accepted fact in the states of the Gulf Cooperative Council (GCC) that their future water demand will be met by desalination. In addition to the GCC countries, desalination is becoming the only viable and economic solution for countries such as Jordan and Palestine. (Beltrán & Koo-Oshima, 2004)

As a result, desalination is becoming increasingly important as a solution to the region’ s water problem. Many water-stressed countries in the Arab region are increasing their water supplies with desalination to meet the needs of the continuous growth of population and industrial, tourism and agriculture developments. Desalinated water can no longer be considered a limited resource because some countries such as Qatar and Kuwait rely 100% on it for domestic and industrial use, whereas Saudi Arabia reliance is nearly 60%. (El Kharraz, 2020)

In this respect the number of desalination plants in the Arab region, both planned and under construction, has increased significantly in recent years, as shown in **Fig. 2**. Consequently, there is increased emphasis on enabling cost effective desalination technologies to provide water of suitable quantity and quality for agricultural applications. (Burn, Hoang, Zarzo, Olewniak, & Campos, 2015)

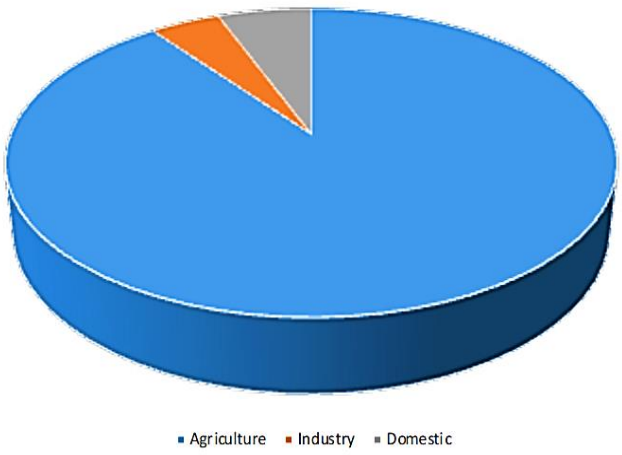

Fig. 1. *Water consumption per sector in the Arab world. (FAO, 2022)*

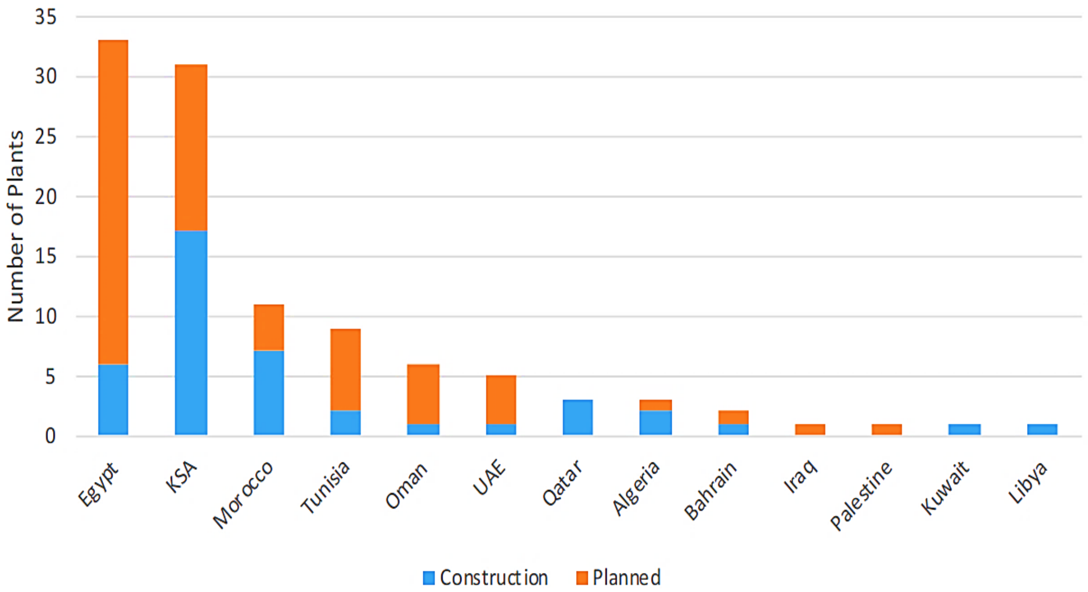

Fig. 4. *Arab desalination projects distribution (2020-2030). (FAO, 2022)*

In fact, many countries have started using desalinated water for agricultural purposes at varying rates to meet their water needs. For instance, in Kuwait where the installed capacity exceeds 1 million m^3/day, only 13% is used for agriculture. And in Saudi Arabia where, the world's largest single producer of desalinated water; only 0.5% of its desalination capacity is used for agricultural purposes. Bahrain implemented a desalination capacity of 620,000 m3/day while it uses only a small proportion of desalinated water of 0.4% for agriculture while Qatar used only 0.1% of its desalination capacity for agriculture. (FAO, 2024) Furthermore, if we consider the example of Oman, due to the increased level of soil and water salinization along Al-Batinah region coast, an increasing number of farmers are using small-scale desalination units for producing irrigation water.

North African countries vary in their demand for desalination from the need to supply water to sea resorts, such as in Egypt and in Tunisia, to becoming an alternative to major water transport schemes, such as Egypt in its Sinai development, and Morocco for supply to its southern region.

Other countries such as Libya and Algeria view desalination as a *de facto* source of water to meet growing demands for fresh supplies. Whereas Syria and Lebanon may not see the need for desalination, Syria (with over abstracted aquifers) still has to consider desalination in its interior far from rivers and the sea.

On the other hand, Yemen, the most water-depressed country in the world, has the additional problem of being forced into a combination of desalination and major transport schemes. Iraq is likely to experience severe water-treatment requirements equivalent to desalination, and it will also need solutions involving desalination in its southern territories. (Beltrán & Koo-Oshima, 2004)

In Abu Dhabi, for example, desalinated and recycled water users demonstrate greater water efficiency per square meter of cultivated land compared to groundwater farms in Al Ain and Dhafra. The reason behind these huge capacities in the region, as indicated in figure 3, is the technological improvements which led to a drop in the cost of desalination. Currently, the global market is led by Saudi Arabia with a total cumulative capacity of 15,378,543 m3/d followed the United Arab Emirates (UAE) with 10 721,554 m3/d. (El Kharraz , 2024)

Nevertheless, it is worth to mention that despite the extensive usage of desalinated water in the Arab region, desalination technologies remain an expensive option for agriculture, and it has environmental challenges that includes energy requirements, water quality, and disposal means of rejected brine which end up in many cases by contaminating groundwater and increasing its salinity. However, it can still be an attractive option for sustainable agriculture if used within specific constraints. (El Kharraz, 2020)

C. Agronomic Opportunities and Socio-Economic externalities of desalination projects

The Arab region faces food security difficulties, particularly in countries seeking to enhance it through increased agricultural production. (El Solh, 2015) Speaking of agricultural water consumption, according to the United Nations report, agriculture alone uses 70% of the world’s water supply. Besides, global food demand is expected to increase by another 70% by 2050. However, according to the report, the main challenge facing the world today is not so much the increase of food production, but rather to provide good-quality irrigation water to farmers in sufficient quantities. (Daghari, Desalination and Agriculture, 2022) In this context, Desalination for sustaining agricultural production is being reported as an alternative water source in some Mediterranean countries faced with the climatological and hydrological constraints. (Ricart, Villar-Navascués, Gil-Guirado, M. Rico-Amorós, & Arahuetes, 2020)

Figures on recent installed capacity around the world and on rates of expansion confirm the momentum of desalination and its promise to overcome the social, political, territorial and environmental problems of traditional hydraulic solutions and contribute to the emancipatory power of technology in ways that conventional solutions such as dams, reservoirs and water transfers are increasingly unable to achieve. As a matter of fact, according to its proponents, desalination not only taps an inexhaustible resource but also has the potential of effectively removing water from political, territorial and ecological conflict. It is, therefore, an alternative with multiple “wins” and few losses at least in comparison to those of the more traditional alternatives. (El Kharraz, 2020)

Furthermore, in a few countries, desalinized brackish water (whose price is typically a third of desalinated seawater) is already widely used by farmers. For instance, 22% of water desalinated in Spain goes to agricultural irrigation. An Australian survey found that 53% of the population envisioned desalinated water usage for irrigation of vegetables as highly likely. (Yermiyahu, et al., 2007) This is due to the numerous advantages ensured by desalination technologies such as Tailored conductivity for irrigation water, Assured supply, consistent quality of agricultural products, Increased production in comparison to other water sources, higher resale price of water due to quality and assurance, and possible recovery of saline soils by irrigation with high quality water. (Burn, Hoang, Zarzo, Olewniak, & Campos, 2015)

Socially speaking, desalination can significantly enhance the water security of a nation, while also supporting regional stability by evading conflict over water resources. Also, the strengths and opportunities of desalination projects include fast deployment with the potential to help remote communities and tourist facilities flourish. Local employment opportunities during the construction and operation of desalination plants are another benefit, but easy access to water also means more work and education opportunities for women who might otherwise be tasked with the time-consuming work of sourcing and carrying water. (Sterling, 2023)

Additionally, it is key to underscore that desalination offers the advantage of consistently producing high-quality, low-risk water that is less prone to the contamination, public health concerns, and user stigmatization often associated with wastewater reuse technologies. (Williams, Beveridge, & Mayaux, 2023)

Consequently, desalination is an essential tool to address global freshwater demand for irrigation, tourism, industrial purposes such as power plants or mining, drinking water, etc., providing significant benefits for homes and industries as such countries work toward socio-economic development. (Sola, Saez, & Luis S´anchez-Lizaso, 2021)

D. Limiting factors and Socio-Economic and Environmental requirements for desalination projects development

The wider application of desalination technologies for agriculture is limited by its relatively high cost besides the need for agriculture to be close to saline and brackish water feedwater sources as well as a safe and cost-effective disposal of the brine (Suwaileh, Johnson, & Hilal, 2020). Differently speaking, in spite of this development, the costs of desalinated water are still too high for the full use of this resource in irrigated agriculture, with the exception of intensive horticulture for high-value cash crops, such as vegetables and flowers (mainly in greenhouses), grown in coastal areas (where safe disposal is easier than in inland areas). (Beltrán & Koo-Oshima, 2004)

Furthermore, environmentally speaking, water, air quality, ocean space, water reservoirs, and other factors may all be adversely affected by desalination facilities. The environmental consequences of these facilities, as depicted in the figure down below, are typically considered at the national level, and their acceptability and mitigation requirements vary depending on the context. World Health Organization (WHO) recommends implementing post installation monitoring programs to monitor desalination plants' impact on sustainability. (FAO, 2022)

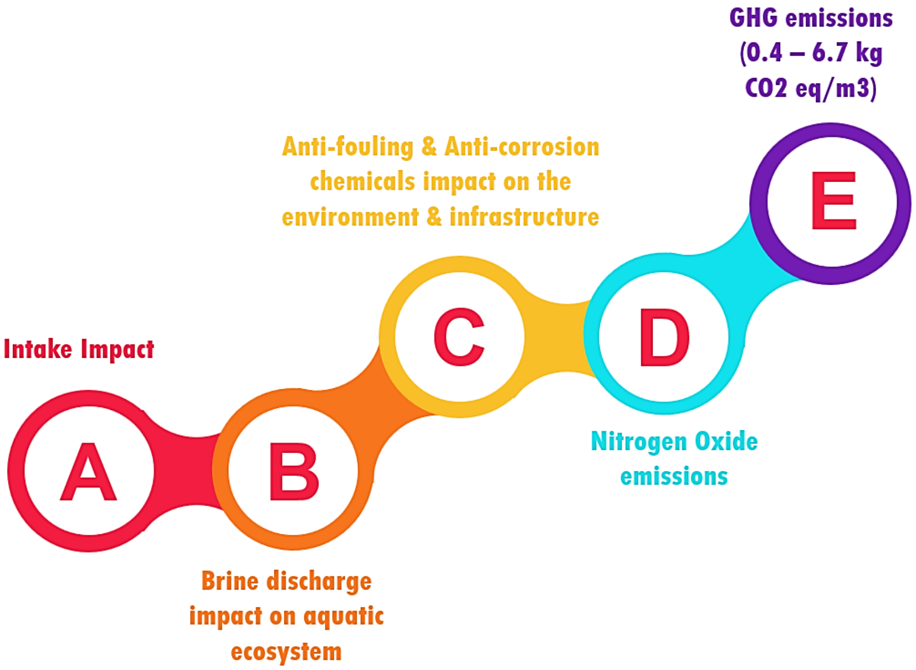

Fig. 6. *Major environmental challenges associated with desalination projects development.((FAO, 2022); (Elmahdi, 2022); (Beltrán & Koo-Oshima, 2004); (Al-Abri, 2022))*

Beyond the concerns about energy costs and environmental impacts, issues that are being examined by social scientists are, for instance, the financing of desalination plants; the sometimes negative reactions of citizens to this new resource; the health dimensions of desalted water; the creation of relative scarcities given the higher costs with particular impacts on farmers and poor urban dwellers; the possibility of capturing cheaper water resources by mining or large agricultural companies; the perpetuation of the cornucopian imaginary (for those who can afford it) of plentiful resources making conservation needless; the geopolitical implications of strengthening through desalination; the reworking of the water-energy-food nexus in some regions of the world, the opportunities for capital investment after the exhaustion of other large water works, and the reinforcement of the attraction of people to coastal areas as well as the more well-known of environmental impacts (marine biota, higher carbon footprint if energy is derived from fossil fuel power plants). (El Kharraz, 2020)

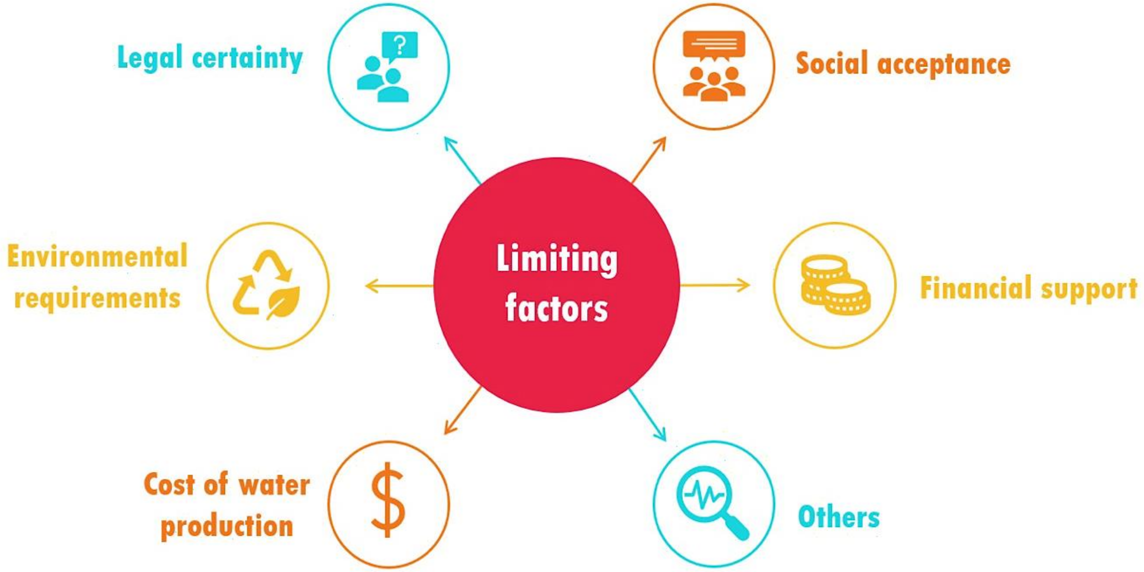

Fig. 9. *Summary of limiting factors used to assess desalination development across different countries.* (Sola, Saez, & Luis S´anchez-Lizaso, 2021)

Additionally, it is key to underscore that continuous increase in global freshwater demand has occurred more rapidly in certain countries owing to certain factors that can influence the development of desalination projects. Consequently, a survey of 34 international desalination experts was carried out to evaluate the main requirements and most limiting factors for the development of desalination projects in different countries. (Sola, Saez, & Luis S´anchez-Lizaso, 2021) As illustrated in **Fig.4 & 7.**

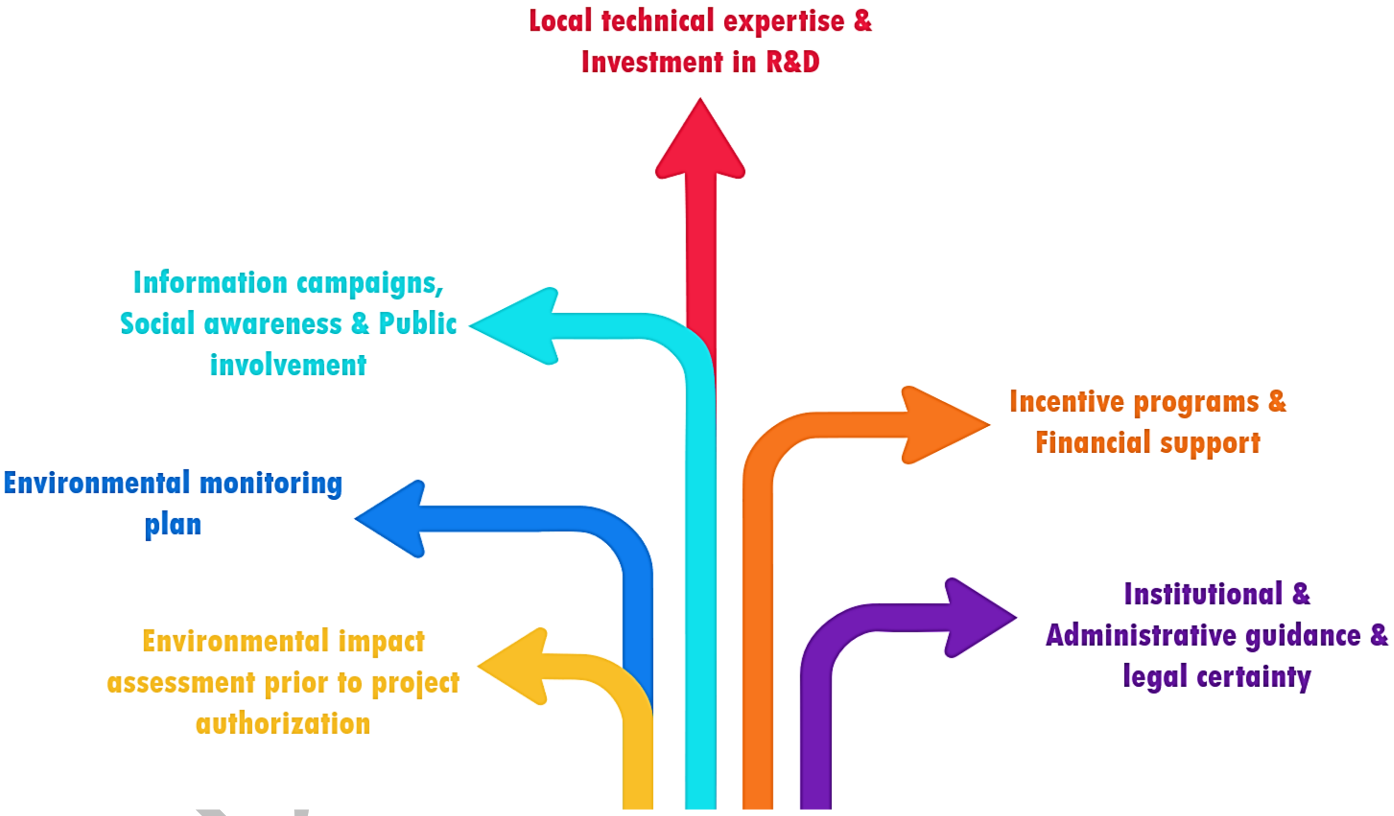

Fig. 12. *Summary of major requirements used to assess desalination development across different countries. (Sola, Saez, & Luis S´anchez-Lizaso, 2021)*

The "requirements" assessment related to socio-economic and environmental aspects of desalination development is presented in **Fig. 6**. According to the EIA requirements assessment, the results showed that Australia and USA impose the highest number of requirements in EIAs, followed by Chile, Spain and Peru, which each impose a high number of requirements.

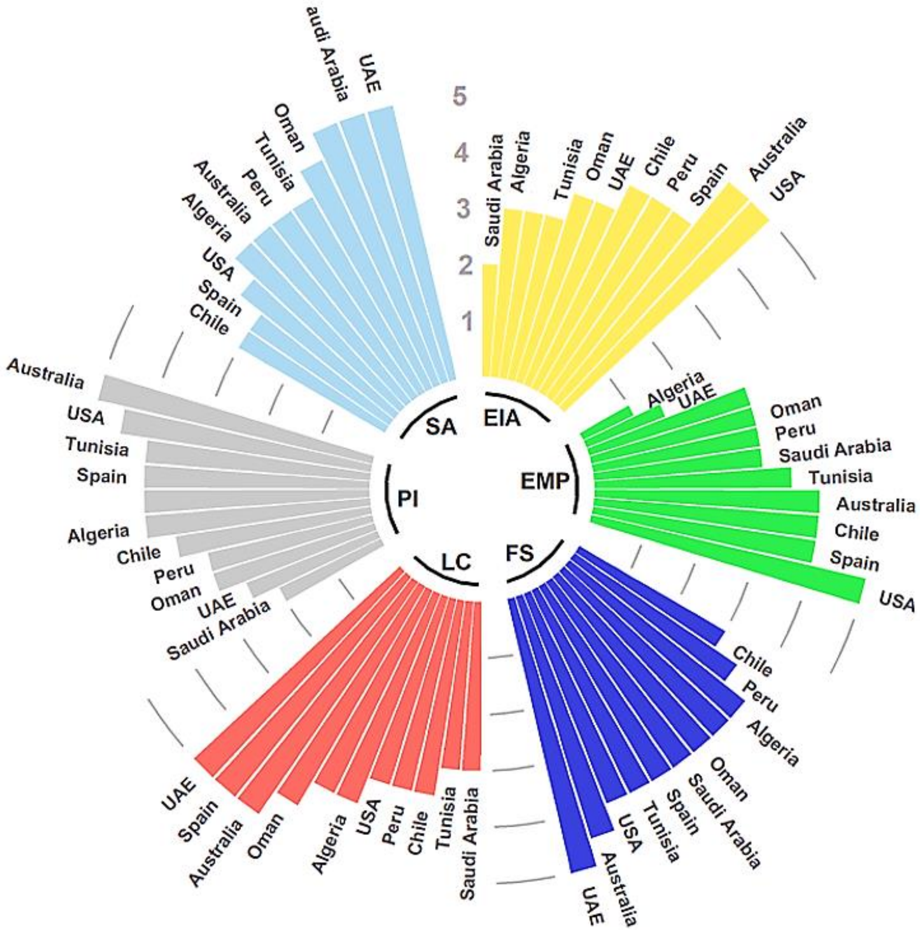

Fig. 15. *Conceptual summary of median values for "requirements", as evaluated by desalination experts for each country analyzed. Requirements were evaluated using a semi-quantitative scale (1–5), where 1 represents a lowest number of requirements and 5 a highest number of requirements. (Sola, Saez, & Luis S´anchez-Lizaso, 2021)*

The “limiting factors” assessment for desalination project development is presented in **Fig. 7**. Within this evaluation, several factors were identified as limiting the development of desalination plants in various countries:

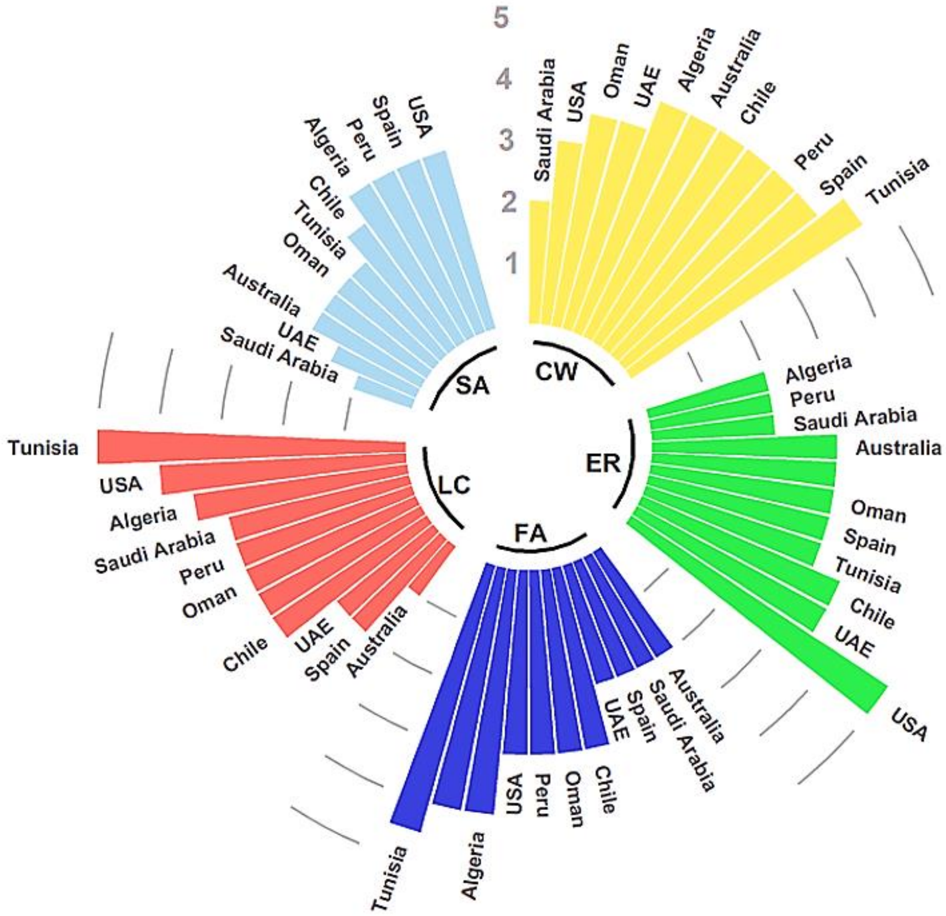

Fig. 17. *Conceptual summary of median values for limiting factors evaluated by desalination experts for each country analyzed. Limiting factors were evaluated using a semi-quantitative scale (1–5), where 1 represents a very low limiting factor and 5 represents an extremely limiting factor. (Sola, Saez, & Luis S´anchez-Lizaso, 2021)*

The obtained results showed high heterogeneity of environmental and socio-economic requirements across different countries. The main barriers identified for desalination development were the cost of produced water, low financial support, and stringent environmental requirements. It was observed that social acceptance of desalination projects is normally high and does not represent a limiting factor for their development. However, low levels of environmental requirements and/or public involvement have been identified as issues and these should be improved in some countries.

Regarding water quality standards for irrigation, damage to crops after irrigation with extremely pure water produced by the world’s largest RO desalinations plants reveals a need for revised treatment standards (Yermiyahu, et al., 2007).

In fact, incorporating desalinated water in agriculture can have varying agronomic effects. Key concerns include its lack of essential nutrients, leading to higher fertilization needs, especially for greenhouse crops. Additionally, its unique chemical composition may degrade soil structure due to sodicity, negatively affecting crop yield, with potential toxicity from high levels of boron and chloride (Ricart, Villar-Navascués, Gil-Guirado, M. Rico-Amorós, & Arahuetes, 2020). In this regard, the results of a pioneer study in Spain, studied the progressive replacement of traditional irrigation water resources with DSW show that the combined use of DSW with traditional resources is the most efficient option, rather than irrigating with DSW alone (FAO, 2024).

Consequently, the correct application and management of specific quality regulations, mixing and management modelling, technical means on the farm, as well as water and soil monitoring can mitigate these risks for agricultural irrigation with desalinated seawater.

II. State of the Art of Desalination Technologies Suitable for Agriculture

A. An overview of desalination technologies

Ever since desalination was initially invented in antiquity, more than 20 different technologies have been used for seawater desalination, broadly categorized into three groups: thermal processes, membrane separations, and emerging technologies. (FAO, 2024) The schematic diagram down below illustrates major desalination technologies and their relative contributions to worldwide installed capacity for seawater and brackish water desalination. MSF accounts for 44.4%, RO 41.1%, MED and other thermal methods 8.4%, ED and other methods 6.1%. (Humplik, Lee, Fellman, & Rahman, 2011)

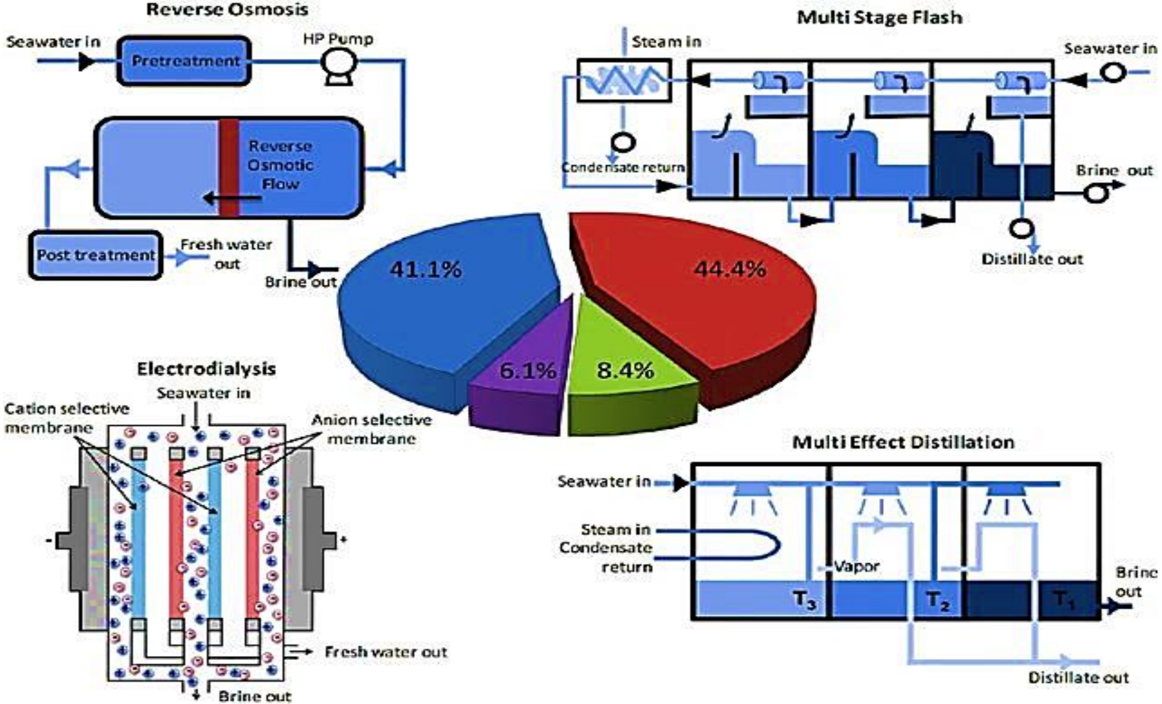

Fig. 20. *Major desalination technologies and their relative contributions to worldwide installed capacity for seawater and brackish water desalination.(Humplik, Lee, Fellman, & Rahman, 2011)*

There are also other emerging technologies which are either limited by unit size or they are still under development at pilot scale among other limitations, such as freezing desalination, humidification/ dehumidification, adsorption desalination (AD), membrane distillation (MD), microbial desalination fuel cells, ammonia driven FO (Oasys), capacitive deionization (CDI), and electro deionization (EDI). (El Kharraz, 2020)

Post-treatment of the water produced is required in all technologies, especially in distillation processes that require mineralization. The post-treatment aims to stabilize the produced water and make it compatible with the distribution network and the end-user requirements. Adjustment of pH to approximately 8 is required. Deionization is necessary in the production of green hydrogen as it helps achieve the very low conductivities required by many electrolysers. It is the final step in preparing ultrapure water by removing any remaining ions, ensuring the purity of the hydrogen produced. On the other hand, carbonation or use of other chemicals such as lime may be applied, and blending with some source water may be done to increase alkalinity and TDS and stabilize the water. Addition of corrosion inhibitors like polyphosphates may be necessary. (El Kharraz, 2020)

A list of energy use and costs for techniques other than distillation is given in Table 1. Only two methods can be regarded as being fully commercial: RO and ED with large plants in operation, whilst CDI has a smaller 1 ML/day plant at the commercial stage. The rest are still experimental, although pilot and demonstration systems have been operated successfully. (Burn, Hoang, Zarzo, Olewniak, & Campos, 2015)

Table 1. *Desalination systems possibly suitable for agricultural water production. (Burn, Hoang, Zarzo, Olewniak, & Campos, 2015)*

Technologies	Energy use, kWh/kL	Total, US$/kL
RO	Brackish water, 0.7 - 2.0	0.39 - 1.5
	Seawater, 1.6 - 12	0.55 - 1
	Submarine water, 2 - 2.5	Solar, 1.3 large plant, 2 - 6.5 small plant
FO	Brackish, 0.25	Not available
ED	Brackish, 1.6 - 2.3	0.47

Direct contact MD	Sea, 40	Solar, 15 - 18 Geothermal, 13 Solar Pond, 0.4 - 1.3 Waste heat, 1.1 - 1.5
Air gap MD	Sea	Solar, 18.3 Waste heat, 5.3
Vacuum MD	Sea, 1.2 - 3.2	Solar, 16 Waste heat, 2
HDH	Brackish	Solar, 3 - 6.4 Geothermal, 1.2
CDI	Brackish, 0.13 - 0.59	Not available

B. Technological advancement (BAT) & Market dynamics

Advances in technology and components of desalination systems have led to an almost 80% reduction in energy use for freshwater production over the past two decades. (FAO, 2024) Moreover, innovations and improvements in membranes and energy recovery devices have been driving the progress of desalination technologies, especially stand-alone or hybrid RO and FO membrane-based processes which have come to dominate desalination markets in the last 10 years. As presented in **Fig.9.**

A recent sustainability study conducted for seawater desalination plants in UAE showed the superiority of RO desalination compared to MSF and MED. The researchers developed a sustainability score and compared it with a UNESCO-developed sustainability score. Both scores showed higher RO sustainability. (FAO, 2022) The study concluded that even though MED and MSF have higher sustainability than RO in social and techno-economic factors, they performed lower in environmental factors.

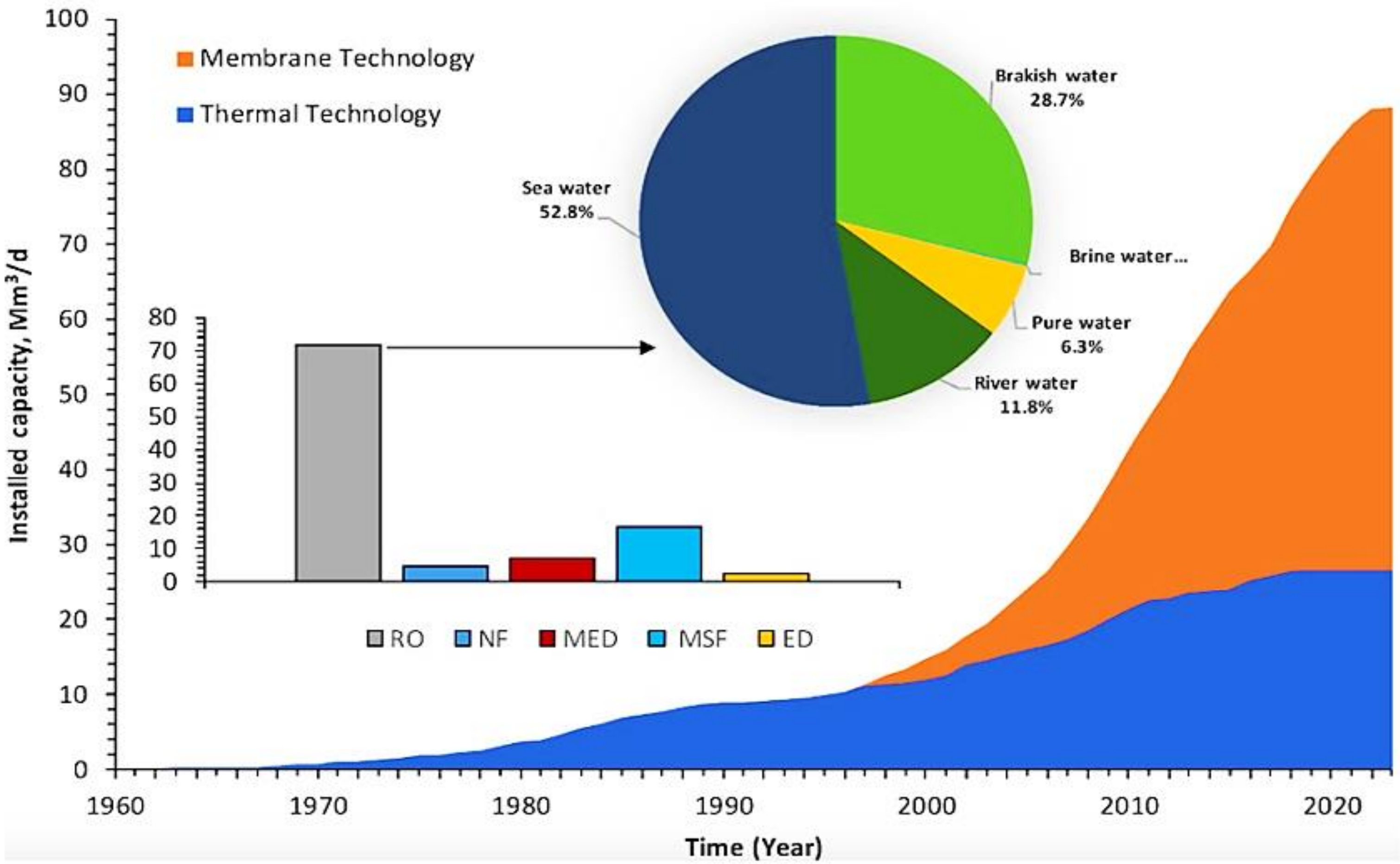

Fig. 23. *The evolution of desalination regarding different technologies. (FAO, 2024)*

Therefore, Amongst the three leading desalination technologies, Reverse Osmosis (RO) is the most widely used. Its main advantages include adaptability to changing conditions, flexible production capacity, less carbon footprint, significant cost savings in brackish groundwater desalination, and a modular design that occupies less land space. (FAO, 2022) **Fig.10** displays the distribution of RO-based desalination plants from 2020 to 2030.

Furthermore, membrane technologies can provide fertilizer solution and irrigation water with an acceptable level of nutrients for fertigation. (Suwaileh, Johnson, & Hilal, 2020) In contrast, RO requiring extensive pretreatment, is prone to membrane fouling, and has a complicated configuration, and necessitates skilled professionals for operation and maintenance (O&M). (FAO, 2022)

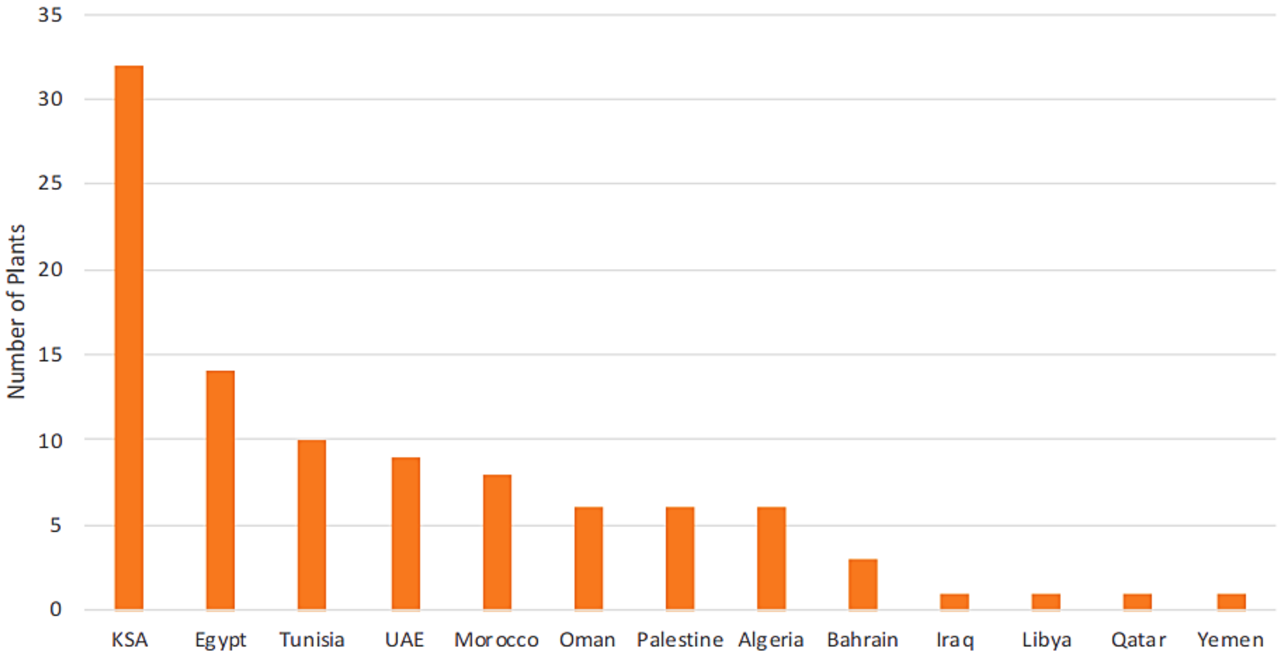

Fig. 26. *Distribution of RO-based desalination plants (2020-2030). (FAO, 2022)*

In the realm of desalination market and technology, several conclusions can be drawn. Firstly, Cost-saving innovations are significantly advancing in desalination. These include efficient energy recovery devices that recycle high-pressure flows for up to 96% savings, advanced membrane materials with 3 - 4 times the productivity of standard elements, and novel low-energy filtration techniques such as forward osmosis and membrane distillation. Other developments include nanotechnology, biomimetics, enhanced hybrid processes, and AI-powered smart system optimization and condition monitoring. These advancements promise substantial reductions in both capital and operating costs, fostering a new era of affordability, especially with regulatory easing. (Herber, 2024) Secondly, the Middle East and North Africa (MENA) region shows remarkable growth and reliability in desalination, meeting escalating water demands effectively. Desalination technologies are adaptable to market requirements, ensuring responsiveness to evolving needs. (Beltrán & Koo-Oshima, 2004)


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III. Energy Efficiency Potential: Emerging agro-industrial companies & Major challenges

Energy efficiency is a crucial factor when commissioning new or upgrading old plants. In Saudi Arabia, which accounts for 35% of the Arab region's dewatering capacity, 25% of its petroleum and gas production is used to generate electricity and water. Seawater desalination is particularly energy-intensive compared to other water treatment methods. As shown in **Fig. 11**, typical SWRO (Seawater Reverse Osmosis) desalination plants consume between 2.5 - 4.0 kWh/m^3. The RO system is the primary contributor to the plant's specific energy consumption (SEC), which averages around 1 kWh/m^3. Pre- and post-treatment processes add 0.2 to 0.4 kWh/m^3, seawater intake consumes about 0.19 kWh/m^3, and other facilities use approximately 0.27 kWh/m^3. The quality and quantity of the target water also impact the SEC. (FAO, 2022)

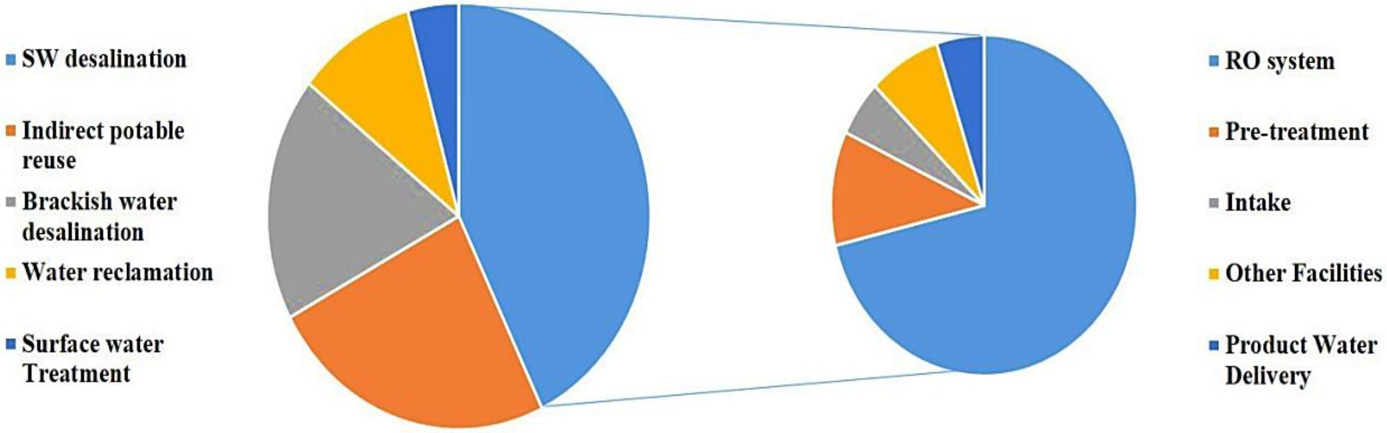

Fig. 29. *Energy consumption of water supply options and an energy breakdown of a SWRO desalination plant.* (FAO, 2022)

In addition to the plant’ s efficiency, the source of energy that drives a desalination plant determines its direct carbon footprint. RO has lower CO2 emissions than thermal desalination technologies. SWRO desalination plants estimated carbon footprint is 0.4 - 6.7 kg CO2 eq/m3. However, this is generally higher than brackish water RO desalination’ s estimated carbon footprint of 0.4 - 2.5 kg CO 2 eq/m3. (FAO, 2022)

On the flip side, renewable energy in particular solar energy is an attractive solution to reduce RO plants carbon footprint, decrease their running costs, and eliminate the link between water prices and fuel costs. **Fig.13** highlights energy consumption in large-scale desalination plants. In fact, numerous studies and plants focused on using solar PV energy to drive RO plants on a small scale, as illustrated in **Figures 12 & 14**, and about 32% of autonomous desalination systems are based on PV powered RO units.

Both PV solar energy and RO are mature technologies with wide commercial network of manufacturers and suppliers. However, the main challenge of Renewable Energy Desalination is that Desalination technologies generally work in steady-state conditions, but Renewable Energy sources are usually non-stationary. In fact, renewable energy generation needs adjustments for continuous supply (energy storage), and desalination technologies can adapt to variable operation.

Furthermore, it is worth mentioning that as water scarcity becomes an increasingly pressing issue in many parts of the world, particularly in the Arab region, a new wave of agro-industrial companies is emerging. As indicated in **Fig.15**. Nevertheless, the launch of desalination plants involves several major challenges, including the need for a comprehensive technical expertise file. Key data required includes information on water distribution and usage for irrigation to enhance agricultural efficiency, as well as quantitative and qualitative aspects of resources such as rainfall, infiltration, flows, recharge, and water quality. (Daghari, Desalination and Agriculture, 2022)

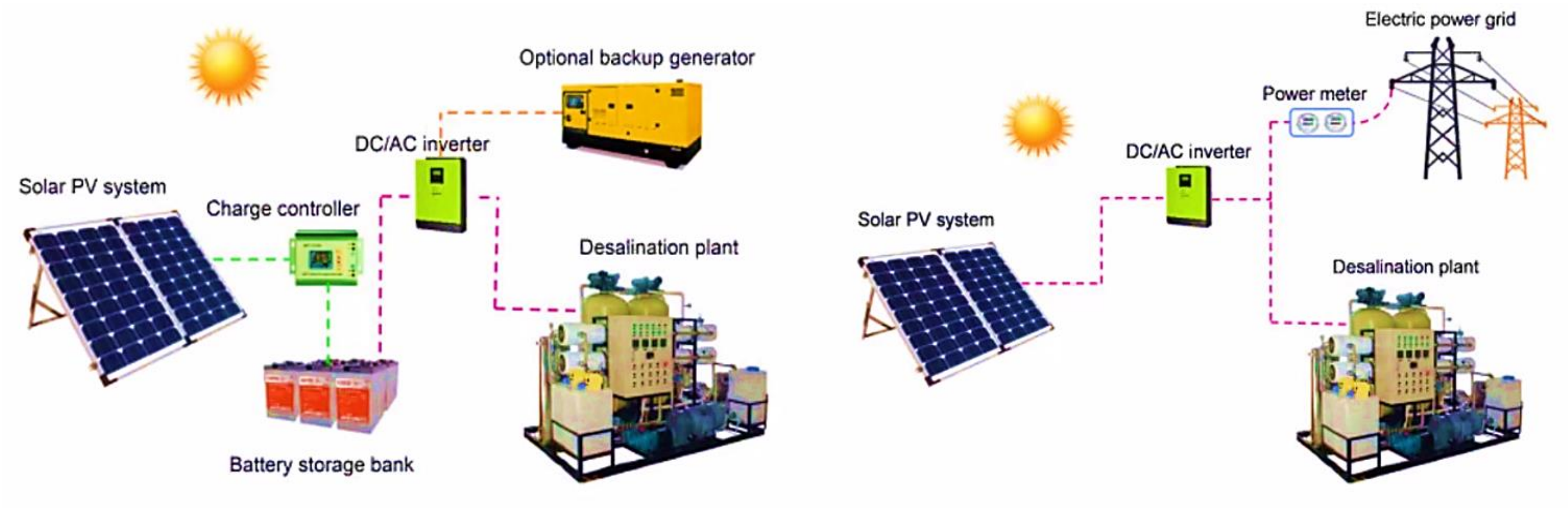

Fig. 31. *Solar desalination configurations. (Gorijian, 2020)*

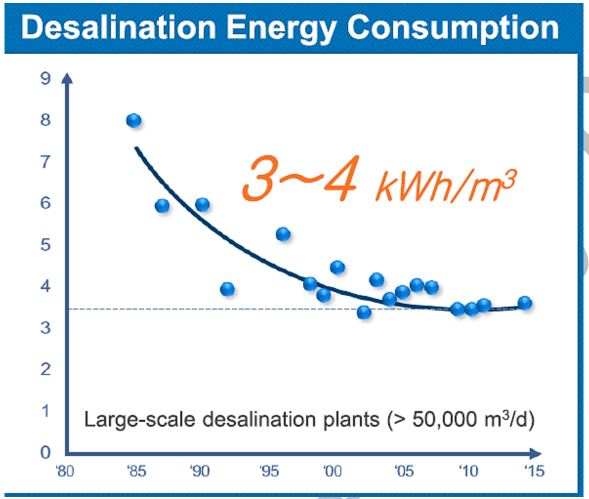

Fig. 32. *Energy consumption in large scale desalination plants.*

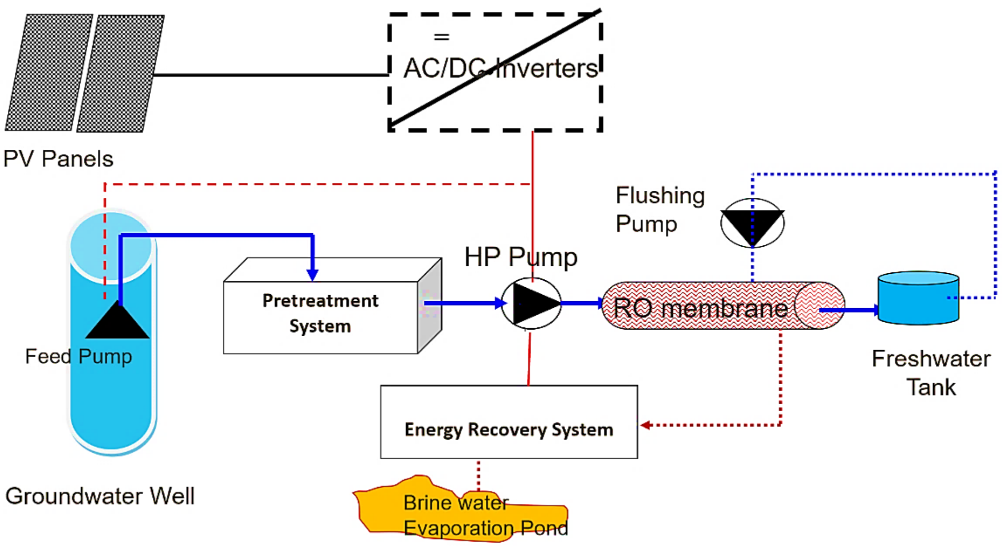

Fig. 35. *A typical solar PV RO desalination unit for irrigation purposes.*

01 **Sundrop Farms**

Utilized concentrated solar power for desalination in Port Augusta, Australia, producing 335,103 m^3 of desalinated water for hydroponic greenhouses at a cost of $205 million, yielding high-value tomatoes.

02 **Sahara Forest Project**

Established in Qatar in 2012, this project provides desalinated water for crop irrigation on a 300 ha area, achieving high yields and expanding to Tunisia with an additional 10 ha.

03 **WaterFX**

A Californian start-up that built a 14-hectare solar thermal desalination plant, producing 3.8 million m^3 of freshwater in 2014 for irrigation over 2800 ha, with operating costs at $450 per 1.210^3 m^3, prompting further developments by the Panoche Water District.

Fig. 38. *Key emerging solar desalination projects. (Daghari, Desalination and Agriculture, 2022)*

IV. Existing policies, Regulatory frameworks & Planning strategies

Desalination as a potential solution to water scarcity has been for long time controversial, because many policy makers and policy documents advocate this option while others show more skepticism and prefer other solutions. (El Kharraz, 2020). As a matter of fact, there are two main trends in regulating desalination plants in the Arab region. The first encourages government participation in designing and running desalination plants. The second trend is to support lower energy intensive desalination projects and causes a lower environmental impact. Governments can support these projects by granting concessionary management contracts to supply residents with water. National water agencies may support desalination projects by analyzing their impact on sustainability at each stage of the desalination process. (FAO, 2022)

When it comes to the Arab region, meanwhile few national and local water management plans take climate change impacts adequately into account, adaptation policies have not yet been properly developed at national level. (El Kharraz, 2020) As a matter of fact, several institutional constraints can be seen in the Arab region water sector. Human resources and related organizations are yet to be improved. The desalination industry has been more concerned with water production rather than integrated water resources management. There also seems to be a lack of policy and incentives to localize technology, which is coupled with minimal investment in research and development.(Beltrán & Koo-Oshima, 2004)

Additionally, as for environmental regulations, it is vital to underscore that, to date, there are unfortunately no specific standards for environmental impact assessments, only guidelines provided by the United Nations Environment Program (UNEP). Environmental impact assessments (EIAs) have not yet been incorporated into management policies. Despite the availability of technology and management strategies to mitigate impacts, established standards and comprehensive EIA studies at both local and regional levels are needed. (El Kharraz, 2020)

Consequently, the desalination sector in the Arab region faces significant challenges due to inadequate policies and regulatory frameworks. Some Arab countries have yet to achieve a balanced approach to water policies, and even where such policies exist, they are often not applied effectively for their intended purposes. Additionally, laws and legislation do not sufficiently address all the issues, and there is a notable failure in implementation and enforcement. Furthermore, the lack of cooperation with both Arab and international peers exacerbate these challenges, hindering the sector's progress. (Al-Abri, 2022)

One the flip side, desalination has gained prominence in national and regional policies across the Arab region in recent years. An example of regional strategies related to desalination, the 5+5 (including Algeria, Morocco, Tunisia, Libya and Mauritania from the Arab region) Western water strategy highlights desalination as a vital solution for chronic water scarcity, emphasizing the need for efficient, low-impact technologies and renewable energy use. Promoting legal frameworks and encouraging private sector investment are essential to meet the growing demand for desalinated water. (El Kharraz, 2020)

In conclusion, to address desalination challenges, policies must include financial incentives like grants, subsidies, or tax breaks to offset the high costs of desalination for farmers. Integrating renewable energy sources to power desalination plants can also reduce environmental impacts and enhance sustainability. Implementing regulations for the safe disposal of brine, such as deep well injection or industrial reuse, is essential for environmental protection. Furthermore, water pricing and allocation policies that encourage efficient use and discourage wastefulness can help reduce overall water demand, making desalination more feasible. Finally, continued research and development are needed to improve desalination efficiency and reduce costs, thereby making it a more viable solution for agriculture. (FAO, 2024)

V. Cost Analysis for Desalination & Economic Feasibility

A. Cost analysis for desalination projects

In recent years, desalination has become more competitive because of increased liquidity and the maturity of financial markets. (FAO, 2022) The price of desalinated water entering distribution systems varies widely globally, ranging from $0.50 to $2.50 per cubic meter for seawater desalination (DSW) and $0.60 to $2.00 per cubic meter for brackish water desalination (DBW) (Herber, 2024) depending on various factors such as capacity and type of desalination plant, feed water (seawater or brackish water) and labor, location, and type of energy used whether conventional renewable energy. (El Kharraz, 2020)

Additionally, proximity to end-users significantly impacts costs, as transporting treated water substantial distances inland requires large-diameter pipelines, booster pumps, and storage reservoirs, which drives up both capital infrastructure and operational electricity expenses. In fact, Recent large-scale desalination projects highlight the significant costs of inland conveyance. The Carlsbad Desalination Plant in San Diego County, producing 190,000 cubic meters of water daily, required about $1 billion for a 54-mile pipeline. Melbourne’s desalination plant in Australia faced a $750 million cost for an 85-mile pipeline. Even shorter distances are costly, such as the $140 million spent on a 25-mile pipeline to Monterrey, Mexico. Regardless of distance, transportation imposes substantial financial burdens. (Herber, 2024)

In contrast, conventional municipal freshwater sources remain significantly cheaper, with water from rivers and lakes costing $0.10 to $0.50 per cubic meter, groundwater and wells $0.30 to $1.00, rainwater harvesting $0.15 to $1.50, and wastewater recycling $0.30 to $1.15. As a result, desalinated water still costs 1.5 to 4 times more than most traditional freshwater sources like lakes, rivers, and shallow wells. (Herber, 2024)

In the Middle East, Saudi Arabia and the UAE are among the cheapest places to desalinate water, given their comparatively low energy prices and the economies of scale at their large facilities. Increased use of renewable energies to run the desalination process may make it even cheaper. (El Kharraz, 2020) In fact, water from Saudi

Arabia’s latest projects costs as low as $0.50/m^3 due to cheap solar power and government fossil fuel subsidies. (Herber, 2024) Additionally, in 2020, Dubai Electricity & Water reported a $0.306/m3 water cost for 545,000 m3/d Hassyan SWRO when online in 2023. This is world’s lowest water levelized tariff so far. (El Kharraz, 2020)

The total Capex of desalination plants in the Arab region in 2021 was approx. $6,818 million, while Opex was $11,002 million. By August 2022, the Capex had increased to $8,162 million, while the Opex was 11,434. (FAO, 2022) As shown in Figures 17 and 18 In 2020, despite the pandemic, the desalination market held steady, as 44% of new capacity was awarded under the COVID-19 pandemic. Even though the total number of new contracted capacity fell from 6.7 million m3/d in 2019 to 4.7 million m3/d in 2020, it was still the fourth highest yearly volume in history. (FAO, 2022)

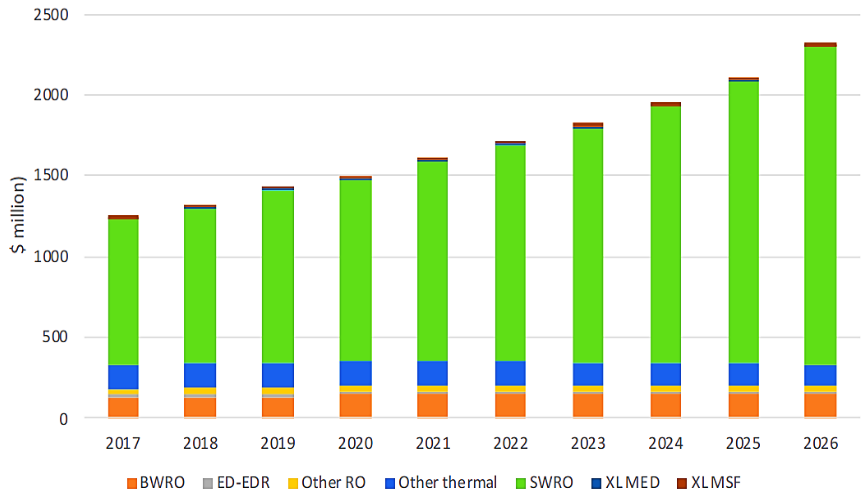

Fig. 40. *OPEX breakdown of desalination plants in Arab region (2017-2026). (FAO, 2022)*

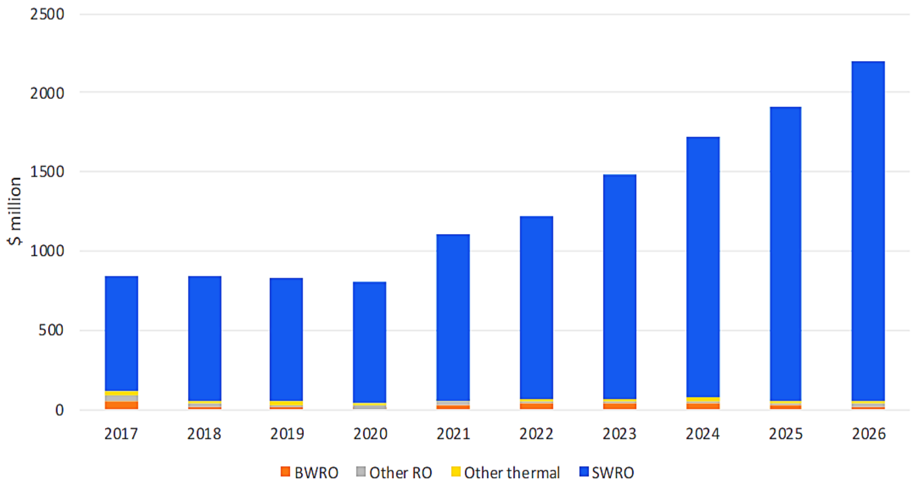

Fig. 43. *CAPEX breakdown of desalination plants in Arab region (2017-2026). (FAO, 2022)*

The table below presents the capital expenditures (Capex) and operational expenditures (Opex) of various large-scale SWRO desalination plants around the world.

Table 2. *Capex and Opex of selected large SWRO desalination plants. (Zarzo, 2012)*

Country	Location	Year	Capacity (m3/day)	Capex	Tariff	Financing Model
Cyprus	Larnaca	2001	52,000	47 M€	0.74 US$/m3	EPC
Singapore	Singspring	2005	136,380	117 MUS$	0.49 US$/m3	BOO
Algeria	Honaine	2005	200,000	225 MUS$	0.756 US$/m3	BOT
Australia	Perth	2006	143,000	387 MAus$	1.17 Aus$/m3	DBO
Spain	Aguilas	2008	210,000	363 MUS$	0.579 US$/m3	EPC + O&M
Algeria	Skikda	2009	100,000	110.8 MUS$	0.7398 US$/m3	DBO
Algeria	Beni Saf	2010	200,000	153.4 MUS$	0.6994 US$/m3	DBO
India	Chennai	2010	100,000	91 MUS$	1.03 US$/m3	BOT
Cyprus	Limassol	2012	40,000	55 M€	0.8725 US$/m3	BOT
Australia	SSDP (Perth II)	2012	306,000	601 MUS$	0.41 US$/m3	Alliance
China	Quingdao	2013	100,000	135 M€	0,71 US$/m3	EPC + O&M
Singapore	Tuaspring	2013	318,500	635 MUS$	0.36 US$/m3	BOOT
Algeria	Tenes	2015	200,000	231 MUS$	0.59 US$/m3	DBO
Singapore	Tuas III	2018	136,000	217 MS$	0,54 US$/m3	DBOO
Saudi Arabia	Shuqaiq 3	2021	450,000	600 MUS$	0.52 US$/m3	BOT
Saudi Arabia	Rabigh	2022	600,000	650 MUS$	0.55 US$/m3	DBO
UAE	Taweelah	2022	900,000	550-1.200 MUS$	0.49 US$/m3	BOT

In terms of desalinated water supply affordability for agricultural applications, desalinated water is more expensive than conventional water resources and it is not affordable for most crops. However, desalinated water might be affordable for high value crops, especially where subsidies on capital costs are provided. Desalinated water is of high quality and can have less negative impact on soils and crops in comparison with direct use of brackish water. (Beltrán & Koo-Oshima, 2004)

A national analysis undertaken by the National Centre of Excellence for Desalination (NCED has shown that existing farmers are unwilling to pay more than AU$1.00/m3 for water and in many regions even this cost is considered to be unacceptably high (e.g., common water costs in southwest Western Australia are AU$0.18 - 0.50/m 3). Comparing this willingness-to-pay with the unit cost of water production in large desalination plants means that seawater desalination is an unlikely option for traditional agricultural practice where subsidies are not available. However, for applications where the cost of water is small compared to the infrastructure investment, i.e., glasshouses and hydroponics, the application of seawater desalination technologies is currently viable. (Burn, Hoang, Zarzo, Olewniak, & Campos, 2015)

B. Economic feasibility of desalination facilities

It is key to recognize that advances in membrane technologies and energy recovery systems helped cut desalination costs in half over the past 20 years (Herber, 2024), making desalination now more economically competitive and attractive than conventional water resources. (Ricart, Villar-Navascués, Gil-Guirado, M. Rico-Amorós, & Arahuetes, 2020). As depicted in **Fig.19**. Furthermore, cost-effective desalination for agriculture is most feasible where large volumes of brackish water are available near the ocean, with existing demand for irrigation. These conditions minimize water production and distribution costs. Low-salinity groundwater allows higher recovery rates and the mixing of feedwater with desalinated water. Being close to the ocean also reduces brine disposal costs compared to inland disposal methods. (Burn, Hoang, Zarzo, Olewniak, & Campos, 2015)

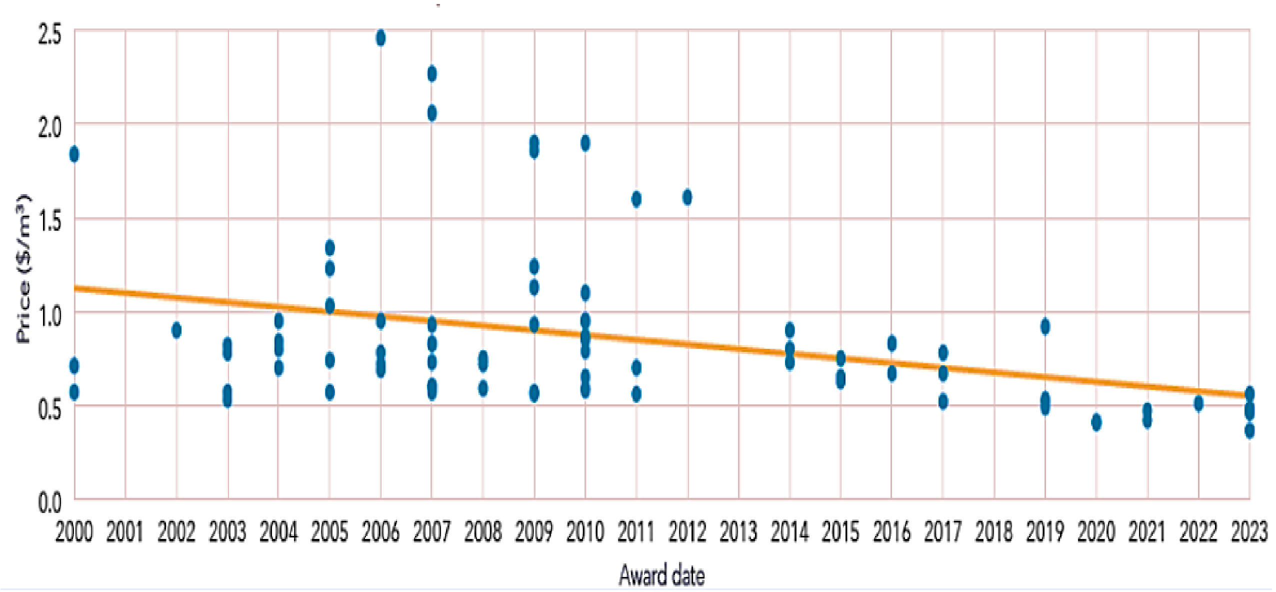

Fig. 46. *The evolution of desalinated water price. (FAO, 2024)*

For industrial users, water supply costs typically do not significantly impact competitiveness, (Beltrán & Koo-Oshima, 2004) small-scale desalination systems for hotels or industrial uses can cost up to $4 - 5/m3. (Herber, 2024)

The ongoing decrease in production costs, coupled with rising expenses for traditional water treatment due to stricter regulations and increasing water scarcity, is anticipated to boost the trend of greater reliance on ocean water as a water source. (FAO, 2024). This reduction in desalination costs can be promoted by prioritizing coastal sites near major demand centers, selecting intake locations with lower biofouling and pollution risks, leveraging existing marine infrastructure for dual purposes, and fortifying facilities, including storage, against natural disasters. (Herber, 2024)

Consequently, desalination of water for agriculture is technically feasible and the appropriate technology is available. However, the major issues for discussion are size of desalination plants; designs; type of crops and areas where desalinated water could be applied; and project financing. Therefore, only economic and environmental considerations can limit its application and must be evaluated and controlled. (Beltrán & Koo-Oshima, 2004)

C. Desalination cost & Crops Economic viability

Currently the cost of desalinated water is still too high for the use of this resource in broad-scale irrigated agriculture. An exception appears to be intensive horticulture for high value cash crops, such as vegetables and flowers (mainly in greenhouses) grown in coastal areas where safe disposal of brines is easier than in inland areas. (Burn, Hoang, Zarzo, Olewniak, & Campos, 2015). In this context, (Awaad, et al., 2020) evaluated the impact of the water cost on crop productivity. They disclosed that the water desalination process could be economically advantageous for farmers to produce great commercial value if they followed the technical recommendations for high crop yield production.

In a survey we carried out with experts from the Arab region, and when we asked them about how pricing for desalinated water is determined for agricultural clients, 40% mentioned that is done through fixed pricing per volume of water, and another 40% that is done through negotiated pricing based on long-term contracts. As per financial barriers for farmers to access affordable desalinated water, they highlighted the importance of facilitating access to government or institutional support and providing financial assistance or subsidies. When we asked them about types of crops that are most irrigated with desalinated water supplied, they highlighted:

- Vegetables (e.g., tomatoes, peppers)
- Fruits (e.g., citrus, grapes)

Finally, when we asked them about what could make desalination more financially viable for agriculture, the responses were:

- Reduced energy costs
- Public-private partnerships (PPPs)
- Technological advancements lowering operational costs

As a matter of fact, vegetable crops such as those in the solanaceous family (i.e., tomato, potato, eggplant and pepper) and the cucurbits family (i.e., watermelon, melon, cucumber and summer squash) are suitable for greenhouse conditions. Success of these crops under controlled cultivation is due to their good adaptation and growth across several cultivation cycles, as well as their economic convenience. These crops represent about 80% of the controlled cultivation in most countries in the MENA region. Furthermore, these crops are produced in large quantities in the MENA region. Subsequently, it is efficacious to use desalinated water for producing these crops under greenhouse conditions. (Awaad, et al., 2020)

For example, Sundrop farms, uses 860,000 m3 of fresh water yearly to irrigate 2000 m2 of greenhouses. While in Spain, greenhouse products (horticultural, flowers and ornamental plants) provide greater added value per unit of irrigated water (5.79 €/m3 on average), followed by vineyards and fruit trees (1.08 and 0.68 €/m3 respectively), and cereal grains (0.06 €/m3). An average of 0.41 €/m3 was estimated for all products. These figures relate to high-value crops, for which the overall water cost may be marginal compared to total costs. In contrast, it is unlikely that the production of cotton, rice or sugar can be effectively supported by water supplied from desalination plants due to their lower economic returns and higher water requirements. Additionally, the irrigation of citric fruit plantations with desalinated water led to increases in production by 10 to 50% (depending on the water quality used prior to introduction of desalinated water), whilst water needs reduced by 20%. For a case of greenhouse production of bananas irrigated with desalinated wastewater, fertilizers and water use were reduced by 50 and 30% respectively, leading to an increase in banana production and the earlier maturation of plants. (Burn, Hoang, Zarzo, Olewniak, & Campos, 2015)

The countries of the MENA region suffer from some of the greatest water shortages in the world. Simultaneously, this region is considered the largest importer of agricultural products. Consequently, solar desalination could be used to provide fresh water for agricultural production in that area. (Awaad, et al., 2020)

On the other hand, Egypt started a major national project in 2019 to establish 100,000 greenhouses, including 5000 greenhouses over an area of 8500 ha in the areas of El-Hammam, Abu Sultan, the Tenth of Ramadan and Al-Amal village east of Ismailia. The use of high-tech greenhouses for some crops has led to a 90% saving in irrigation water with a six-fold increase in productivity compared with open agriculture, as well as increasing the supply of different vegetable varieties in the market for citizens, at economic prices throughout the year. (Awaad, et al., 2020)

Furthermore, (Awaad, et al., 2020) showed that a greenhouse-cropping system is used frequently in the region of Souss-Massa in Morocco; this region produces about 77% of Morocco’s vegetables, 40% of the production of citrus fruit, and only 2% of the production of olives and it covers an area of more than 15,000 ha. Nevertheless, the region has a great problem of water scarcity as the annual precipitation does not surpass 200 mm, and the water shortage is more than 260 million cubic metres. Moreover, agricultural production in this region uses about 90% of the available water. Consequently, the use of desalinated seawater to irrigate crops such as tomatoes, berries, and various vegetables can be an economic alternative to ensure the continued production of horticultural products.

Irrigation in Tunisia, particularly in the coastal area of Dyiar-Al-Hujjej, is threatened by seawater intrusion, leading to disrupted agricultural yields. A study analyzed the feasibility of using desalinated water to stabilize irrigation. The results showed that relying solely on desalinated water results in negative net income for most crops, except strawberries. Even with agro-industrial development, most open-field crops remain unprofitable, except tomatoes. Blending desalinated seawater with saltwater also results in negative income for key crops. However, replacing open-field crops with greenhouse cultivation is beneficial when using desalinated water. The high cost of desalination (0.5 USD/m³) compared to the average irrigation water price in Tunisia (0.05 USD/m³) limits its recommendation to crops with low water needs and high added value. (Daghari, et al., 2021)

This leads to the conclusion that the use of desalinated water for agriculture will be viable where there is limited access to water that is fit for purpose and it is most likely to be cost effective in a tightly controlled environment, using agricultural practices with the most effective water use and crops with high productivity. Such conditions are often associated with greenhouses and the production of high value irrigated crops. However, it is also important to mention that the high level of financial support and subsidies provided to the agricultural sector in the EU countries for example make this option more viable.

VI. Financing Modalities & Delivery Models of contract

A. Financing modalities

The economic viability of desalination projects often hinges on a delicate balance between public interests and private investment returns, necessitating a comprehensive evaluation of risk-sharing strategies and long-term sustainability considerations. (FasterCapital, 2024) Hence, securing the necessary capital for desalination endeavors of significant magnitude necessitates a multifaceted approach, blending traditional financing avenues with innovative funding mechanisms, as depicted in the following table :

Table 3. *Different financing modalities (FasterCapital, 2024)*

Financing modality	Explanation	Example
Multilateral Development Banks (MDBs)	Institutions providing loans and guarantees to support large-scale projects.	Jubail Desalination Plant in Saudi Arabia.
Green Bonds and Climate Financing	Bonds issued to fund environmentally friendly projects with positive impacts.	Poseidon Water Project in Huntington Beach.
Direct Government Funding	Government fully funds the project, especially when water security is a national priority.	Desalination plants carried out by the public company AQUAMED in Spain.
Revenue Bonds	Bonds repaid from the income generated by the plant, often used with long-term sales agreements.	Perth Seawater Desalination Plant in Australia.
Corporate Financing	Large corporations finance the plant independently due to substantial water needs.	BHP Billiton Desalination Plant in Chile.
Public-Private Partnerships (PPPs)	Collaboration between government and private sector to share risks and rewards.	Carlsbad Desalination Plant in California, Ait Chtouka Desalination Plant, Morocco.

In this context, a recent study evaluated the impact of the public sector involvement on desalination projects feasibility in three Arab countries (Algeria, Egypt and Tunisia) presenting of the main markets for Spanish desalination companies with different desalination projects' structures. The cases of Algeria and Tunisia represent two extremes because in the Algerian case the public sector is present in the shareholding and decision making of the company project. As illustrated in Figure 20, while in the case of Tunisia the public sector is not part of the company project as presented in figure 21. (Montano, García-Lopez, & Melgarejo, 2021)

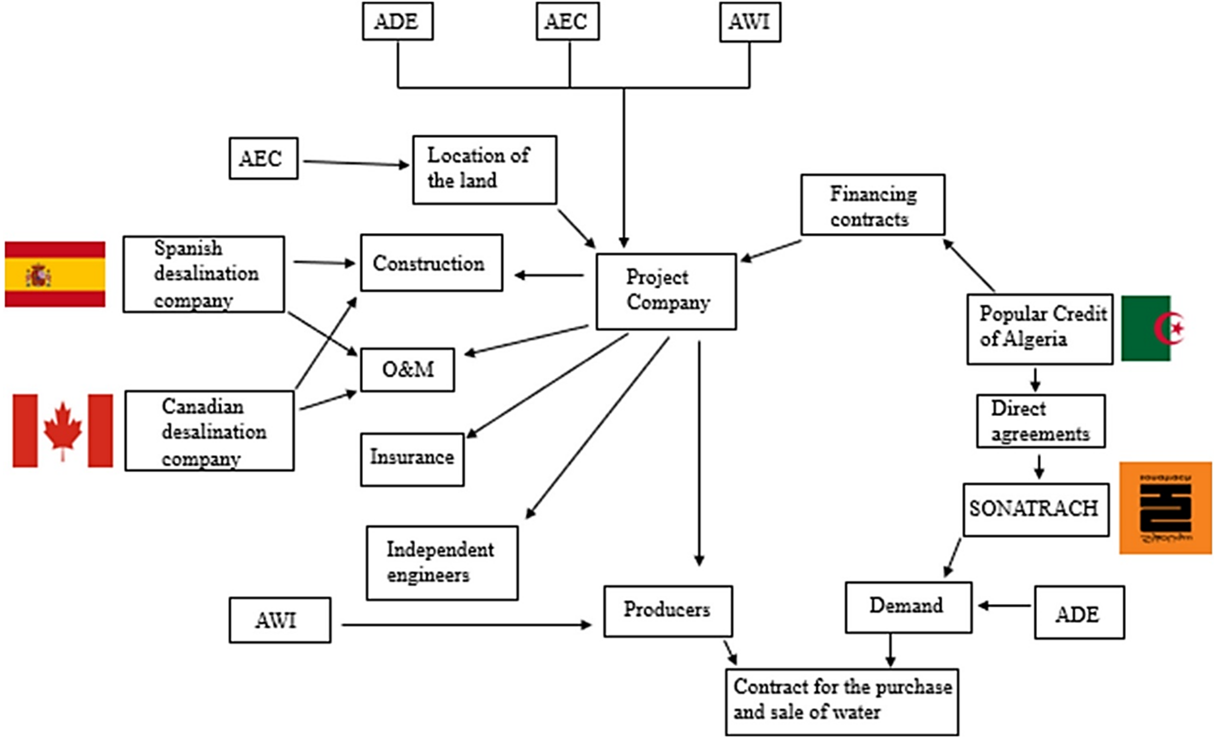

Fig. 48. *Complete structure of the Algerian Project. (Montano, García-Lopez, & Melgarejo, 2021)*

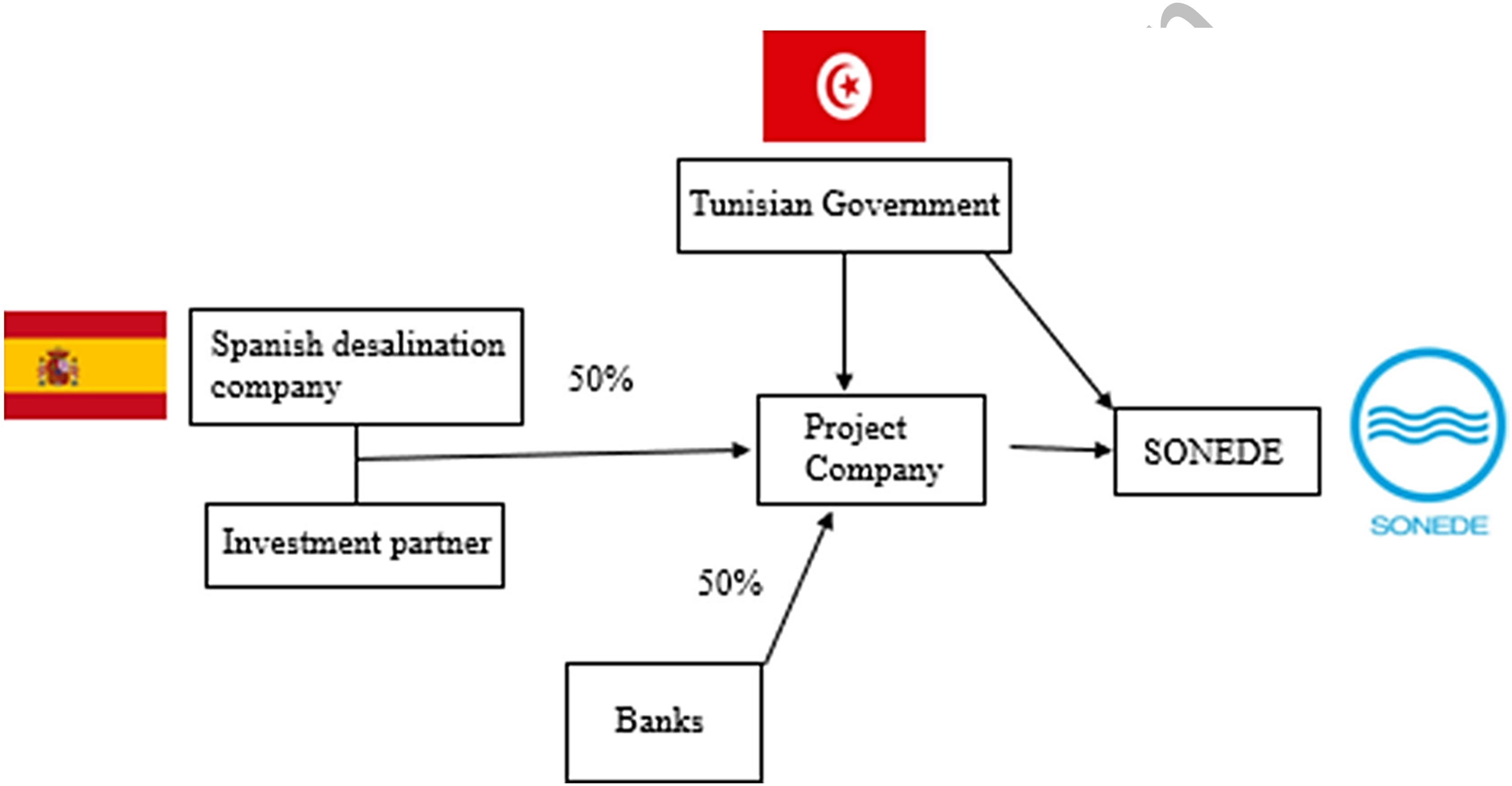

Fig. 50. *Complete structure of the Tunisian Project. (Montano, García-Lopez, & Melgarejo, 2021)*

In contrast, the Egyptian case is an intermediate option between them, as the public sector has a presence in the company project but is not present in the shareholding of this Company. (Montano, García-Lopez, & Melgarejo, 2021) As shown in the figure down below:

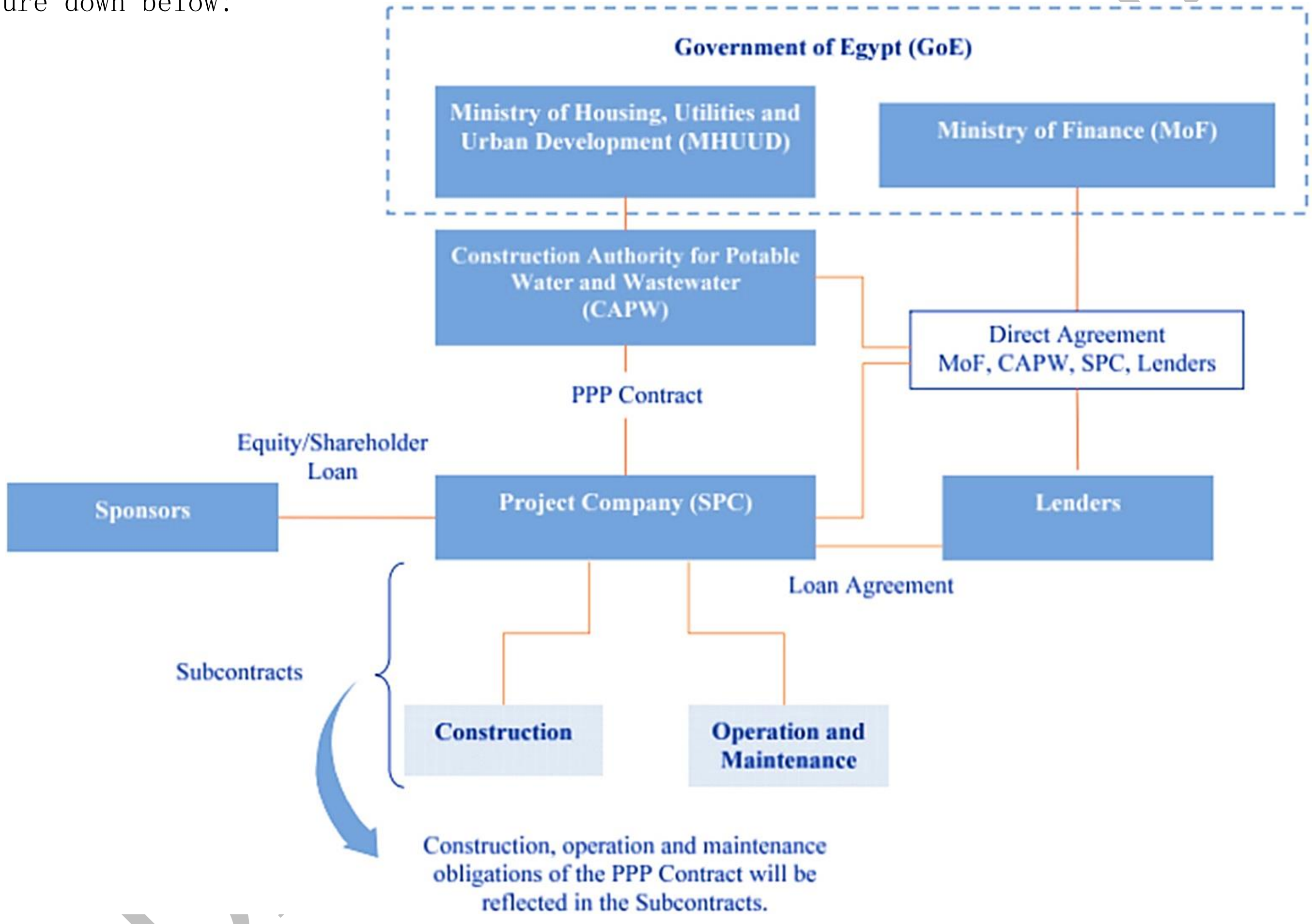

Fig. 52. *Complete structure of the Egyptian Project. (Montano, García-Lopez, & Melgarejo, 2021)*

The study concluded that the degree of public sector involvement greatly influences the financial feasibility of desalination projects. Algeria's model, with strong state participation, offers a more secure investment environment compared to Tunisia's, which lacks formal government guarantees. Egypt's intermediate approach balances public sector guarantees with limited financial involvement, attracting private investment while maintaining oversight. The analysis suggests that robust public sector involvement, like Algeria's, is essential for successful desalination project financing, while Tunisia's model may need reevaluation to improve economic viability.

On the other hand, in a survey we distributed among experts from the Arab region, 80% among them highlighted that the primary sources of funding for your desalination operations come from private investment, followed by government subsidies and loans/credits. When asked about maintaining the financial viability of desalination operations, 40% of the interviewed experts highlighted the limited access to financing as a main challenge. In addition, when asked about the type of investment they believe is more reliable for funding desalination projects, they all agreed on Public-private partnerships (PPP), followed by Private investment (e.g., individual investors or private companies), and a mix of international and private investment.

D. Delivery Models of contract

Different delivery models are used to procure desalination projects. (FAO, 2022) The delivery model chosen depends on several factors, including the type of owner or client, whether it is a public agency or private entity, the project's risk profile, the owner's experience with similar projects, and the source of project funding, which may involve loans, grants, bonds, equity, or a combination of these.((FAO, 2022); (Al-Abri, 2022)) A desalination project can be classified under any of the following terms and models of contract :

- EPC (Engineering, Procurement, and Construction)

It is a contractual agreement between a project owner and the contractor. The contractual framework in an EPC contract enables the owner to transfer the complete risk of design, procurement, and construction to the contractor.

The contractor is solely responsible for completing the project and handing it over to the owner in a turnkey condition. (BlackRidge, 2023) As illustrated in the scheme below.

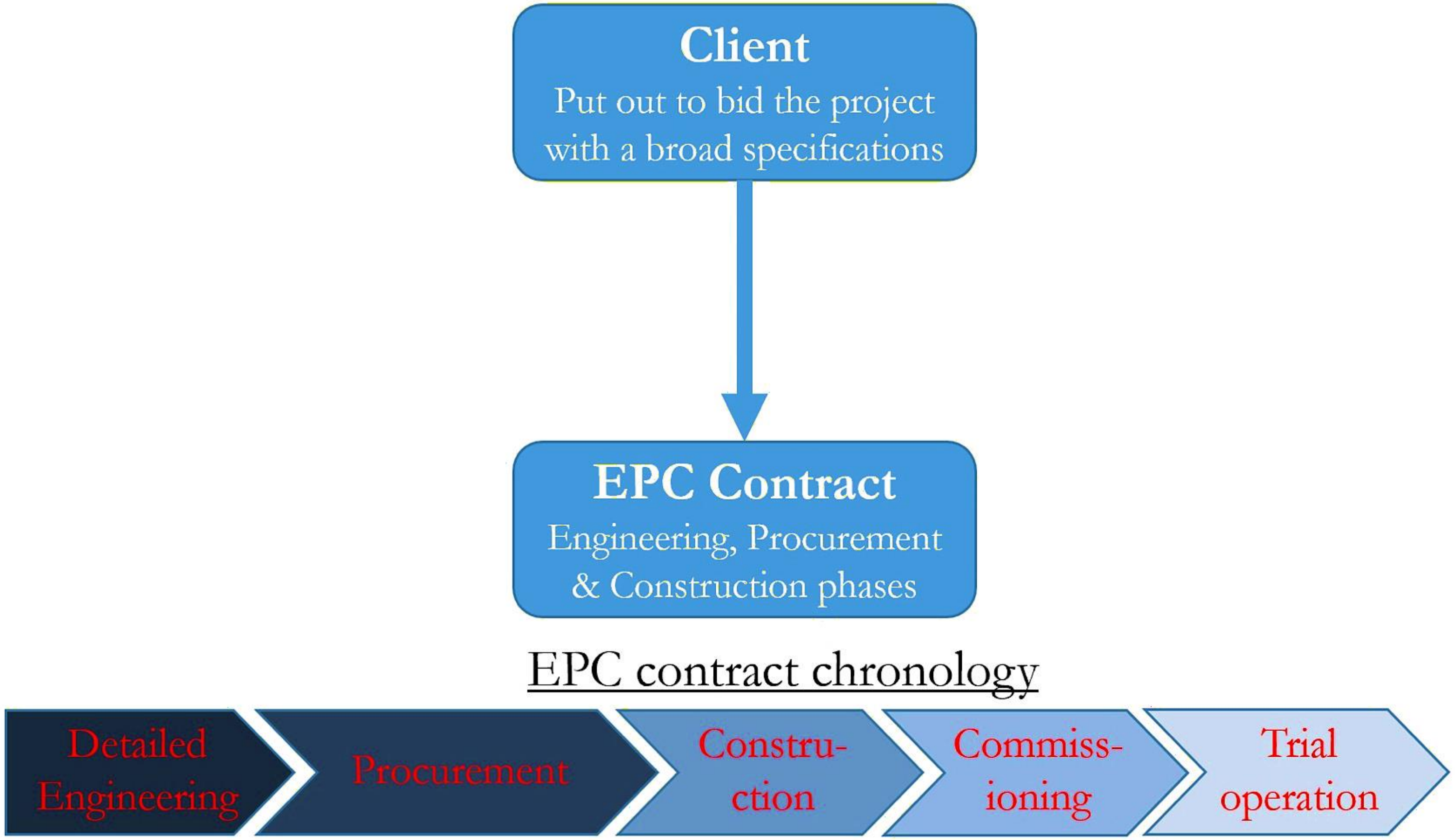

Fig. 54. *The EPC delivery model scheme.*

- DBO (Design, Build and Operate)

During the bidding process, the clients needing the desalination plant award contracts for construction, operation, and maintenance (O&M) as a single package. In some cases, different consortium members making the bid carry different responsibilities in the contract for construction and operation. The model requires fewer legal frameworks than other models (such as BOT) and incentivizes long-term reliability as a key development goal since the operational component of the contract requires more stringent legal frameworks than those of models based on BOT. This model was used for the Basra water supply projects. (FAO, 2022)

Fig. 56. *The DBO delivery model scheme.*

- BOT (Build, Own, Transfer)

In this delivery model, a private developer building is involved, owning and operating a facility for an initial contract period. As illustrated in the figure down below. By the end of contract period, it may be transferred back to the client, so we called BOT or held by the developer and new supply contract put in place, so we called BOO. (FAO, 2022) It is vital to underscore that, in 2020, private finance enabled significant investment in new desalination projects, particularly using the Independent Water Producer (IWP) model with long-term BOT contracts, mostly in the GCC. These BOT projects, such as Jubail 3a, Jubail 3b, and Yanbu 4, now produce desalinated water at prices below $\$0.50/m^3$. (FAO, 2022)

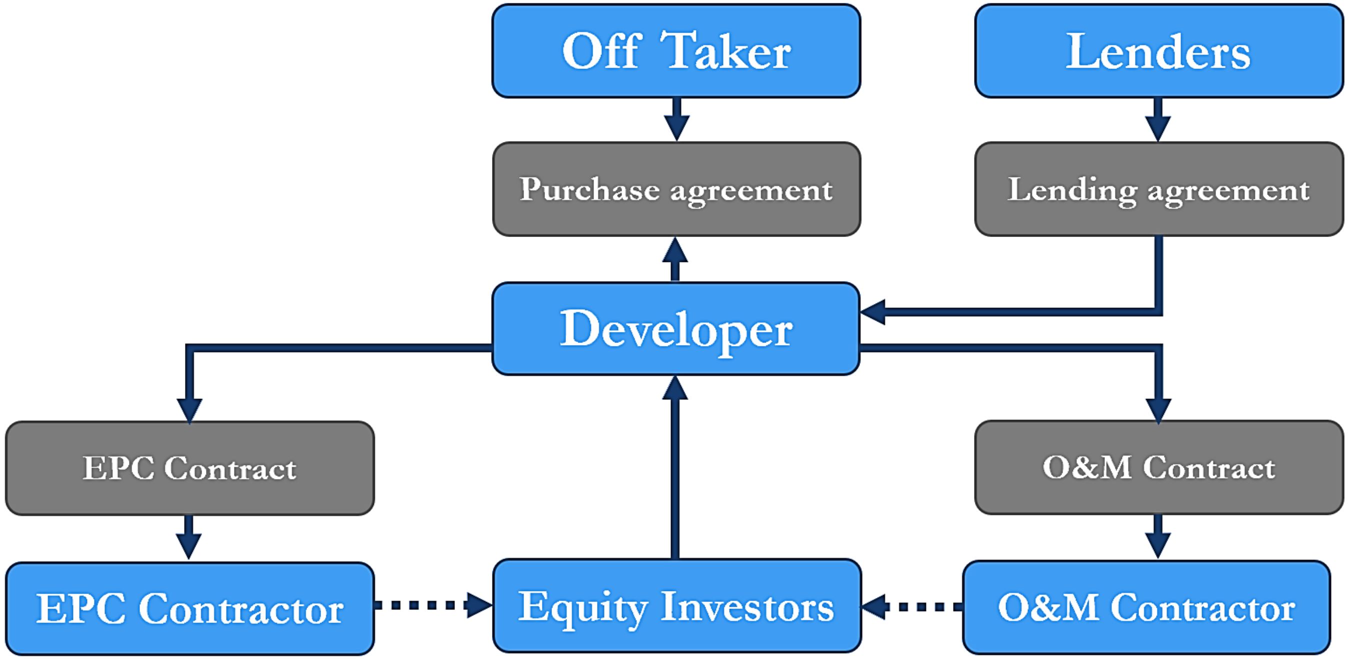

Fig. 58. *The BOT delivery model scheme.*

Among the previously mentioned contracts, Build-Own-Operate-Transfer (BOOT) water desalination projects are gaining popularity worldwide. BOOT projects enable municipalities and public utilities to transfer the risks associated with the costs of desalinated water to the private sector, providing a more sustainable and financially viable solution. (FAO, 2022)

Regarding the Arab region, Private Public Partnerships (PPPs) have been extensively discussed in the Arab region in the last decade. Consequently, many countries have entered into PPPs to manage their water supply networks and construct new infrastructure to provide water and sanitation services, including Algeria, Egypt, Morocco, Tunisia, Jordan, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. Particular attention has been paid to their relations with institutional and regulatory frameworks, market risks, off-taker risks, tariff structures, desalinated water charges, construction, technical and operational risks, financing mechanisms, credit enhancements, and environmental risks. (FAO, 2022)

In Oman for example, Oman Power and Water Procurement (OPWP) is the entity that develops desalination projects requirements of power and water capacities through the fair and transparent competition process. The private sector investment in the desalination sector is about USD 2.6 bn up to 2019. The current capacity is around 1.5 Mm3/d and will reach 2 Mm3/d by 2023. (El Kharraz, 2020) As a result of privatization and changes to its foreign capital investment law, Oman has made significant efforts to improve the foreign investment climate and broaden private sector participation. (FAO, 2022)

In North Africa, major government actors in water resource management in Morocco include the Ministry of Equipment and Water and the National Office of Electricity and Water (ONEE). (Pérez, 2024) However, Moroccan PPPs are also gaining traction. The planned 800,000 m3/d Casablanca plant is expected to use a BOT contract, while a new law will, when enacted, expand the list of public bodies that can participate in PPPs. (FAO, 2022) Similarly, Egypt’s massive desalination program for 2050 is expected to require private financing. Tunisia’s Gabès desalination plant will also follow a BOT model. (FAO, 2022)

In contrast, Infrastructure constraints affect PPP applications, requiring collaboration with established institutions, development of water storage systems, water pricing policies, and incentive programs. Another constraint is the public’ s perception of private sector participation in PPPs including fears of price increases, unethical practices, and inadequate information. Moreover, investment and produced water costs are self-evidently key factors in influencing decision makers to select appropriate technologies, which can be combined with local incentives and contract delivery models. (FAO, 2022) As a matter of fact, government regulations and policies play a major role, significantly influencing operations and pricing in the adopted business model.

C. Financial schemes: Business Models Canvas (BMC)

The Business Model Canvas (BMC) for desalination plants encompasses several key components that interact to create a sustainable and efficient operational framework. These components include value propositions, customer segments, key activities, and partnerships, which collectively facilitate the delivery of desalinated water.

- Value Proposition: The primary offering is the provision of fresh water through desalination, addressing water scarcity issues in various regions. (Al-Nory & Graves, 2013)
- Customer Segments: Target customers include municipalities, agricultural sectors, and industrial users, each with distinct water needs. (Widyarti, Hartono, Handayani, Rokhimah, & Kusuma, 2023)
- Key Activities: Essential activities involve the operation of desalination technologies, maintenance, and supply chain management to optimize water production. (Al-Nory & Graves, 2013)
- Key Partnerships: Collaborations with technology providers, government agencies, and environmental organizations are crucial for resource sharing and regulatory compliance. (Widyarti, Hartono, Handayani, Rokhimah, & Kusuma, 2023)

These components interact dynamically, ensuring that the desalination plants not only meet immediate water demands but also adapt to changing socio-economic conditions and technological advancements.

Notably, the business model (BM) of seawater desalination plants in Morocco encapsulates the core aspects of their financial and operational frameworks, along with an in-depth analysis of the stakeholders engaged in these projects. (EL BELKASMI & BOUTTI, 2023) Table 4. represents a well-organized visual map of the various aspects of the seawater desalination project in Agadir Each subheading addresses a specific aspect of this crucial initiative, from project inception to key partners, costs, key activities, procurement, and much more This structure enables a comprehensive understanding of the technical, economic, and strategic components of this major undertaking for the Agadir region. (EL BELKASMI & BOUTTI, 2023)

Table 4. *A visual Map of the seawater desalination project in Agadir. (EL BELKASMI & BOUTTI, 2023)*

Project Launch The desalination project in Agadir was initiated following the DBOT (Design, Build, Operate, Transfer) model The tender process began in 2012, the contract was signed in May 2014, resizing negotiations started in September 2016, construction work began in July 2018, and the plant was commissioned on July 1, 2022.	**Global Investment** The total investment for the project amounts to 4 billion MAD (approximately 400 million euros) over a period of 30 years, covering construction and operational costs.	**Construction Costs:** The construction costs of the desalination plant amount to 15 billion MAD, including infrastructure, the necessary equipment for the desalination process, as well as an additional financial cost of approximately 500 million MAD for interest and other fees.
Recurrent Operating Costs Recurrent operating costs encompass administrative fees, energy costs, transportation expenses, taxes, permits, and other operational expenditures The exact cost of	**Desalination Station Coverage Rate** The station provides drinking water supply for Greater Agadir, from Tamri to Ait Melloul, and also supplies irrigation water for the Chtouka plain, initially covering 15,000	**Key Partners** The main partners of the project include ONEE, the Ministry of Agriculture, the Souss Massa Hydraulic Basin, ORMVA, the Souss Massa Wilaya,

producing potable water and irrigation is confidential, but it remains moderately high compared to the global average due to Morocco's status as a non-oil-rich country.	hectares and expandable up to 30,000 hectares.	the neighboring municipalities, and the Ministry of Equipment.
Key Activities	**Supply**	**Key Resources**
The central activities primarily involve the sale of drinking water and irrigation water, in compliance with current legislation.	The EPS (Engineering, Procurement, and Construction) contract with Abengoa governs the construction and operation of the desalination plant, ensuring a supply of high-quality water.	The key resources include a grant of 2 billion DH for irrigation, a credit of 18 billion DH for drinking water, and contributions from partners totaling approximately 2 billion DH.

While the BMC provides a structured approach, it is essential to consider the environmental impacts and sustainability challenges associated with desalination, such as energy consumption and brine disposal, which can complicate the overall business model. (Ziolkowska & Reyes, 2016)

VII. Capacity development in the Arab Region: Desalination market growth & Major construction challenges

In the Arab region, desalination sector has developed into one of the biggest markets in the world enabling mainly in the Arab Gulf countries enabling them to contribute years of training to their neighboring countries. As outlined in in **Fig.26.** Nevertheless, nowadays, Desalination plants face significant operational and technical risks, particularly in operation and maintenance (O&M), which impact financial stability and revenue streams. To add to that, a substantially continuous need for the development and training of human resources to run the existing and future desalination plants in the Arab region. (FAO, 2022)

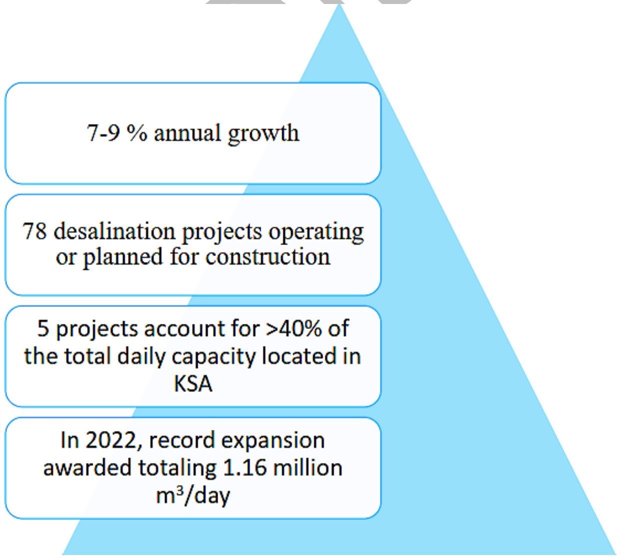

Fig. 61. *Desalination market growth. (Al-Abri, 2022)*

Plant suppliers are attempting to solve this problem by establishing training facilities and programs within the host country or abroad. Efforts like Oman’ s MEDRC and Saudi Arabia’ s Academy are pioneering initiatives aimed at developing local expertise needed to operate and maintain desalination plants effectively. Also, International desalination companies and institutions conduct training courses regularly, such as DH Paul and Masar Technologies DME Desalination Institute, Haward Technology Middle East, Bushnak Academy, and Apex. In addition, international

VIII. Good Practices: Case Studies & Replicability Potentials

Multiple indicators suggest that the trend of widespread desalination use worldwide will continue. In the UN World Water Development Report 2021, it’s estimated that approximately 2.2 billion people worldwide lack access to freshwater, and up to 5.7 billion people could face water scarcity for at least one month a year by 2050. (FAO, 2024) Hence, several coastal countries see water desalination as a solution to water scarcity. (Daghari, Desalination and Agriculture, 2022)

A. Desalination for agriculture in North Africa

Morocco faces significant water supply challenges due to its semi-arid climate, inconsistent rainfall, and growing population. To ensure water security, the government has prioritized desalination. Agriculture, which contributes 14% to GDP, consumes nearly 88% of the country’s water, and water scarcity could reduce GDP by up to 6.5%. To address this, Morocco is focusing on unconventional water sources like desalinated seawater and treated wastewater. (Pérez, 2024)

In 2020, Morocco launched the National Programme for Potable Water Supply and Irrigation 2020-2027 (PNAEPI), part of the National Water Plan (PNE) 2020-2050, with a budget increase to $14.3 billion in May 2023. Currently, the country has eleven desalination plants, with plans to expand to twenty by 2030 to support drinking water, agriculture, and industry. Future plants will use renewable energy, with Metito Utilities and Tahliya Group developing a multi-user irrigation project using desalinated water. (Pérez, 2024)

Additionally, Osmosun and Moroccan industrial group PCS have formed Osmosun MA to develop small to medium desalination projects for isolated areas. The Franco-Moroccan company Sand to Green is leading a regenerative agriculture project in the Guelmim-Oued Noun region, using a solar-powered desalination unit to irrigate a 38-hectare ecological plantation. This unit, producing 140 cubic meters of fresh water per day, supports the transformation of desert land into fertile ground. (Magoum, 2024)

In Algeria, desalination is seen as crucial to preventing future water shortages. The country's Mediterranean conditions allow for lower desalination costs, leading to the construction of large-scale plants with a total capacity of over 2 million m³/day since the 2001 water crisis. Libya has also invested in desalination, operating around 10 stations. In Tunisia, while desalination is technically feasible, it is prohibitively expensive, and the country relies on mixing dam water with aquifers to combat seawater intrusion instead. (Daghari, Desalination and Agriculture, 2022)

B. Desalination for agriculture in the Middle East

Arab countries are planning to increase desalination capacity from 36 million cubic meters a day in 2011 to around 86 million cubic meters a day by 2025. Most of this investment is expected to be in the Gulf countries. The estimated investment needs by 2025 amount to $38 billion, with $27 billion allocated to the Gulf countries. (FAO, 2024)

Abu Dhabi, for instance, is food-secure but not food self-sufficient, relying heavily on imports for 90% of its food. The region's water comes from three main sources: groundwater (65%), desalinated water (30%), and recycled water (5%). However, groundwater, crucial for agriculture and natural ecosystems, is depleting rapidly and is essentially a non-renewable resource. With current usage rates, groundwater could be exhausted by 2060-2070, leading to increased salinity in aquifers. Abu Dhabi faces a significant water deficit, overusing its water budget by 60%. To ensure future food security and reduce dependency on imports, the Emirate must conserve groundwater and develop a water-efficient agricultural system that can be quickly scaled up. (Amer, Adeel, Boer, & Saleh, 2016)

Qatar, on the other hand, consumes approximately 1.2 million cubic meters of desalinated water daily, but agriculture requires an additional 3.5 million cubic meters, achievable only with advanced water conservation methods like greenhouses, drip irrigation, and hydroponics. Each cubic meter of desalinated water produces 45 kilograms of salt, leading to a daily salt byproduct of 157 million kilograms, negatively impacting marine life. To support Qatar's agricultural needs, 1.8 gigawatts of power generation is required, equivalent to nearly 4,000 hectares of solar panels. With only 1% of the terrain arable and 68,716 hectares available for farming, Qatar would need to reclaim an additional

30,000 hectares to meet even reduced food production goals of 1.7 million tons per year. (Amer, Adeel, Boer, & Saleh, 2016)

Saudi Arabia faces significant agricultural challenges due to its dry climate, poor soil quality, limited water supply, and limited arable land. Despite these constraints, the country achieved self-sufficiency in water-intensive crops like wheat by investing in agricultural policies from the 1970s. By 2006, wheat production reached over 2.6 million tons, but this led to the depletion of non-renewable groundwater resources. Consequently, Saudi Arabia shifted from self-sufficiency to focusing on water desalination to meet growing demand. Groundwater provides 84% of the water supply, while desalination accounts for 8%, with agriculture consuming nearly 86% of the total water. Due to inefficient water use, exacerbated by low water tariffs and prioritization of fresh water for agriculture, the government is ending wheat subsidies and banning wheat production to conserve water. By 2016, Saudi Arabia planned to rely entirely on wheat imports and had allocated $12.3 billion for agricultural infrastructure development. (Amer, Adeel, Boer, & Saleh, 2016)

What is more, over 50 brackish water desalination plants have been installed by farmers in the Jordan Valley, using reverse osmosis technology with capacities ranging from 360 to 2400 m^3/day. These plants abstract 11.7 million cubic meters (MCM) of water annually, producing 7.7 MCM of desalinated water and 4.1 MCM of brine. The salinity of the brackish water ranges from 1300 to 7000 ppm, with desalinated water averaging 195 ppm. The plants operate 24 h/d in the summer and 12 h/d in the winter, using the electric power grid. The desalinated water, diluted to about 700 ppm, is used for irrigating high-value crops like bananas, strawberries, and dates. The investment cost per cubic meter of installed capacity averages $89, with large plants having lower desalination costs ($0.33/$m^3$) compared to small plants ($0.48/$m^3$). The average desalination cost across all plants is $0.38 per cubic meter. (Qtaishat, et al., 2016)

In contrast, small-scale desalination units are used by farmers in Oman to support low-yielding field crops. The majority of inland desalination facilities (80%) in Oman are RO type with limited capacities (less than 10,000 m3/d). More than 50% desalinate inland or brackish water (TDS 3,000 mg/l≤20,000 mg/l). (FAO, 2024)

Additionally, in December 2014, the Economic and Social Commission for Western Asia (ESCWA) and the Swedish International Development Cooperation Agency (SIDA) launched a four-year project to enhance food and water security in the Arab region. The project aims to improve coordination between agriculture and water institutions, focusing on assessing the impact of water availability on agriculture, developing integrated food and water security policies, assessing food security, and increasing food production efficiency. It is led by ESCWA in collaboration with the League of Arab States and other regional organizations, building on previous climate change impact assessments. (El Solh, 2015)

In conclusion, in spite of technological advances in farming, Arab policymakers concluded that food security cannot be achieved through food self-sufficiency alone. Hence, several Arab countries have thus turned to international commodity trading and foreign land agreements to ensure food security and preserve scarce water resources. (WB, 2012)

C. Desalination for agriculture worldwide: Confronting Attitudes between Managers and Farmers in Alicante and Murcia (Spain)

While desalination water costs and quality standards are well-studied, the interaction between desalination plant managers and irrigation communities in addressing water scarcity has received less attention (Ricart, Villar-Navascués, Gil-Guirado, M. Rico-Amorós, & Arahuetes, 2020). A specific study examined how these managers and farmers work together to close the gap in desalinated seawater for agricultural irrigation in Alicante and Murcia, Spain. A total of 11 irrigation communities have been selected to conduct the study, as showcased in the following table, which account for more than 58,000 irrigators and 120,000 ha, approximately 82% of the TST total irrigated area. Each irrigation community is currently using desalinated water, directly or by swap, and almost all are connected to a desalination plant managed by ACUAMED a Spanish public entity that manages desalination infrastructure. (Ricart, Villar-Navascués, Gil-Guirado, M. Rico-Amorós, & Arahuetes, 2020)

Table 5. *Irrigation communities' basic characterization. (Ricart, Villar-Navascués, Gil-Guirado, M. Rico-Amorós, & Arahuetes, 2020)*

Irrigation Community	Irrigable Surface	Irrigated Surface	Irrigators	Average Farm Size (ha)	Main Crops [8]	Irrigation Method
Águilas	6029	≈4800	1620	3 [1]	Vegetables and fruits	Drip (100%)
Campo de Cartagena	41,920	38,319	5 9678	4	Vegetables and fruits	Drip (96%), sprinkler (2%), and flood (2%)
Alhama de Murcia	7200	5096	2318	< 1 [2]	Vegetables and fruits	Drip (80%) and flood (20%)
El Saltador	2500	2300	≈1000	1.5 - 4 [3]	Vegetables and fruits	Drip (98%) and sprinkler (2%)

Librilla	2532 [4]	≈1900	1916	< 1 [4]	Vegetables and fruits	Drip (40%) and Flood (60%)
Lorca	23,905	23,905 [6]	≈12,000	1.5	Vegetables and fruits	Drip (80%) and Flood (20%)
Mazarrón	4803	3595	1150	<1	Vegetables and fruits	Drip (100%)
Puerto Lumbreras	4022	≈3000	880	3 - 4 [5]	Vegetables and fruits	Drip (90%), sprinkler (2%), and flood (8%)
Pulpí	8451	≈7000	1239	3 [6]	Vegetables and fruits	Drip (70%) and Sprinkler (30%)
Riegos de Levante Izquierda del Segura	≈26,000	≈24,000	≈22,000	1 =	Fruits and vegetables	Drip (45%) and Flood (55%)
Totana	10,765	6979	4216	<1 [7]	Vegetables, fruits and essences.	Drip (80%) and Flood (20%)

Source: own elaboration from the questionnaires. [1] Some farms up to 200 - 300 ha; [2] Some farms up to 400 ha; [3] Some farms up to 40 - 50 ha; [4] Professional farmer: 20 ha, with 7 - 8 large fruit and vegetable companies (25 - 30 ha each one); [5] Some farms up to 50 - 100 ha; [6] One horticultural company uses 800 ha and a fruit company, about 300 ha; [7] Some horticultural companies up to 150 ha; [8] Vegetables include lettuce, broccoli, artichoke, cauliflower, tomatoes, celery, potato, onion, and pepper; while fruits include citrus, melon, watermelon, grape, and mango.

- *Services and Management Developed by ACUAMED*

Apart from water concessions, irrigation communities establish agreements with ACUAMED to use desalination infrastructure, covering cost recovery, operation, maintenance, and payment conditions. However, some communities criticize these contracts as rigid and unfavorable, as they require payment for desalinated water regardless of usage.

As a matter of fact, irrigators offer mixed feedback. Six communities give positive assessments, while four provide negative feedback. One has mixed views. Positive feedback focuses on the reliable water supply, good communication with desalination plant staff, and high-water quality. Negative assessments mention technical issues like limited storage, low production rates, distribution network limitations, and poor maintenance.

Many negative perceptions stem from how contracts are managed, with communities arguing they are forced to accept unfavorable terms without knowing full financial conditions. This has led to accusations of unfair management, with some communities viewing ACUAMED as bureaucratic and solely focused on revenue collection. Corruption scandals and large investments in the desalination plants contribute to this distrust.

Consequently, many irrigation communities believe desalination management should be handled by SCRATS (the organization representing all irrigation communities) and the Segura River Basin Authority, rather than allowing individual negotiations with ACUAMED. They argue that collective negotiation would improve fairness and unity of action.

In contrast, from ACUAMED's viewpoint, disagreements arise from conflicting interests and the users' lack of understanding regarding infrastructure financing and cost recovery. ACUAMED acknowledges that costs, especially those related to investments, are a major issue but claims that these costs are non-negotiable.

- *Water pricing, tax and cost*

Economically speaking, the water prices set by ACUAMED desalination plants for agricultural use, ranging between 0.38 EUR/m3 in the Águilas-Guadalentín plant, 0.48 EUR/m3 in Torrevieja plant and 0.57 EUR/m3 in Valdelentisco plant and including pumping-distribution costs that are respectively 0.09, 0.08 and 0.13 EUR/m3, are lower than those reported by irrigation communities. As represented in the following figure. This is mainly due to additional factors such as water leakage, distribution tolls, surcharges, and their own infrastructure-related costs.

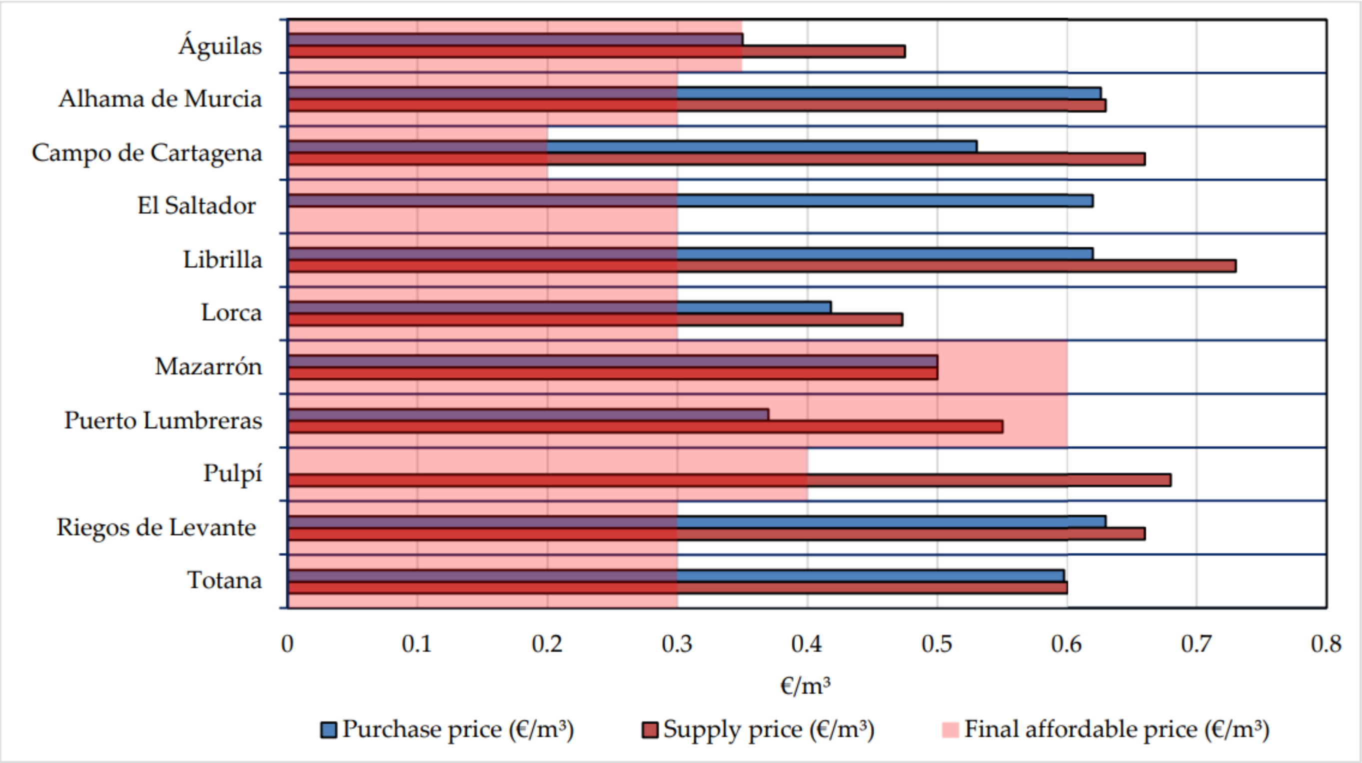

Fig. 27. *Purchase price, supply price and final affordable price of desalinated water by irrigation community. Source: own elaboration from the questionnaires. (Ricart, Villar-Navascués, Gil-Guirado, M. Rico-Amorós, & Arahuetes, 2020)*

As a result, an ongoing reassessment of the pricing structure of desalinated water for agriculture is crucial. This is by considering the additional costs faced by irrigation communities. This could involve efforts to reduce transport leakages, streamline distribution infrastructure, or subsidize costs to ensure affordability for farmers.

- *Regulatory framework*

Regarding regulations, ACUAMED and the plant managers have indicated that there is a preliminary project by the Segura River Basin Authority aimed at interconnecting all desalination plants. This project is designed to address issues related to regulation and storage capacity by utilizing existing post-transfer hydraulic infrastructure.

Additionally, ACUAMED is not responsible for the operation and maintenance of the distribution pipes that carry water to the consumption points beyond the delivery points to irrigators. Their primary obligation is to deliver the agreed-upon monthly volume of water based on the capacity of each desalination plant. Consequently, any demand exceeding this volume is not guaranteed.

Furthermore, ACUAMED does not handle the integration of desalinated water into general distribution systems that involve multiple water sources. They suggest that constructing regulatory elements could be a viable solution if these elements are deemed profitable, considering the investment costs and user interest. Nonetheless, ACUAMED asserts that they are limited to their contracted actions and will only undertake the construction and operational costs of regulatory elements if agreements are in place, despite the existence of other infrastructure managed by different entities.

- *Water quality standards*

Regarding water quality standards for desalinated water, three key issues have been assessed: conductivity, boron concentration, and management measures. Most irrigation communities have established quality control systems that monitor parameters such as conductivity with weekly or bi-weekly analytics. The reported conductivity levels of desalinated water are within acceptable ranges, with values from ACUAMED's plants falling between 200-500 µS/cm in Torrevieja, 400-600 µS/cm in Valdelentisco, and 500-900 µS/cm in Águilas-Guadalentín. The majority of irrigation communities rate the quality of desalinated water as good or very good, with conductivity levels rarely exceeding the 1300 μS/cm threshold considered suitable for most crops. As illustrated in the following table.

While the concentration of boron in desalinated water is generally not perceived as problematic, some communities have faced issues. In Lorca, the boron concentration has occasionally surpassed 0.5 mg/L, causing difficulties for citrus crops. ACUAMED has referenced contract terms allowing up to 1 mg/L of boron. Other communities, such as Pulpí and Puerto Lumbreras, have also experienced boron-related problems, leading them to mix desalinated water with other water sources to reduce boron levels.

It is key to underscore that most irrigation communities believe that no additional post-treatment is needed for desalinated water before use. However, except for a few cases, they mix desalinated water with other water sources to improve overall water quality, utilize available conventional resources, and reduce costs. This practice complicates the potential for requesting specific water quality from desalination plants tailored to crop needs, as it would necessitate irrigation ponds with varying water qualities and potentially increase production costs. Only a few communities consider requesting specific water qualities, with interest primarily based on existing practices or concerns about boron levels if desalinated water were their sole source.

Eventually, several deductions can be reached allowing to replicate the experience effectively. On top of them, ensuring transparent contracts is crucial. Agreements should be fair, flexible, and fully disclosed before signing. This avoids rigid terms and fosters trust between irrigation communities and management entities. Additionally, collective negotiation through representative bodies should be encouraged given that unified agreements ensure balance and prevent individual communities from facing unfavorable terms, promoting fairness and unity of action.

What is more, addressing technical issues like storage capacity and maintenance is essential along with ensuring that the infrastructure operates efficiently helps prevent disruptions and dissatisfaction among users. Good communication between desalination plant staff and users is vital. Direct, responsive contact strengthens trust and enhances overall management.

It is essential to highlight that a flexible cost structure is also significant. Pricing based on actual usage avoids discontent with fixed charges for unused services, leading to better user satisfaction. Finally, minimizing bureaucracy and involving local authorities can help mediate negotiations and ensure transparency, fostering a smoother collaboration between stakeholders.

IX. Recommendations and Future Perspectives

A. Technical and Financial recommendations

Advancing desalination projects for agricultural purposes requires a strategic approach that emphasizes the cultivation of high-value crops, which offer substantial financial returns per unit of water used. Horticultural products such as vegetables, flowers, ornamental plants, vineyards, and tree fruits are particularly well-suited for desalinated water due to their higher market value, which justifies the associated costs. Conversely, crops like cotton, rice, and sugar, which demand more water and offer lower economic returns, are less ideal candidates for desalination.

Greenhouses emerge as a highly recommended cultivation environment for these high-value crops. By providing a controlled environment, greenhouses facilitate more efficient water use and enhance the benefits of desalinated water. Crops including tomatoes, potatoes, eggplants, peppers, watermelons, melons, cucumbers, and summer squash are well-suited to greenhouse conditions, maximizing the potential of desalinated water.

When evaluating desalinated water options, brackish water desalination (BW) stands out as a more cost-effective solution compared to seawater desalination (SWD). With BW typically costing about one-third of SWD, it presents a more economical choice for agricultural applications. However, it is important to manage inland brackish water sources carefully since groundwater is not as renewable as seawater.

The adoption of advanced membrane technologies, such as reverse osmosis (RO) and electrodialysis (ED), powered by photovoltaic systems (PVs), offers efficient and sustainable solutions for agricultural desalination. These technologies, especially when integrated with renewable energy sources, represent the most effective methods available.

Financially, a balanced model combining public and private sector involvement is crucial for the success of desalination projects. Public sector support provides essential project guarantees and mitigates risks, while private sector engagement introduces efficiency and innovation. Public-private partnerships (PPPs) with long-term build-operate-transfer (BOT) contracts are particularly effective, allowing municipalities and utilities to transfer financial risks to private entities, thus ensuring long-term sustainability and financial viability.

Regarding the plant size, large-scale desalination plants are generally preferable due to their benefits, including public sector involvement, better access to financing, and reduced operational and maintenance challenges. Site selection is also critical; coastal locations near major demand centers with safe brine disposal options should be prioritized. Choosing sites with lower risks of biofouling and pollution, utilizing existing marine infrastructure, and preparing facilities for natural disasters are vital for ensuring the efficiency and resilience of desalination projects.

B. Environmental recommendations: Emerging Sustainable Strategies

Several environmental life cycle assessments determine that desalinated water use for irrigation leads to higher environmental impacts in several categories such as global warming, energy use, soil quality, and aquatic ecotoxicity. This often leads the authorities in charge of water resources to promote water demand management i.e. avoiding illegal withdrawals, reducing leaks in drinking water or irrigation networks and reusing wastewaters. If these measures are not sufficient, the authorities promote a change of the existing uses, with a clear priority to supply cities or recharge aquifers, and possible restriction of water delivery to agriculture (FAO, 2024)

In this context, there are several emerging sustainable strategies to mitigate desalination repercussions besides advanced treatment technologies. (FAO, 2024) Including:

- Waste minimization: This involves reducing the volume of saline effluent generated by industries and desalination plants. This can be achieved through process optimization, waste segregation, and reuse of wastewater.
- Zero liquid discharge (ZLD): ZLD is a treatment process that aims to produce a solid or concentrated liquid waste stream with no liquid discharge. This can be achieved through membrane separation, evaporation, and crystallization processes.
- Resource recovery: This involves recovering valuable materials from saline effluents, such as salts, metals, and nutrients. This can be done through processes such as crystallization, evaporation, and electrowinning.
- Integration with renewable energy sources: The use of renewable energy sources, such as solar and wind power, can reduce the environmental impact of saline effluent treatment.

B. Political and Social recommendations

To support the development of desalination projects for agricultural applications, comprehensive legal, legislative, and regulatory frameworks should be established. Advanced research focused on agricultural desalination technologies must be promoted, with an emphasis on localizing both the technologies and manufacturing processes. Additionally, providing subsidies and incentive programs to assist small-scale farmers is essential. (Al-Abri, 2022) Additionally, a stakeholder forum should be created to facilitate knowledge exchange, capacity-building activities, and prioritize relevant initiatives. Offering expertise and promoting best practices that encourage farmers to adopt non-conventional water sources for irrigation is crucial. In fact, access to desalinated water should be made available to everyone, not just large-scale farmers but also small farmers or groups of small farmers who can collaborate to share a desalination unit for their irrigation needs. This approach is already in practice in the Arab region, such as in Mahdia, Tunisia. Eventually, the private sector should be empowered to assist key decision-makers in planning desalination projects, ensuring that these initiatives are evaluated holistically, considering their economic, environmental, and social impacts. (FAO, 2022)

By following these recommendations, desalination projects for agricultural applications can become more economically viable, environmentally sustainable, and better integrated into broader agricultural and water management strategies.

Conclusion

This study aimed to examine the opportunities, challenges and concerns related to the use of desalinated seawater for agricultural irrigation. As a result, desalination presents a promising solution for addressing the water scarcity challenges faced by the Arab region, particularly in the context of agricultural development. As traditional freshwater sources become increasingly depleted, the adoption of desalination technologies can provide a reliable and sustainable water supply for irrigation. This not only enhances agricultural productivity but also contributes to food security in a region heavily reliant on agriculture for its economy and livelihoods.

The successful development of desalination projects for agricultural applications requires a multifaceted approach that prioritizes high-value crops and efficient cultivation methods. By focusing on crops such as vegetables, flowers, and fruits, which offer greater financial returns, the higher costs of desalinated water can be justified. Greenhouse cultivation, which promotes water efficiency, further enhances the viability of desalinated water in agriculture. Additionally, brackish water desalination proves to be more cost-effective than seawater desalination, particularly when paired with advanced membrane technologies like reverse osmosis and electrodialysis powered by renewable energy. These technologies, coupled with a balanced financing model that involves both public and private sectors, can ensure the financial sustainability of desalination projects.

Economically speaking, despite the varied costs of desalinated water—ranging from to 2.50 $ to 0.50 $ per cubic meter for seawater desalination and 2.00$ to 0.60 $ per cubic meter for brackish water—the ongoing advancements in membrane technologies and energy recovery systems have significantly reduced these expenses. As a result, desalinated water is becoming increasingly competitive for agricultural use. To put it differently, while desalinated water remains more expensive than traditional sources, its environmental, social, and economic benefits make it a compelling option. It can reduce dependency on non-renewable water resources, prevent rural migration, and support high-value crop production, making the higher costs more justifiable. Besides Public-Private Partnerships (PPPs) with long-term contracts provide a viable delivery model, transferring financial risks and promoting long-term sustainability.

Moreover, large-scale plants are preferred due to their operational efficiency and public sector support, while site selection near coastal areas with safe brine disposal and low environmental risks is crucial for long-term success. This can only be achieved via a continuous assessment of the environmental impact of desalination processes, ensuring that they are implemented alongside efficient water management practices. By investing in innovative desalination technologies and sustainable agricultural practices, the Arab region can effectively harness its coastal resources, promote agricultural resilience, and secure a more sustainable future for its agricultural sector. In addition, collaboration between governments, private sectors, and local communities will be crucial in developing policies that support these initiatives while addressing potential challenges such as energy consumption and brine disposal. Furthermore, education and awareness programs can empower farmers to adopt these new technologies and practices, fostering a culture of sustainability that benefits both the environment and local economies. This holistic approach not only enhances food security but also contributes to the overall economic stability of the region, paving the way for a more resilient agricultural landscape.

The findings of this study are intended to support future efforts in addressing the concerns of irrigation communities, focusing on key factors and barriers, including different models of seawater desalination, water pricing, energy consumption, storage capacity limitations, regulatory issues, and environmental impacts. Overcoming these obstacles is crucial for turning current challenges into best practices for desalination use and management. Consequently, making desalination a key component in sustainable agricultural practices, contributing to water security and economic development.

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