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# Evaluating environmental and socio-economic requirements for improving desalination development

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ABSTRACT

The continuous increase in global freshwater demand highlights desalination technology as one of the most feasible options for addressing global water scarcity. This increase has occurred more rapidly in certain countries owing to certain factors that can influence the development of desalination projects. 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 based on a semi-quantitative analysis. 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. We 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. The knowledge obtained in this research may be used to inform scientific advice and advance toward the sustainable development of desalination projects.

## 1. Introduction

The continuous increase in global freshwater demand highlights the important role played by desalination technology as one of the most feasible options for addressing global water scarcity. There are currently more than 18,000 desalination plants around the world, representing a capacity of more than ~99.8 million $m^3$/day (DesalData, 2021; Eke et al., 2020). Desalination production capacity has increased significantly in the last decade, representing a continuous increase of about 7% per year since year 2010 until the end of 2019. Therefore, a substantial increase in desalinated water production is expected, dominated mainly by reverse osmosis technology due to its lower energy consumption and higher efficiency compared to other technologies (Shahzad et al., 2017; Zarzo and Prats, 2018). Although the scale of this development in the increase of desalinated water production differs across countries despite the global lack of freshwater. Much freshwater production through desalination is concentrated in the Middle East and North Africa, representing over ~50% of the total production capacity installed (DesalData, 2021; Eke et al., 2020).

Among the main factors relating to the development of desalination plants are (i) the complexity and requirements of national laws, (ii) the economic and energy costs of water production, (iii) government commitment to the technology as a complement to its water matrix policy, (iv) the legal certainty of the country, (v) the management of brine discharges, (vi) public/private financing for the development of desalination plants, (vii) the requirements established during environmental impact assessments (EIAs), and (viii) social acceptance of the projects (Eke et al., 2020; Ibrahim et al., 2018; Kress, 2019; Miller et al., 2014; Sadhwani Alonso and Melián-Martel, 2018; Shemer and Semiat, 2017; Sola et al., 2019b). These uncertainties, which vary among countries, may represent a threat to desalinated water production and socioeconomic development (Shemer and Semiat, 2017).

The start-up financial costs for implementing desalination plants and/or the water production costs represent major obstacles to implementation in some countries since non-governmental organizations without public support are not always able to cover these costs and the citizens are unable to pay the entire production costs (Shemer and Semiat, 2017). In addition, environmental impact is one of the most important issues limiting the sustainable development of desalination projects. Highly stringent environmental requirements are not always justified based upon empirical scientific criteria and may represent an

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**Abbreviations**

| | |
|---|---|
| EIA | Environmental impact assessments |
| EMP | Environmental monitoring plans |
| IDA | International Desalination Association |
| AEDyR | Spanish Desalination and Reuse Association |
| UAE | United Arab Emirates |
| USA | United States of America |

obstacle to the development of desalination plants in some countries (Navarro Barrio et al., 2021; Petersen et al., 2019; Sola et al., 2019a). The most important tool for managing and minimizing the impacts of desalination projects is the Environmental Impact Assessment (EIA). EIAs include studies and administrative procedures aimed at identifying the potential environmental impacts of project development (i.e., desalination) and provide corrective measures to minimize and mitigate these impacts (Elsaid et al., 2020; Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018; Sola et al., 2019a, 2019b). EIAs assess whether a project's impacts are in line with environmental norms and authorities' guidelines; ultimately, projects not complying with these may be rejected or cancelled (Elsaid et al., 2020).

Environmental monitoring plans (EMPs) are programs that impose monitoring and corrective measures arising from the EIA process, ensuring sustainable development during the operational phase of the project. In the case of desalination, EMPs are mainly related to identifying possible negative impacts associated with brine discharges on marine environments and adopting proper mitigation measures when such impacts are identified (De-la-Ossa-Carretero et al., 2016a; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013).

The aim of this research was to study the main requirements and most limiting factors for the successful development of desalination projects in several countries. This was achieved using a survey of global experts in the desalination field. The knowledge gained from this research may be used to (i) improve EIAs and EMPs in countries with high installed desalination capacities, (ii) facilitate an increase in the development of desalination projects in countries with high need and potential, and (iii) identify potential improvements to ensure the environmentally sustainable development of desalination projects worldwide. The manuscript includes a semi-quantitative analysis of main requirements (EIA and EMP requirements, financial support, public involvement, legal certainty, and social aspects) and most limiting factors (cost of water production, environmental requirements, financial support, legal certainty and social acceptance) for desalination development. The paper is structured as an original article, i) chapter 2 includes the methodology of requirements and limiting factors analyzed for the countries evaluated; ii) chapter 3 shows the results obtained for countries evaluated; iii) chapter 4 includes a discussion and recommendations to improve desalination sustainable development in countries where requirements are very low and/or limiting factors are very high.; iv) presents the general conclusions.

## 2. Materials and methods

### 2.1. Requirements for desalination development

A survey of desalination experts was structured into two major components (Fig. 1). First, the main *requirements* related to desalination project development were defined. These were defined as the environmental and socio-economic aspects related to desalination development within each country (Ibrahim et al., 2018). The requirements were selected according to the published literature and were summarized into six main requirements to reduce the survey's complexity and thus obtain higher response rates. These included: i) the presence or absence of the EIA process required for desalination project installation, and the environmental requirements of the EIA, as the land use, energy consumption, air pollutant emissions regarding energy demand, impact on the environment, the noise pollution, among others (Fuentes-Bargues, 2014; Liu et al., 2013; Sadhwani Alonso and Melián-Martel, 2018); ii) the presence or absence of EMPs for the operation phase, and the number of environmental requirements within the EMPs, as the control of saline plume dispersion, effluent quality, saline sensitive species, among others (Sola et al., 2019a, 2019b, 2019b); iii) social acceptance of desalination projects among the population, as the perception, support and concerns of the population about installing a desalination plant, (Heck et al., 2016, 2018); iv) financial support of the construction and operation of desalination projects to complement the hydric matrix (Eke et al., 2020; Mohammadi et al., 2020); v) public involvement in the development of desalination projects (Eke et al., 2020; Montano et al., 2021); and vi) the legal certainty to ensure the successful development of a desalination project, such as the existence of an appropriate legal framework (Alvez et al., 2020; Eke et al., 2020).

Within each requirement, no sub-factors were considered; thus minimizing the survey's complexity, which reduced the time demand for completion and facilitated a high number of surveys responses from leading experts. Increasing the complexity of the survey would have resulted in a lower response rate, which would have negatively impacted the accuracy of the results and led to subsequent misrepresentation of the data (Ibrahim et al., 2018).

The requirements were evaluated using a semi-quantitative scale where 1 represented the lowest degree and 5 the highest degree for each requirement (Table 1). In addition, the number of years of processing and/or authorization of desalination projects in the survey for each country was compiled through a free value response. Furthermore, it was assessed whether countries required an EIA process for desalination

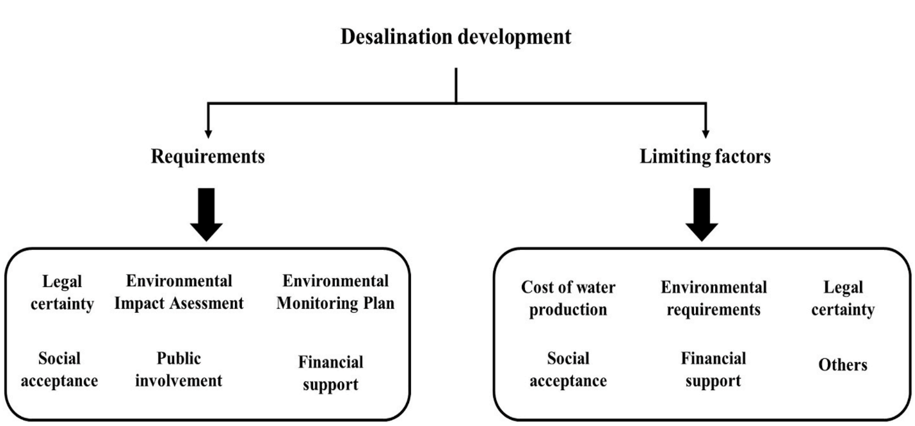


**Fig. 1.** Summary of requirements and limiting factors used to assess desalination development across different countries.

**Table 1**
Semi-quantitative scale used for requirements evaluation by survey respondents.

| Score | Semi-quantitative scale for requirements evaluation |
|---|---|
| **1** | Represents the lowest legal certainty; lowest number of requirements in EIAs; lowest number of requirements within EMPs; lowest social acceptance of desalination projects; lowest involvement in project development; lowest funding availability |
| **2** | Represents a low degree for each requirement |
| **3** | Represents a medium degree for each requirement |
| **4** | Represents a high degree for each requirement |
| **5** | Represents the highest degree for each requirement |

project development and/or if they implemented an EMP for the operational phase of desalination plants. Likewise, data on the nationality, number of years working in the desalination sector, working sector (e.g. water management and treatment companies, scientists, and academics), and number of countries worked in were collected for each desalination expert interviewed.

### 2.2. Limiting factors for desalination development

The second group identified the most *limiting factors* for desalination development in each country (Fig. 1). These were defined according to published literature and summarized as five main factors. These included: (i) the cost of desalinated water produced (Al-Karaghouli and Kazmerski, 2013; Mezher et al., 2011; Miller et al., 2014; Mohammadi et al., 2020; Shahzad et al., 2019); (ii) the number of environmental requirements established in the EIA process for managing environmental impacts related with the installation of a desalination project (Shemer and Semiat, 2017; Sola et al., 2019b); (iii) social acceptance among the population, as the perception, support and concerns of the population about installing a desalination plant (Heck et al., 2016, 2018); (iv) legal certainty of the country, such as the lack of legislation that may cause legal uncertainty for projects development (Alvez et al., 2020); and (v) financial availability for the desalination projects, whether public, private or public-private financing (Eke et al., 2020).

Within each most limiting factor, no sub-factors were considered; thus minimizing the survey's complexity and increasing the response numbers (Ibrahim et al., 2018). The limiting factors were evaluated through a semi-quantitative scale (Table 2).

Once the assessments were collected for each country, only those with a minimum of two surveys returned by different experts were considered in the analysis. This allowed us to compare the experts' assessments based on the different factors and requirements considered, and to reduce any potential bias derived from the non-objective personal perception of each of the experts regarding their local desalination realities. The median measure was used to compare the results obtained from the surveys.

### 2.3. Desalination survey of experts

The survey was aimed at desalination experts with strong and long-term backgrounds in the desalination field. To facilitate a multidisciplinary approach and obtain accurate results, the surveys involved experts from water management and treatment companies, constructors and/or operators' companies, workers in research and development in the water industry, scientists and academics, and workers in international consulting companies (among others). For this purpose, the survey was disseminated through board members of the IDA and Spanish Desalination and Reuse Association (AEDyR), as well as to researchers and scientists around the world with strong backgrounds in desalination. The online survey was carried out using the google docs platform (*https://docs.google.com*), with the survey link disseminated to experts via email. In addition, the results obtained were complemented with face-to-face surveys carried out during the International Desalination Association (IDA) Congress, which took place in Dubai from October 20th to 24th, 2019. A total of 34 desalination experts were interviewed, which resulted in 28 interviewees (83.3%) through disseminating the survey link via email, and 6 interviewees face-to-face (17.7%) realized during the IDA Congress. A total of 69 evaluations were obtained from 34 respondents to analyze the most limiting factors and requirements for each country. Each survey was filled out anonymously. An example of the disseminated survey is presented in the Supplementary Material (S1).

**Table 2**
Semi-quantitative scale used for limiting factors evaluation by survey responders.

| Score | Semi-quantitative scale for limiting factors evaluation |
|---|---|
| **1** | Represents a very low limiting factor |
| **2** | Represents a slightly limiting factor |
| **3** | Represents a more limiting factor |
| **4** | Represents a strongly limiting factor |
| **5** | Represents an extremely limiting factor |

## 3. Results

### 3.1. Desalination surveys

A total of 34 interviews were compiled, with the results showing respondents with a general average of 17.7 years working in the desalination sector and an average of more than 4.2 countries in which they have conducted associated activities (Table 3). It should be noted that 76.5% of the surveys compiled were obtained from experts in the industrial sector. The experts from the desalination industry sector showed averages of 19 years working in the field and operations in 5.1 countries, compared with 12.6 years and 1.7 countries for experts from the scientific sector (Table 3). An expert from the law sector was also surveyed but was not included in the global analysis since using only one respondent would have been misrepresentative of the sector .

A total of 13 nationalities were present in the data, although the largest numbers of surveys were obtained from Spanish, American, and Australian experts, accounting for 41%, 12% and 9% of total surveys, respectively (Fig. 2A). The respondents of most nationalities showed an average of more than 10 years of experience in the desalination sector and more than two countries where they had worked in the field (Fig. 2B and C).

A total of 69 evaluations were obtained to analyze the requirements and limiting factors for each country (Fig. 3). This resulted in 23 countries being evaluated, of which 11 countries were analyzed since they met the requirement of having more than two experts per country. Spain, Australia, USA, Algeria and Chile accounted for 10–13% of the total number of evaluations obtained .

### 3.2. Authorization years for the development of desalination projects

An accurate understanding of the results showed marked differences in the authorization time required for desalination projects among the different countries analyzed (Fig. 4). The USA showed the longest authorization time, with an average of 13.6 ± 6.2 years, followed by Peru and Israel, with averages of 7.5 ± 4.5 and 5.3 ± 1.4 years,

**Table 3**
Summary of survey numbers, average years in desalination, and average countries worked by sector for the different survey interviewees.

| Sector | Number of surveys | Average yearsin desalination sector | Average number ofcountries worked in |
|---|---|---|---|
| Industry | 26 | 19.0 | 5.1 |
| Research | 7 | 12.6 | 1.7 |
| Law | 1 | 20.0 | 1.0 |
| Total | 34 | 17.7 | 4.2 |

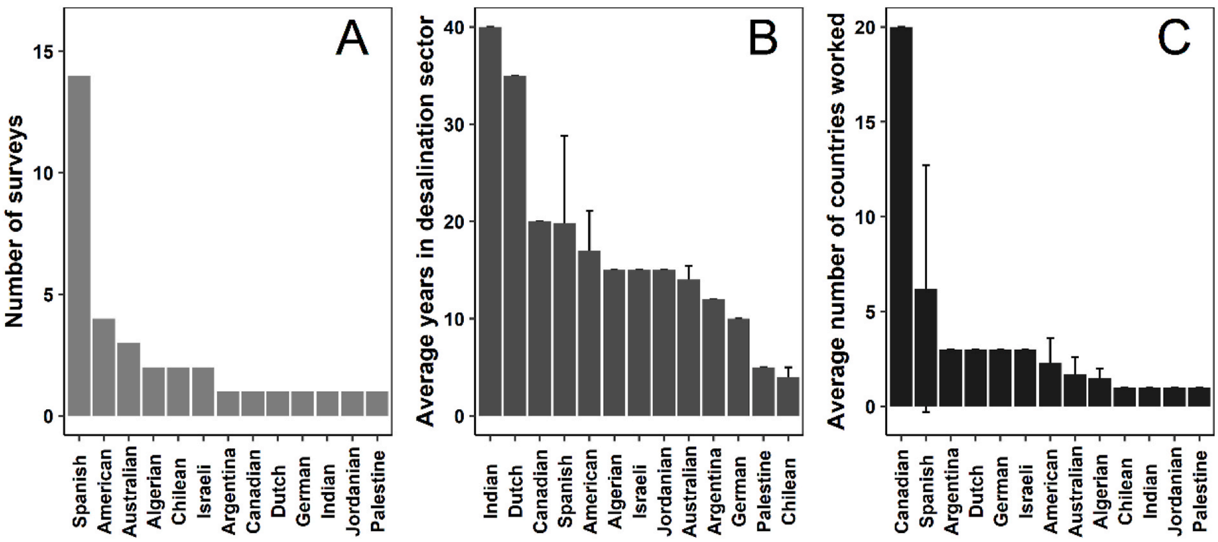


**Fig. 2.** Number of surveys (A), average years in the desalination sector (B), and average number of countries worked in (C) by nationality of survey experts.

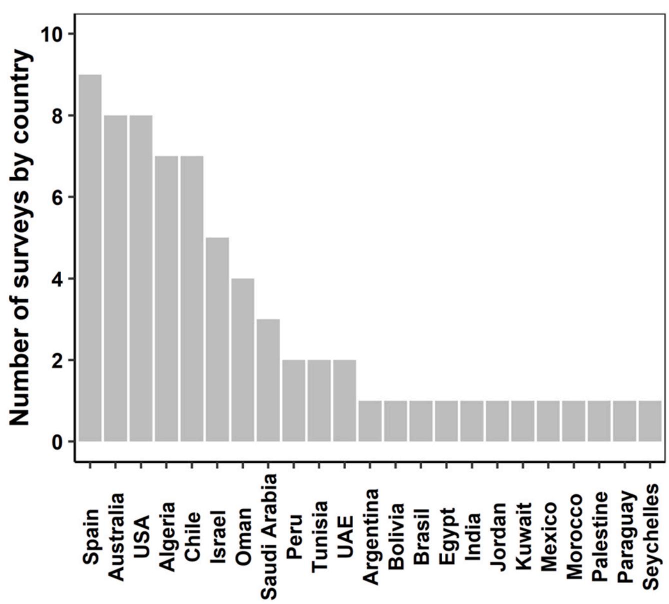


**Fig. 3.** Country evaluations obtained to evaluate the requirements and limiting factors of desalination development.

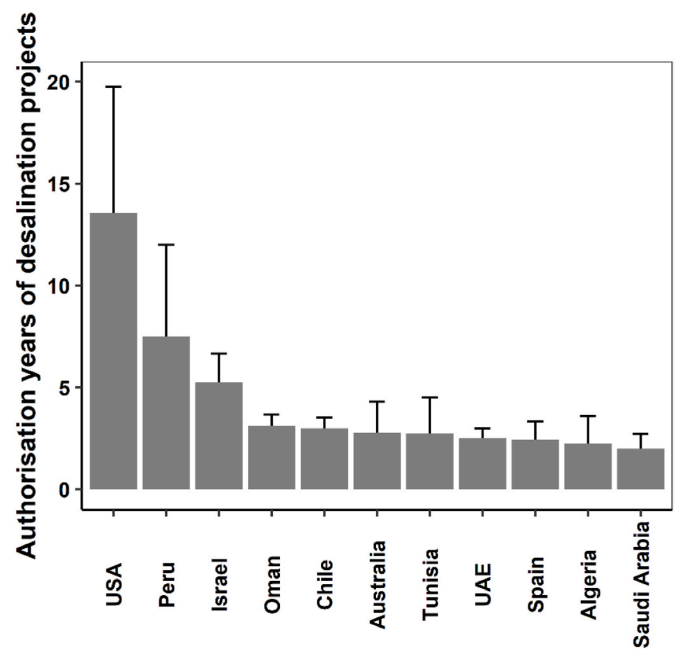


**Fig. 4.** Average authorization time required for a desalination project in each country based on the results obtained from the different desalination experts surveyed. Error bars indicate standard deviation.

respectively. Saudi Arabia and Algeria showed the shortest authorization times, with averages of $2 \pm 0.7$ and $2.3 \pm 1.4$ years, respectively. For the remainder of the assessed countries, the average authorization time ranged from 2.4 to 3.1 years.

### *3.3. Requirements of countries where desalination projects have been developed*

Within the environmental regulation of the countries analyzed, according to results obtained from desalination experts, most countries demonstrated that they require an EIA to develop a desalination project (Table 4). However, 50%, 33.3%, and 20% of total surveys conducted for Peru, Saudi Arabia, and Israel, respectively, indicated that they do not require an EIA; and 50%, 25%, and 14% of total surveys for Tunisia, Oman, and Algeria, respectively, indicated that EIAs are only required in certain cases.

The results showed significant heterogeneity in the requirements for EMPs among the different countries analyzed (Table 4). For Spain, Australia, and the USA, the results show that these countries always require an EMP. For Chile, Israel, and Saudi Arabia, 87.5%, 80%, and 66.7% of the total surveys, respectively, indicated that an EMP would be required. In contrast, for Tunisia, United Arab Emirates (UAE), Oman, and Algeria, 100%, 100%, 75%, and 57.2% of the total surveys, respectively, indicated that these countries do not require EMPs and/or these are only applied in certain cases.

The “requirements” assessment related to socio-economic and environmental aspects of desalination development is presented in Fig. 5. 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. In contrast, Saudi Arabia impose a low number of requirements.

Regarding the EMP requirements assessment, the USA imposes the

**Table 4**
Percentage of the total number of surveys conducted for the existence of environmental regulations for each country arising from expert responses.

| Country | Environmental regulation | Yes | Sometimes | No | Total number |
|---|---|---|---|---|---|
| **Algeria** | EIA | 85.7 | 14.3 | 0.0 | 7 |
| | EMP | 42.9 | 42.9 | 14.3 | |
| **Australia** | EIA | 100.0 | 0.0 | 0.0 | 8 |
| | EMP | 100.0 | 0.0 | 0.0 | |
| **Chile** | EIA | 100.0 | 0.0 | 0.0 | 7 |
| | EMP | 87.5 | 12.5 | 0.0 | |
| **Israel** | EIA | 80.0 | 0.0 | 20.0 | 5 |
| | EMP | 80.0 | 20.0 | 0.0 | |
| **Oman** | EIA | 75.0 | 25.0 | 0.0 | 4 |
| | EMP | 25.0 | 50.0 | 25.0 | |
| **Perú** | EIA | 50.0 | 0.0 | 50.0 | 2 |
| | EMP | 0.0 | 0.0 | 100.0 | |
| **Saudi Arabia** | EIA | 66.7 | 0.0 | 33.3 | 3 |
| | EMP | 66.7 | 0.0 | 33.3 | |
| **Spain** | EIA | 100.0 | 0.0 | 0.0 | 9 |
| | EMP | 100.0 | 0.0 | 0.0 | |
| **Tunisia** | EIA | 50.0 | 50.0 | 0.0 | 2 |
| | EMP | 0.0 | 100.0 | 0.0 | |
| **UAE** | EIA | 100.0 | 0.0 | 0.0 | 2 |
| | EMP | 0.0 | 50.0 | 50.0 | |
| **USA** | EIA | 100.0 | 0.0 | 0.0 | 8 |
| | EMP | 100.0 | 0.0 | 0.0 | |

EIA: environmental impact assessment; EMP: environmental monitoring plan.

highest number of requirements, followed by Australia, Chile, and Spain, which impose a high number of requirements. Algeria and UAE impose the lowest number of EMP requirements.

In addition, most countries analyzed show significant financial support for desalination plant development, with UAE showing the highest funding level. Chile showed a medium capability to obtain good financial support.

Most countries analyzed showed a high degree of legal certainty to facilitate the development of desalination projects. The results showed highest legal certainty for Australia, Spain, and UAE. Saudi Arabia and Tunisia showed a medium degree of legal certainty to facilitate desalination development.

Most countries analyzed showed a high level of social acceptance of desalination projects among their population, with highest levels seen for UAE, Saudi Arabia, and Israel. Chile, Spain, and USA showed a medium degree of acceptance for desalination projects.

Regarding the public involvement assessment, the results showed highest involvement for Australia, followed by USA, Tunisia, Spain, Israel, and Algeria, each with high involvement. UAE and Saudi Arabia showed low public involvement.

### 3.4. Limiting factors for desalination development

The "limiting factors" assessment for desalination project development is presented in Fig. 6. Within this evaluation, the cost of desalinated water production showed as a strongly limiting factor for desalination plant development in most countries analyzed. In Saudi Arabia, this factor presented as a slightly limiting factor.

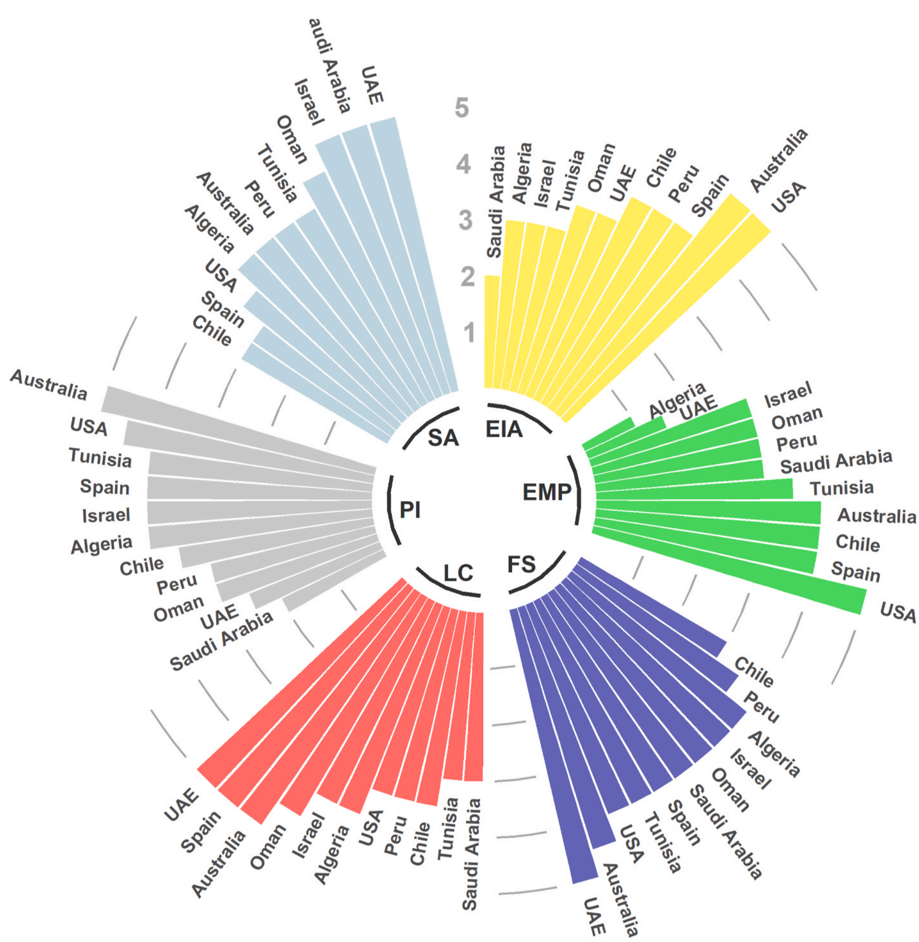


**Fig. 5.** Conceptual summary of median values for "requirements", as evaluated by desalination experts for each country analyzed. Requirements were evaluated using a semi-quantitative scale (1–5), where 1 represents a lowest number of requirements and 5 a highest number of requirements. EIA: environmental impact assessment requirements; EMP: environmental monitoring plan; FS: financial support; LC: legal certainty; PI: public involvement; SA: social acceptance.

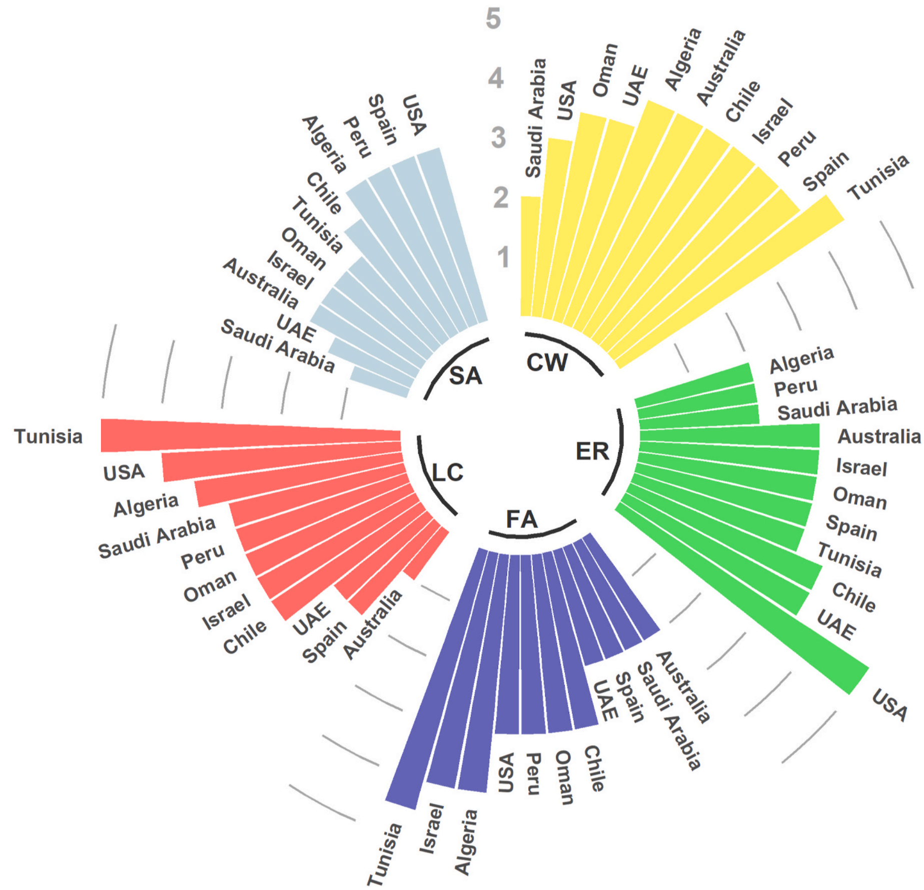


**Fig. 6.** Conceptual summary of median values for limiting factors evaluated by desalination experts for each country analyzed. Limiting factors were evaluated using a semi-quantitative scale (1–5), where 1 represents a very low limiting factor and 5 represents an extremely limiting factor. CW: cost of desalinated water produced; ER: environmental requirements; FA: financial availability; LC: legal certainty; SA: social acceptance.

The environmental requirements were generally moderately limiting factors for project development in most countries. However, in the USA, the results showed that these requirements represented an extremely limiting factor. In Saudi Arabia, Peru, and Algeria, these requirements presented as a slightly limiting factor.

In terms of financial availability, the results showed that this is a highly limiting factor for Tunisia, Algeria, and Israel. The results indicated this is a slightly limiting factor for Saudi Arabia, Australia, UAE, and Spain.

Legal certainty typically presented as a moderately limiting factor in most countries. This factor represented an extreme barrier and strongly limiting factor for Tunisia and USA, respectively. The results showed that it represents a very low limiting factor for Australia, UAE, and Spain.

Compared with the others limiting factors analyzed, social acceptance was the least significant. For Spain, Peru, Algeria, and USA this presented as a moderately limiting factor.

Fig. 7 shows the totals of the limiting factors by country. The results show higher levels of limiting factors for Tunisia, USA, Algeria, Israel, and Chile, whereas Saudi Arabia, Australia, and UAE present the lowest levels of limitations for desalination project development.

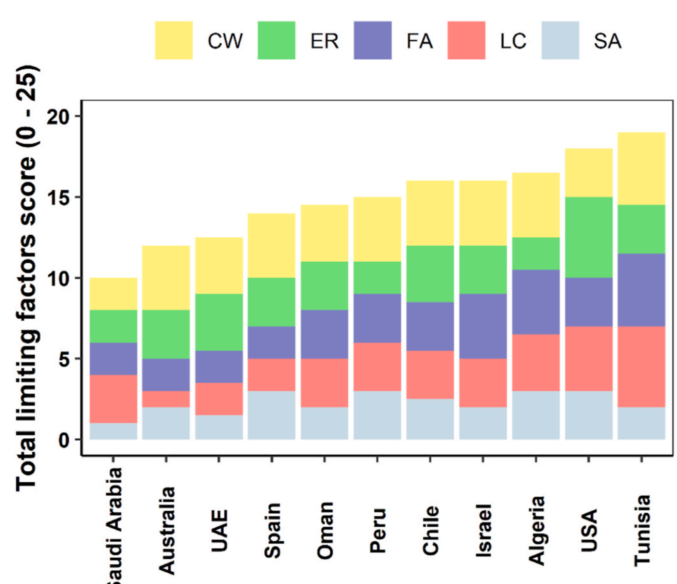


**Fig. 7.** Total limiting factors evaluated by desalination experts for each country analyzed. Limiting factors were evaluated using a semi-quantitative scale (1–5), where 1 represents a very low limiting factor and 5 represents an extremely limiting factor. CW: cost of desalinated water produced; ER: environmental requirements; FA: financial availability; LC: legal certainty; SA: social acceptance.

## 4. Discussion

The results presented in this research represent a first approach to assess how different socio-economic and environmental factors impact desalination development in different countries. An accurately understanding of these factors provides highly relevant information for moving toward sustainable desalination development and addressing increasing freshwater global demand (Eke et al., 2020; Jones et al., 2019; Shahzad et al., 2017).

From the survey analysis carried out in this study, we show that the surveyed experts have expertise in several countries and long-standing experience in the desalination sector. The information obtained from global desalination experts is relevant to evaluating the pros and cons of the main factors involved in desalination development. Other studies such as Ibrahim et al. (2018) also used the experience of desalination experts to assess the sustainability of thermal distillation and reverse osmosis technologies. However, our research is the first to use information gained from desalination experts to assess desalination development worldwide.

Our results show marked heterogeneity in the requirements and limiting factors among the different countries evaluated, showing a close relationship with the authorization time for project development. USA showed the longest authorization time, followed by Peru and Israel, although Peru showed a high standard deviation from the average value, suggesting different responses among the desalination experts. Likewise, USA and Israel presented as having high levels of limiting factors compared with the other countries assessed; these factors were mainly related to environmental requirements in USA and economic factors in Israel. However, most countries analyzed showed an average authorization time of less than three years.

We identified that the **cost of producing desalinated water** is a highly limiting factor in many of the countries analyzed, e.g., Tunisia, Algeria, Spain, and Australia. However, in Saudi Arabia and the USA, this factor represented only a slight limiting factor. The cost of desalinated water production is highly complex because it depends on many factors such as the technology used, energy costs, plant location, feedwater quality, capital costs, water intake and brine discharge costs, regulatory requirements, and maintenance and financial costs (among others) (Al-Karaghouli and Kazmerski, 2013; Eke et al., 2020; Kettani and Bandelier, 2020; Mohammadi et al., 2020). The energy costs represent the highest costs for most technologies used in seawater desalination, e.g., for thermal distillation and membrane desalination technologies, the energy costs are 60% and 44%, respectively, of the total water costs (Al-Karaghouli and Kazmerski, 2013). Therefore, seawater desalination is commonly more efficient and more sustainable when using reverse osmosis than when using thermal desalination owing to the lower energy consumption and desalinated water costs (Eke et al., 2020; Zarzo and Prats, 2018). Also, innovative desalination methods should be considered to meet the needs of achieving sustainable desalination to improve desalination efficiency over existing methods (Choon Ng and Shahzad, 2018; Shahzad et al., 2018a,b).

Likewise, the results obtained are in accordance with the energy costs published by Eke et al. (2020), showing higher energy costs for Spain and Algeria (21% and 24% of total energy cost, respectively) than for UAE and USA (14% and 18% of total energy cost, respectively), indicating that the economic costs of desalinated water production are more limiting in some countries than in others (Fig. 6).

The results show that **environmental requirements** associated with the EIAs and EMPs required for managing the environmental impacts of desalination plants were very low in countries such as Saudi Arabia, Algeria, and UAE, as compared with the others countries assessed. Moreover, these countries do not require an EMP or would impose an EMP with very low requirements, limiting the potential to (i) evaluate if measures adopted during the EIA are adequate and/or (ii) identify potential environmental impacts of brine discharge to facilitate their mitigation (De-la-Ossa-Carretero et al., 2016b; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013). EIA is the most important tool for adopting specific mitigation measures to address the environmental impacts of desalination plants. Therefore, in countries where an environmental assessment has not been properly carried out, the ecological value of a desalination plant location or brine discharge areas associated with the construction and/or operation phase of the plant may become deteriorated (Elsaid et al., 2020; Petersen et al., 2018; Roberts et al., 2010). However, even in countries where the environmental regulation requirements are low, desalination plants can operate without producing impacts on the marine environment when adequate measures are adopted by desalination operators. For instance, in Algeria, where two SWRO plants with capacities of 200,000 $m^3$ operate without an EMP, the potential impact of brine discharge from one plant was minimized through a proper dilution system using multiport diffuser devices (Belatoui et al., 2017; Loya-Fernández et al., 2018; Portillo et al., 2013), whereas in the other plant (with the same characteristics), brine discharge resulted in a large saline plume distribution with high salinity values and slight detrimental effects on benthic communities around the brine discharge area (Belatoui et al., 2017).

USA, Australia, Spain, and Chile presented as having high environmental regulation requirements. Our results are in line with the environmental requirements imposed in the EIAs for brine discharge management in Spain and Chile, as published by Fuentes-Bargues (2014) and Sola et al. (2019a, 2019b); although the EIA of both countries has some requirements that should be improved. High environmental requirements have not been a severe problem for desalination development in Spain, Australia, or Chile (Molinos-Senante and González, 2018; Sola et al., 2019a, 2020b). However, the results showed that environmental requirements are the most limiting factor for project development in USA, indicating an average of 13.6 years for authorizing a project compared with an overall average of 4.3 years across all countries. The development of desalination of projects with higher production capacities is limited in some parts of Europe and the Americas owing to rigid environmental protection laws in these regions (Eke et al., 2020). The enforcement of stringent environmental laws is not always justified scientifically and can delay the development of desalination projects, representing a barrier to the production of desalinated water for homes and industry. The experience obtained to date shows it is possible to ensure the long-term sustainable operation of desalination plants without environmental impacts on the marine environment when an appropriate environmental assessment process is carried out and mitigation measures are adopted (Kelaher et al., 2020; Pistocchi et al., 2020; Sola et al., 2020a).

The results showed a high degree of financial support in most of the countries evaluated, with UAE presenting the highest level financial support. However, this is a very limiting factor in Tunisia, Algeria, and Israel. According to the results of Eke et al. the Middle East Bank sponsors a large number of global desalination projects, which is a key factor responsible for the high production capacity of countries from this region, i.e., UAE or Saudi Arabia. Nevertheless, European and North African banks finance desalination projects due to the high freshwater demand in regions where water is scarce (Eke et al., 2020; Jones et al., 2019). However, some countries experiencing financial difficulties may be supported by strong government involvement in desalination projects, such as in Algeria and Israel (Drouiche et al., 2011; Kress et al., 2020).

According to the **legal certainty** factor, Australia, Spain, and UAE showed the highest legal certainty degree among the countries assessed. However, this factor presented as a high limiting factor for Tunisia and USA, and the most limiting factor for desalination development in Tunisia (followed by the cost of water production and financial support). A low legal certainty may affect the trust of foreign companies for developing desalination projects, which could affect the countries' development (Alvez et al., 2020). In the case of Tunisia, the banks demand greater financial responsibility from the project companies. This may justify that in the results obtained in this study, legal certainty represents a strong limiting factor for desalination project development in this country (Montano et al., 2021).

Regarding **public involvement** requirements in desalination development, our results showed that most countries have a high degree of public involvement. Nevertheless, Saudi Arabia and UAE showed a low involvement degree, although this would be offset by the high degree of financial support in these countries (Eke et al., 2020).

Appropriate government involvement in desalination development is relevant to integrated water management. For instance, this requirement would offset water desalination costs and the price of water sold through public subsidies, which may affect 20–30% of the estimated cost of water desalination. Therefore, countries with lower public sector involvement may affect companies not participating technically and/or financially, which evidences that public involvement may represent a great importance for the viability of developing a desalination project (Montano et al., 2021). Similarly, government involvement may provide subsidies to integrate renewable energies in desalination projects to amortize the short-term costs; thus reducing energy costs and aiding sustainable desalination development (Kettani and Bandelier, 2020; Pistocchi et al., 2020; Shahzad et al., 2017). A further point to be addressed is that government commitment for desalination project development can be affected in certain countries depending on the political trend, e.g., Spain (Downward and Taylor, 2007).

In this research we also explored the influence of **social factors**. As evidenced by our results, social acceptance may be the least relevant limiting factor (compared with the other factors) in desalination development. In addition, most countries showed a high potential acceptance of desalination projects. 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 (Eke et al., 2020; Hernández-Sánchez et al., 2017; Jones et al., 2019).

According to the analysis carried out, the main requirements and limiting factors for desalination project development were evaluated. Some of these requirements and limiting factors overlapped in both analyses, such as environmental requirements, legal security or financial support. The aim was to understand whether the presence of very high or very low requirements could be a limiting factor according to the analysis of socio-economic and environmental aspects for successful desalination projects development. For example, in the case of the USA and Australia, both presented a high number of environmental requirements but they only result in a limiting factor for the USA.

Table 5 summarizes the general recommendations for countries where the requirements for desalinination development are very low and/or the limiting factors are very high. For instance, for the USA, the limiting factor is scientific advice for sustainable desalination without producing environmental impacts on the marine environment when environmental requirements are a significant barrier to desalination plant development. In the case of the USA, the perception on potential environmental impacts on marine ecosystems from brine discharge and water intake have been identified as a barrier to desalination project development (Heck et al., 2016, 2018). Likewise, in Chile, the number of environmental requirements has increased significantly over time. However, this increase was related with the inclusion of additional requirements related to other types of effluents, such as sewage, but not related to the SWRO plant operation and the management of brine discharges effects on marine environment (Sola et al., 2019a). For other countries (e.g., Tunisia, Spain, and Israel) the limiting factor is carrying out highly cost-effective projects through the proper analysis and design of desalination projects (within each country's context) aimed at reducing the costs of desalinated water production (Al-Karaghouli and Kazmerski, 2013; Mezher et al., 2011; Pistocchi et al., 2020). Also, the high economic costs of desalinated water production, which limit desalination development in Australia, can be attributed to the use of energy from renewable sources and expensive designs for water intake and brine discharge infrastructure (Shemer and Semiat, 2017).

Promoting the development of adequate environmental regulations in countries where the environmental requirements are very low, such as in Saudi Arabia or Algeria, would help correctly manage the environmental impacts of desalination. The application of EMPs with specific environmental requirements according to plant location would help assess whether measures adopted during the EIAs are appropriate and allow monitoring of the potential effects of desalination plants during the operation phase, e.g., in UAE or Algeria (Belatoui et al., 2017; Sola et al., 2019a, 2019b).

**Table 5**
General summary of recommendations to improve desalination sustainable development in countries where requirements are very low and/or limiting factors are very high.

| Country | Requirements | Limiting factors |
|---|---|---|
| **Algeria** | Increase the number of EMP requirements | Carry out highly cost-effective projects to reduce costs of desalinated water produced. Improve financial availability. Improve legal certainty. |
| **Australia** | – | Carry out highly cost-effective projects to reduce costs of desalinated water produced |
| **Chile** | – | Carry out highly cost-effective projects to reduce costs of desalinated water produced. Scientific advice to facilitate environmental assessment process. |
| **Israel** | – | Carry out highly cost-effective projects to reduce costs of desalinated water produced. Improve financial availability. |
| **Oman** | – | Carry out highly cost-effective projects to reduce costs of desalinated water produced. |
| **Perú** | – | Carry out highly cost-effective projects to reduce costs of desalinated water produced. |
| **Saudi Arabia** | Increase the number of EIA and EMP requirements. Improve public involvement. | – |
| **Spain** | – | Carry out highly cost-effective projects to reduce costs of desalinated water produced. |
| **Tunisia** | – | Carry out highly cost-effective projects to reduce costs of desalinated water produced. Improve financial availability. Improve legal certainty. |
| **UAE** | Increase the number of EMP requirements. Improve public involvement. | Carry out highly cost-effective projects to reduce costs of desalinated water produced. Scientific advice to facilitate environmental assessment process. |
| **USA** | – | Scientific advice to facilitate environmental assessment process. Improve legal certainty. |

Improving government involvement to support desalination projects is also an important factor, e.g., in UAE and Saudi Arabia, as is increasing financial availability for desalination projects, e.g., as Algeria, Israel and Tunisia. Improving legal certainty in those countries that protect the builders and/or operators of desalination plants, e.g., in Tunisia, USA, or Algeria, is also recommended (Drouiche et al., 2011; Eke et al., 2020; Shemer and Semiat, 2017).

The experience gained to date shows that it is possible to achieve a long-term sustainable desalination when adequate measures and proper requirements are implemented (Fernández-Torquemada et al., 2019; Pistocchi et al., 2020; Sola et al., 2020a). Further, through an appropriate analysis of the pros and cons of desalination technologies it is possible to maximize the benefits and design of desalination projects within the context of reducing the energy costs of the water produced under an expected increase in the development of global desalination efforts (Al-Karaghouli and Kazmerski, 2013; Shahzad et al., 2017;(Zarzo and Prats, 2018) Zarzo and Prats, 2018).

Future evaluations could sample a larger number of desalination experts, covering more countries. This study obtained surveys from 23 countries; however, assessment was only possible for 50% of the countries when requiring replication. In future, this study could be extended to compare these factors across a greater number of countries such as China, which represents a significant desalinated water production capacity. Also, other global regions where the global desalination capacity is developing significantly, e.g., East Asia and Pacific regions that produce around of 18% of global desalinated water could be included (Jones et al., 2019). However, most of the important countries in terms of desalinated water production, such as Saudi Arabia, UAE, USA or Spain, were covered, validating the applicability of the results (Jones et al., 2019). Our results present a first approach to understanding which factors mainly affect desalination development globally based on a semi-quantitative analysis. For future research, data could be compiled from each country for quantitative assessment and comparison with the requirements evaluated in this study.

In addition, some limitations have been identified in this research that may be considered. Firstly, the sampling distribution of desalination experts could be more equitable, since there is a strong influence of Spanish experts that may affect in the results. However, the Spanish desalination ex perts and companies have a wide presence in desalination projects and as IDA board members over the world (DesalData, 2021). This study could be extended to compare the requirements and limiting factor across a greater number of nationalities. Furthermore, the answers may be influenced by expert's subjective understanding of the scale requirements and limiting factors assessed. Nevertheless, most of them have expertise in several countries and long-standing experience in desalination sector which makes the comparison robust.

## 5. Conclusions

The results show large heterogeneity in terms of the requirements and limiting factors for desalination development across different countries. Special attention should be given to countries where strong limiting factors would represent a barrier to desalination development. Our results showed that environmental requirements are the most limiting factor for project development in the USA, showing a high number of years for authorizing a project compared with the overall average across all countries. However, the environmental requirements established in EIAs or EMPs may be too low in other countries such as Algeria, and these should be improved. In addition, the cost of producing desalinated water is highly limiting factor in many of the countries analyzed whereas most countries showed high potential acceptance of desalination as an essential tool to address freshwater demand for many purposes. The environmental and/or socio-economics requirements should be improved where very low requirements have been identified. The knowledge obtained in this research could be used to enhance scientific advice, advance toward sustainable desalination development, and address global water demand challenges.

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## CRediT authorship contribution statement

**Iván Sola:** Conceptualization, Formal analysis, Investigation, Data curation, Supervision, Writing – original draft, Writing – review & editing. **Claudio A. Sáez:** Formal analysis, Supervision, Funding acquisition. **José Luis Sánchez-Lizaso:** Methodology, Formal analysis, Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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