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Ragab Ragab *Editors*

Biosaline Agriculture as a Climate Change Adaptation for Food Security

Springer

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Prof. Atef Hamdy

This book is dedicated to the memory of Professor Dr. Atef Hamdy who worked at the Mediterranean Agronomic Institute, CIHEAM/Bari for several decades before his passing away. Professor Hamdy was a friend, a colleague, an expert, and a leading scientist in the field of non-conventional water resources for irrigation. Professor Hamdy was a Project Leader of several research projects on the use of non-conventional water resources (saline/brackish water, treated wastewater, drainage water, etc.) and the use of non-conventional crops (e.g., halophytes crops and fodder). Professor Hamdy trained and inspired many young professionals, published several books and reports, and supervised numerous Master theses on non-conventional water resources and Bio-Saline Agriculture. On a personal side, Professor Hamdy was a close friend to the editors for several decades. His kindness, human touch, and caring attitude toward others are just a few *characteristics to mention here to describe him. Professor Hamdy left a wealth of knowledge available for future generations to benefit from and he will be remembered always for his dedication, commitment to the use of non-conventional water resources, and for improving agriculture production.*

Foreword

The increased demand for freshwater supplies in arid regions threaten the future sustained availability of fresh water for irrigation and crop production. Currently, the quantity of water in these regions is very limited and most of the time is saline. The current climate change predictions indicate that many arid and semi-arid regions presently irrigated will face increasing temperatures and decreasing rainfall, further aggravating the water scarcity in these regions. The need to increase food production in these regions can only be achieved by either increasing the productivity of irrigated lands and/or by increasing the area under irrigation. In addition, alternative water supplies such as saline/brackish water as well as more efficient use of existing water supplies are essential to avoid food crises in regions such as the Middle East, North Africa, and to sustain food production. However, numerous risks face the use of saline/brackish water if not properly managed, such as the increase in soil salinity and yield reductions. On the other hand, saline/brackish water could be looked at as an opportunity for irrigation, whether used directly or being desalinated or mixed with treated wastewater. This book will include information on the relationship between climate change, salt-affected habitats, and salinization processes.

Soil salinization is one of the more subtle and progressive causes of soil degradation, threatening some of the most productive lands currently under irrigated agriculture. It is also an increasing environmental concern for those areas for which the suggested climate change scenarios predicted an increase in temperature, decrease in rainfall (i.e. aridity increase), and/or sea level rise. Salinity is also a natural inherent condition of many ecosystems contributing to global biodiversity supporting halophytes.

Salinization is a problem that has long been associated with agriculture, both as a constraint and as the result of inappropriate management practices. In addition, agriculture intensification, as well as changes in temperature and precipitation patterns expected from climate change, are likely to further affect the salt-water balance of fragile ecosystems.

There is no great deal of information on the relationship between climate change, salt-affected habitats, and salinization processes. Hence, there is a need to establish a better picture of the most affected or vulnerable areas and to promote practices that can be used to adapt agricultural production in areas susceptible to climate change. This will contribute to food security and reduce stress on ecosystems.

The aim of this book is to showcase the global potential of Biosaline Agriculture. Other objectives of the book include an update on the development of recent innovations in the field of Biosaline Agriculture, the use of saline/brackish water, and the desalination of seawater. Different chapters will also discuss solutions that are adapted to local conditions and are part of a sustainable development perspective.

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Preface

Globally, salinity is the most prevalent abiotic stress that severely reduces the growth and yield of several important field crops to a great extent. In more than 100 countries, about 20% of its irrigated agriculture is salt affected. That represents 100 million ha of arable land is adversely affected by high salt concentration which reduces crop growth and yield.

The Salinization trend is increasing world-wide due to freshwater scarcity, climate change, and sea level rise. However, salt-tolerant crops and innovative agricultural practices can help to ensure food security. This book reports different interventions presented in the international Forum of Biosaline agriculture that has been held in Laayoune, Morocco (2019). The conclusion of this event demonstrated the potential of using alternative crops and management based on contributions from different experts who presented their experiences in several regions (South America, North Africa, and the Middle East).

It is now accepted that salinity is an intrinsic part of our landscape and that we need to adopt practices to safeguard the environment and minimize the negative impact of salinity. Indeed, the need to address the spread of salinity worldwide, particularly in Semi-Arid and Arid regions is urgent. It has been estimated that total land and water degradation caused by salinity costs $27 billion as a loss in crop yield per year.

The objective of this book is to suggest different approaches for sustainable management of salt-affected regions.

The book will include (i) Detailed knowledge of plant physiology under saline condition, (ii) Deep understanding of the salinity-biophysical processes in the context of atmosphere, plant, water, soil, and groundwater relationships, (iii) Tools for measuring soil salinity changes over time, (iv) Tools for modeling and anticipating the evolution of the system (salinity, yield, dry matter, uptake, groundwater, …) as a whole and evaluating possible management alternatives, (v) Set of indicators for communicating with decision-makers and stakeholders.

The introduction of this book highlighted the issue of “Why we need to use saline water and saline soil resources” to alleviate the impact of freshwater scarcity due to population growth and climate change and how to minimize the impacts of salinity on soil, plant, and the environment through sound management of irrigation water, soil, nutrients, and crops. Chapter 1 provided an overview of the salinity situation and the adaptation and mitigation strategies with special reference to the Middle East and North Africa and South America. Chapter 2 focused on the best practices for saline and brackish water management. Chapter 3 presented the progress and novelty of new approaches to managing saline water for conventional, nonconventional, and forage crops. Chapter 4 offered insights on land management when irrigating with saline water, Chap. 5 listed the challenges faced when using saline water in irrigated agriculture. Chapter 6 illustrated how the SALTMED Model can be used as a reliable tool for Field, Water, Crops, and N-Fertilizers management when using fresh, saline, and brackish water. Chapter 7 debated whether desalination cost and technology are suitable for agriculture production.

Although the Editors of this book have organized an independent review of all articles, the contents remain the sole responsibility of the authors. Finally, the Editors would like to thank the Phosboucraa Foundation in Laayoune, University Mohamed VI Polytechnic in Benguerir, and the International Center for Biosaline Agriculture in Dubai for their participation and financial support.

Benguerir, Morocco Redouane Choukr-Allah
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This book is the fruit of the collaborative efforts of eminent experts in the use of unconventional water including saline, treated wastewater, and desalinated water in agriculture. We would like to extend our thanks to Nadine Depre and Ragab Ragab for reviewing the chapters of this book; Mrs. Rachida Karouani for formatting the chapters; and Mrs. Halima El Omari for collating the chapters from contributors. In addition, we would also like to thank the following scientists for their significant contributions to the book:

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Contents

Part I Introduction to the Book

Part II Best Practices for Saline and Brackish Water Management

Part VII Use of Desalination Technology to Produce Non-saline Water for Irrigation

Editors and Contributors

About the Editors

Redouane Choukr-Allah is Former Professor at Hassan II Institute of Agronomy and Veterinary Medicine, Morocco, and currently a senior professor at University Mohamed VI Polytechnic, Benguerir. Dr. Redouane Choukr-Allah is a horticultural, soil, and water environmental specialist with more than 35 years of experience in coordinating and managing field-based projects and technical teams involved in the use of saline water and the use of treated wastewater in Horticulture. He holds a master's degree in Agronomy from the Institute of Agronomy and veterinary Hassan II Rabat, Morocco, and a Ph.D. in environment Horticulture from the University of Minnesota, St. Paul, USA. He served as head of the Horticulture Department from the period 1983 to 1996 and head of the salinity and plant nutrition laboratory since 1996. Currently, he also serves as a senior fellow at International Center for Biosaline Agriculture (ICBA). He also served as a technical coordinator of a 12-million US$ project, financed by USAID on water resources sustainability in Morocco. His most recent research focus is Sustainable Agriculture and resilience to Climate Changes. He has extensive experience in the use of saline water and treated wastewater in agriculture, and soil and groundwater pollution prevention. He has written numerous peer-reviewed Journal papers, authoritative texts, and books in the field of non-conventional water resources.

Ragab Ragab is President of the International Commission on Irrigation and Drainage, ICID, Fellow Principal Research Scientist, water resources management specialist at UK Centre for Ecology and Hydrology, UKCEH, Vice President of the International Commission on Irrigation and Drainage, ICID (www.icid.org) (2010–2013), Chairman of the UK National Committee on Irrigation and Drainage (2007–2011), Chairman of the Permanent Committee on Strategies and Organization, ICID (2011–2014), Chairman of the Work Group on Water-Energy-Food Nexus, (2000–present), Founder of the Work Group on the Use of Poor Quality Water for Food Production, ICID (1997–present), and Editor, Journal of Agricultural Science, Cambridge University Press (2013–present). As a summary of his professional expertise, Dr. Ragab Ragab worked for over 30 years as a principal Hydrologist and Agriculture Water Management specialist at CEH. Expert in catchment hydrology, drought management, irrigation, drainage, soil hydrology, water use efficiency, use of poor-quality water for crop production, urban hydrology, the impact of land use, and climate change on water resources. Has experience working for both Universities and Research centers. Leader of several projects in the UK and overseas. In addition to the UK, he has extensive field experience and has carried out numerous projects in North Africa, Europe, the Middle East, the Mediterranean region, and India. Developed two widely used models, SALTMED for field scale as a tool for integrated management of water (saline and not-saline), soils, crops, and N-fertilizers and IHMS (Integrated Hydrological Modelling System) for catchment/basin scale. Recipient of several International Awards. His scientific interests are mainly: Building cross-sectoral collaborations to understand the dynamic interactions across the water-energy-food nexus using new scientific knowledge to help stakeholders set objectives for water resources management and transforming science into management solutions. Improving water productivity and water use efficiency, irrigation and drainage management, agricultural water management, soil physics/soil hydrology, remote sensing application in hydrology, hydrological modeling at the catchment scale, quantifying the impact of climate and land use changes on water resources, identifying the gap between water supply and demand and suggest management solutions to narrow the gap, and water, soil, and fertilizers management modeling and experimentation at field scale.

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Part I
Introduction to the Book

Chapter 1
Using Saline Water in Biosaline Agriculture for Food Security

Redouane Choukr-Allah and Ragab Ragab

Abstract Soil salinization is a worldwide problem affecting more than 830 million hectares of agricultural land, and around 1–2 million hectares per year are salt-affected, significantly reducing crop productivity and making the land inappropriate for cropping. This introduction will highlight the need to use saline water resources, and the appropriate practices to minimize their impacts on soil, plant, and the environment as well as the best management of irrigation water, soil, and crops under saline conditions. In addition, we will describe the state of the art and the most recent advances in measurements and modeling of salinity as well as examples of successful stories in managing saline water and soils.

Keywords Salinity · Management · Mapping · Best practices · Modeling

1 Introduction

Water scarcity is related to a disequilibrium between available natural water and water demand and can present a serious socio-environmental issue for sustainable development. This could lead to a potential cause of social conflict within and between countries, due to the increasing demand mainly related to rapid population increase and urbanization, industrialization, and climate change impact (Kummu et al. 2010; Macedonio et al. 2012; Zhang 2016). Nonconventional Water Resources (NWR), particularly saline water resources, can be seen as alternative water sources that can overcome water scarcity. The use of NWRs is becoming more and more of a great opportunity for solving water resource limitations, especially in arid and semi-arid areas (Choukr-Allah 2021).

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This chapter will highlight the need to use saline water resources, and the appropriate practices to minimize their impacts on soil, plant, and the environment as well as the best management of irrigation water, soil, and crops under saline conditions. In addition, this book will describe the state of the art and the most recent advances in measurements and modeling of salinity as well as examples of successful stories in managing saline water and soils.

Based on the Global Map, soil salinization is a worldwide problem affecting more than 830 million hectares of agricultural land (FAO 2021) in over 118 countries (Zaman et al. 2018). The Global Map of Salt-Affected Soils (GSASmap) indicated that 85% of salt-affected topsoil are saline, 10% are sodic, and 5% are saline sodic and 62% of salt-affected subsoils are saline, 24% are sodic, and 14% are saline sodic. Globally, around 1–2 million hectares per year are salt-affected, significantly reducing crop productivity, and making the land inappropriate for cropping (Hopmans et al. 2021; Abbas et al. 2013).

Several initiatives to grow crops using brackish and saline water took place in the last 70 years and several international initiatives have been taken to explore and re-introduce indigenous knowledge and practices for food production in saline soils. These efforts were carried out by organizations such as the US Salinity Laboratory in Riverside, the International Biosaline Agriculture Centre, ICBA in Dubai, UAE, as well as by several organizations in Australia, The Netherlands, and India. Recently, the FAO (2019) has developed a thematic working group with the objective "to examen the opportunities that could be provided by saline water and saline soil for biosaline agriculture." Increasing investments in saline agriculture agree with most of the UN Sustainable Development Goals, in particular "Zero hunger" (SDG 2) and "Addressing freshwater scarcity" (SDG 6).

The growing demand for irrigation water to ensure food security for rapid population growth with limited water supplies urges several countries using unconventional water resources. These include saline drainage water, brackish groundwater, and treated wastewater. In fact, irrigated agriculture plays a major role in producing 40% of global food production (World Bank 2021) and more than 90% of agriculture depends on irrigation in arid- and semi-arid regions. To accomplish this production goal, agriculture will necessarily increase further into marginal lands (Pancaldi and Trindade 2020; Ahmadzai et al. 2021; Khanna et al. 2021; Razzaq et al. 2021). Most arid countries have no other options but to use non-conventional water resources, including saline water. Despite the presence of large amounts of such saline water, it is only used in limited amounts for irrigation, even though this water has the potential to be used to grow several crops if appropriate management practices are followed. However, the successful, long-term use of saline water requires adequate knowledge of salinity issues combined with a proper field management to minimize the negative impact of salinity on the soil, the crop, and the environment. As indicated by several authors, poor land and poor water management are major factors impeding the productivity and sustainability of these crops in many countries (Ondrasek et al. 2014).

Recently, attempts have been made by different sectors to reduce land degradation and manage soil salinity. Sustainable land and water management practices, such as Non-Conventional Agriculture, NCA (minimum tillage/minimum soil disturbance, good crop rotation, and the optimum amount of crop residue retention) in combination with effective irrigation water management could minimize the negative effects of conventional practices (Zhang 2016).

2 Best Management Practices Under Saline Conditions

Using sustainable indicators to compare and quantify different cropping systems, crops, and agronomic management practices could be used as guidelines for improving the sustainability of irrigated drylands experiencing degradation. However, since soil salinity has an impact on soils, plants, and the environment, the integrated evaluation of innovations/technologies is essential to assess their potential to maintain the sustainability of agricultural production (Hopmans et al. 2021).

Soil salinity is a multi-factorial phenomenon and a complex process that can occur by unsustainable and inappropriate agriculture practices and land use, incorrectly managed water resources, and the consequences of climate change with extreme droughts.

Secondary soils salinization can also be caused to: (i) poor chemical composition of irrigation water, with the concentration of monovalent ions (sodium and potassium salts) exceeding the concentration of bivalent cations salts (calcium, magnesium, and iron) and (ii) the groundwater water table rise toward the surface due to poor or absence of drainage leading to salt accumulation within the root zone.

Soil salinization reduces agricultural productivity by affecting the processes of nitrogen uptake and plant growth development. It does also disrupt soil's biological activity, due to the decline of food supplies for soil microflora necessary for ecosystem functioning. The rise in soil salinity further deteriorates soil ecosystem services and reduces revenues for farmers and smallholders. The great degradation of natural vegetation and forests is the ultimate consequence of salinization of arid agricultural lands.

It is always recommended not to stress the plant during the early growth stage to maximize yield production under saline conditions by using another source of fresh water, in order to avoid the negative effect of water salinity during the stage of the growing cycle (seedling establishment). This will avoid a decrease in germination percentage and help seedlings to grow strongly and be tolerant in next stages (Ragab et al. 2008).

The successful use of saline water for irrigation requires a basic understanding of the scientific principles affecting the interactions between climate, the applied water, soil, and crop. Equally important is the application of suitable technology and management practices that will facilitate the optional use of this poor-quality water. A higher level of management is needed to successfully use saline water and the adoption of new irrigation management practices will be necessary. Since climate, water quality, soil type, and crop tolerance to salinity varies from location to location, site-specific appropriate on-farm management practices need to be developed to attenuate the negative impact of salinity on soil, plant, and the environment.

Therefore, in assessing the suitability of saline water for irrigation, it is important to consider the following: (i) Crop tolerance threshold to salinity must be known, (ii) management practices to prevent or minimize salt accumulation in the soil profile should be already in place, (iii) advanced irrigation and drainage technology that are suitable for the use of saline water need to be adopted, and (iv) saline drainage water following the irrigation can be reused for growing fish, shrimp, and algae to increase water productivity.

3 Modeling

The cropping systems, crop types, quality and amount of irrigation water application, and the adopted agronomic practices (Zhang et al. 2021) as well as the efficiency of the drainage systems, play an important role in soil salinity development and management. Soil salinization is known to be a slow process and short-term field experiments and monitoring cannot project the long-term impact of using saline water on the soil, ecosystem, and the environment. Therefore, models can be used to project the long-term impacts of several agronomic practices and using saline water on soil and water productivity and sustainability (Ragab 2023, Chap. 15 of this book). Calibrated and validated models can be run using hypothetical "what if" scenarios depicting different field management or possible climate change scenarios without the need to conduct expensive, time-consuming, labor-intensive, and long-term field experiments.

Models can also be used to obtain certain crop parameters that are difficult or expensive to measure at the field. With the knowledge of the yield, the model can be used to derive these parameters such as Leaf Area Index, LAI, crop salinity tolerance level, $\pi 50$, average root zone salinity, crop photosynthesis efficiency, and more.

Models can help in irrigation scheduling and crop water requirement estimation and predict yields and soil salinization. SALTMED model (Ragab 2023, Chap. 15) is a generic type of model that can be used for any irrigation system, water quality (saline/brackish or fresh), any soil type, crops, and trees. The current version was successfully tested against field experimental data (Ragab 2023, Chap. 15).

The SALTMED model simulates the crop growth and dry matter, water, and solute movement under various irrigation systems (surface and sub-surface) and under full and deficit irrigation including the Partial Root Drying Method, PRD. The model also simulates drainage flow to open and tile drains, shallow water table height, nitrogen cycle, and estimates the actual and potential evapotranspiration as well as the water use efficiency and crop water productivity. The current version allows up to twenty fields or treatments to run simultaneously.

The model has been applied to the field experiments in different countries. These experiments included several crops, different water qualities, such as saline water, treated wastewater, and fresh water, different irrigation strategies such as deficit irrigation (applying less water than the total crop water requirement) and applied water stress during certain growth stages.

The model has been validated with field data of drip-irrigated tomato and potato crops in Syria, Egypt, Crete, Serbia, and Italy; sugar cane using sprinkler irrigation in Iran; cotton using drip irrigation in Greece; quinoa using saline water in Denmark; quinoa, sweetcorn, and chickpea using drip irrigation in Morocco; vegetable crops in Brazil; quinoa and amaranth using saline water in Italy; rain-fed and irrigated chickpea in Portugal; quinoa under deficit drip irrigation in Morocco; sweet pepper in green-houses using saline water in Turkey, legumes (lentil, chickpea, and faba bean) using saline water in Syria; quinoa using fresh and saline water in Turkey; and potato using gated pipes in Egypt. In all these investigations, the model showed its capability and reliability in predicting the field-measured yield, dry matter, soil moisture, soil salinity, and water productivity.

The model was also used in other studies to derive the salinity-yield response function and to assess the impact of climate change on the amaranth (in Italy) and corn (in Morocco), and water requirement, yield, length of the growing season, sowing, and harvest dates in Italy and Morocco. The model has recently been intensively used in Egypt on a variety of field crops, in Pakistan, in Iran, in Portugal, and in Morocco. More information and applications were published in a Special Issue of the Journal of Irrigation and Drainage (Ragab 2020). More details about SALTMED model are given in Ragab (2023, Chap. 15 of this book) including a link to download the model, the user's guide, and publications.

4 Successful Stories on the Use of Saline Water in Some Arid and Semi-arid Countries

The agricultural practices in some Middle East and North Africa region (MENA) countries have emerged from the local experience gained by the farmers depending on water availability and prevailing agricultural conditions and economic factors. Each country has its own experience in producing crops that is specific to its local conditions (FAO and AWC 2018). Also, each country has its own crop varieties which are a result of its research work and farmers' experiences. Several research, published papers, and reports present case studies on the use of saline water in agriculture particularly under conditions of water scarcity in the MENA region. The following is a brief review of saline water use and practices in different MENA countries.

In Egypt, the water authority is using drainage water (up to ECw 4.5 dS/m) after it is blended with fresh Nile water. Another emerging strategy of alternating different types of water quality has been introduced lately. Research has shown that it is possible to irrigate sensitive crops (maize, pepper, onion, alfalfa, etc.) directly with drainage water in rotation with fresh Nile water, and salt-tolerant crops (wheat, cotton, sugar beet, etc.) and moderately sensitive crops (tomato, lettuce, potato, sunflower, etc.) can be irrigated with drainage water but after seedling establishment with fresh Nile water. Based on these results, the Government is reclaiming more land using drainage water (Abo Soliman and Halim 2012). Historically, the natural flooding from the Nile not only supplied a continual source of nutrients but also provided natural flushing of salts to the Mediterranean Sea. Ultimately, the difference in the long-term sustainability of irrigated agriculture in both areas was attributed to salinity control via the leaching of salts.

The use of saline water for crop production has a long history in Iran. Management practices employed by the farmers in using these waters are similar to those practiced with the use of non-saline waters (Cheragi and Halim 2012; Choukr-Allah 2021). In general, crop production is based on using high inputs of seeds, fertilizer, and water. Agronomic practices such as land preparation, irrigation methods, and crop rotation are suboptimal.

In Tunisia, research projects covering some Tunisian regions have been conducted to evaluate the adoption and performance of different management strategies to improve crop production under salt and drought conditions. Research studies related to soil salinity control include: (1) the cultivation of alternative and tolerant-salt varieties such as new cultivars of olive trees, quinoa, jatropha, sesbania, and aloe vera, (2) irrigation water management using drip irrigation and sub-surface drip irrigation, and (3) improvement of crop tolerance to salinity by application of exogenous proline (Hachicha 2023, Chap. 3 in this book).

In Morocco, in the Southern Oasis of Tafilalt, the focus was on growing several crops (alfalfa, date palms, and okra) using different systems of irrigation (furrow and drip) with conjunctive use of fresh water (from a surface water source) and saline water (groundwater with ECw varying from 6 to 10 dS/m). The use of drip irrigation allowed an average water saving of 3225 m^3/ha for the different crops tested, resulting in a 38% water saving compared to furrow irrigation (Choukr-Allah 2021).

The most popular crops grown with saline water in Saudi Arabia are wheat, sorghum, alfalfa, and barley. Saline water is also used to irrigate tomatoes, onions, and watermelon (Al-omran et al. 2023, Chap. 6 in this book). Cyclic reuse strategies using saline and desalinated water have been tried, with tomato and lettuce showing that such methods can be successful for commercial production. It was concluded that the country could expand the use of saline groundwater for irrigation.

The growth of halophytic grasses could be a good option for forage production and the rehabilitation of salt-affected lands as practiced in the UAE. Sesbania a short-lived perennial legume and moderate salt tolerant species (threshold ECw 5 dS/m or 3,500 ppm), yielded up to 175 t/ha/year (3 cuts) when irrigated with water of ECw 3 dS/m.

5 Conclusion

This book will enrich the reader with a great deal of new knowledge representing the state of the art and innovative approaches for the management of salinity. This book presents holistic and integrated management of water, crop, nutrients, land, and the environment under saline conditions. The best practices and successful stories worldwide have been reported. Saline water management that safeguards the environment and minimizes the negative impact on crop production has also been presented. Suitable salinity-tolerant crops and forage crops have been presented as well as their seed priming and nano-priming techniques as tools to improve their germination and salinity tolerance. Land management to improve the productivity of saline and saline sodic soils were also reported. The desalination technologies and their suitability for use in agricultural production were analyzed. The use of models, such as SALTMED model, as integrated water, crops, land, and nutrients management tools and their benefits have been discussed in detail.

This book tackles the salinity issue from all angles and directions through an integrated holistic approach that accounts for water salinity, soil salinity, crop salinity tolerance, nutrients availability, the environment, and the ecosystem services. It presents real and tried best field practices worldwide and will equip the reader with practical tools readily available to use.

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Part II

Best Practices for Saline and Brackish Water Management

Chapter 2
Salt-Affected Soils and Their Management in the Middle East and North Africa (MENA) Region: A Holistic Approach

Redouane Choukr-Allah, Zineb El Mouridi, Yamina Benbessis, and Shabbir Ahmad Shahid

Abstract The Middle East and North Africa (MENA) region consists of twenty-one countries located in different agroecological environments, from Mediterranean to hyper-arid climate. The region faces three climatic constraints: aridity, recurrent drought, desertification and salinization, the latter also in part human-induced. The level of salinity development in terrestrial environments varied due mainly to differences in rainfall, temperature and drainage capacity of soils. However, the conditions are different in areas where irrigated agriculture is followed with irrigation requirements to be met through saline/brackish water. The inefficient use of these marginal quality waters can cause salinity and sodicity buildup in the rootzone to impair plant growth to a level where economical agriculture is not a viable option and the farms are abandoned. It is therefore essential to map soil salinity in these areas and either innovate agriculture through the development of crop zones based on salinity levels or implement an integrated salinity management program to improve farms' productivity. In this chapter, the current situation of salt-affected soils in the MENA region is highlighted with proposed management options to improve farm productivity and food security.

Keywords Salinity · Eco-ecological zones · Management · Mapping · Reclamation

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1 Introduction

The World Bank Data on the MENA region reports 21 countries/territories as MENA: Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Malta, Morocco, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, West Bank and Gaza (Palestine); Yemen (https://data.worldbank.org/). Large areas of Libya, Egypt, Bahrain, Kuwait, Qatar and the United Arab Emirates are entirely desert (FAO 2013). The region possesses 1.6% of the world's water resources and hosts 6% of the world's population (Khater 2002), about the same population as the European Union (EU). The three smallest countries (Bahrain 1,472,674, Djibouti 1,000,000 and Qatar 2,986,953) have the lowest population in the region (about 5.5 million inhabitants). Of the total land area of the MENA region, only one-third is agricultural land (cropland and pastures), while only 5% is arable (cropland). The rest of the land is either urban or desert. Due to the dry climate, about 40% of the cropped area in the region requires irrigation. The region is one of the most land and water-constrained regions of the world and is predicted to become hotter and drier in the future due to climate change that will put more pressure on soil and water resources for agriculture. Only 4% of land in the region has soils of high or good suitability for rain-fed cereal cultivation and 55% is unsuitable (OECD-FAO 2018). The soils currently used for farming are severely degraded to the point where their productivity is estimated to have been reduced by up to 30 to 35% of potential productivity. Soil degradation in rain-fed systems is caused by wind and water erosion, while in irrigated systems the farming practices themselves are responsible for *soil salinity and sodicity* (OECD-FAO 2018). Thus, the soil salinity in the MENA region is a major concern for the sustainability of irrigated agriculture and water management.

The unsustainable use of soil and water resources will lead the region's arable land and water resources to reduce and the region will be a difficult environment for agriculture, as it also suffers from severe land constraints. In two-thirds of the countries, less than 5% of the land is arable, while Saudi Arabia, Lebanon, Tunisia, Morocco, Yemen, Mauritania and Syria have huge desert pastures for livestock grazing. The productivity of water use is only half the world average. The need for the region to address these challenges, with limited land and water resources, will be further compounded by the expected impact of more frequent extreme climate-related events.

The MENA region countries/territories are located in different environmental conditions, where rainfall patterns, temperature and frequency are heterogeneous, as well as soil types. In general, MENA is a water and arable land-scarce region and the crop production is less than those of the developed countries. Due to water scarcity in the MENA region, agriculture is accomplished through irrigation to offset the crop water requirements. The use of saline water causes salinity zones under different irrigation systems (Shahid 2014). Due to the dry climate, about 40% of cropped area in the region requires irrigation. For good crop production, it is essential to irrigate the crops with a suitable quality of water, which is scarce in the region, therefore, marginal quality water (saline/brackish) is used for irrigation. This causes salinity build-up in soils. A pre-screening of soils against different salinity and sodicity waters is suggested to assess the fate of soils against irrigation cycles with salty water (Shahid and Jenkins 1992a, c; Shahid 1993) and to determine after how many irrigation cycle's soils become saline, sodic, or saline-sodic.

Soil and water salinity is common in the countries of the MENA region and is affecting the national production. Losses from salinity alone across the region are estimated at US$ 1 billion annually, or US$ 1,600 to US$ 2,750 per hectare of affected lands (UNEP 2020). In order to use the soil and water resources sustainably, it is essential to address the salinity issue in a holistic way to understand and manage it properly. In this chapter, salinity issues, their impacts on agriculture and the environment, as well as potential options to manage salinity are presented and discussed. It is hoped that countless numbers of scientists and institutions will benefit from the information presented in this chapter.

2 Geographical Location of the MENA Region

The 21 countries in the MENA region cover some territory in Asia, Africa and Europe and include the Mediterranean and Red Sea and Arabian Gulf. The MENA occupies an area of 15 million square kilometers (Fig. 1).

Fig. 1 Map of Middle East and North Africa region

3 Climate of the MENA Region

Due to the geographic location of various countries in the MENA region close to the seas and the continental areas, there are differences in the climate. However, in general, the region is mainly located in the arid, semi-arid and desert environment, where there is insufficient rainfall and high temperature, and thus soils are dry most of the year. The summers present temperatures above 40 °C, winters are mild in the coastal areas, and inland deserts become very cold (even below 0 °C). Specifically, the Middle East (ME) has a hot and arid climate, and in some countries, irrigation is accomplished by river waters, e.g., the Nile delta in Egypt, the Tigris and Euphrates watersheds. In these countries, drought is increasing compared to previous decades. The MENA is a transitional area between equatorial and mid-latitude climates.

4 Water Resources of the MENA Region

The MENA region is a water-scarce region, where the annual water share per person is about 1,274 m^3, in a few countries water share is up to 50 m^3 per capita per year. In general, 50% of the MENA countries have below 500 m^3 available water per capita per year. Irrigation is managed through conventional and modern irrigation systems and 85% of fresh water is used for agriculture. The region is the most water-stressed in the world, and two-thirds of countries continue to use groundwater at rates exceeding renewable internal freshwater resources, which over time become saline/brackish, and the recycling for irrigated agriculture will cause severe soil salinization and sodication problems and crops yield decline.

5 Soils of the MENA Region

Of the total land of the MENA region, only one-third is agricultural land (cropland and pastures), while only 5% is arable (cropland). The soils in the region are heterogeneous based on the differences in the soil formation factors (climate, organisms, relief, parent material and time) and the processes (transformation, translocation, losses and additions). In the Jenny Equation (Jenny 1941), which is S = f(cl, o, r, p, t,…), the “S” represents soil formation, “cl” is climate, “o” is organisms in the soil, “r” is relief such as the topography, “p” is the parent material. In the MENA region, in general, the aridity, drought and desertification are main environmental concerns, limiting the soil formation, and hence in some countries soils are poorly developed, such as psamments (sandy soils) classified as Entisols (Soil Survey Staff 2014) or Arenosols (WRB 2015). Following is the summary of soil types in some of the MENA region countries (FAO-ITPS 2015) (Table 1).

Table 1 Major soil types in the MENA region countries

Countries in the MENA region	Major soil types
Maghreb region Morocco, Tunisia, Libya and Algeria	Soils are categorized into three broad divisions: (i) Along the Mediterranean and Atlantic coasts, soils are Kastanozems (Xerolls) and Luvisols (Alfisols) (Sedenot 1999; Madrpm 2000; Halitima 1988) (ii) In the Atlas Mountains far from the coast, the soils are Leptosols (lithic subgroups) and Cambisols (Inceptisols) (Yigini et al. 2013) (iii) In the southern part, soils are Calcisols (Calcids), Gypsisols (Gypsids), Leptosols and Cambisols (Jones et al. 2013)
Egypt	Dominant soils are Vertisols, Arenosols (Psamments), Fluvisols (Fluvents), Calcisols and Gypsisols (Aridisols)
Jordan, Syria, Labanon, Iraq and Palestine	The soils of the valleys are Arenosols (Psamments) and Fluvisols (Fluvents). In the highlands, steppe and desert regions, the main orders are Calcisols (Calcids) and Cambisols (Aridisols), Arenosols (Psamments) and Leptosols (Lithic subgroups), and Vertisols which are calcareous in the subsoil horizons
Oman, Kingdom of Saudi Arabia, Kuwait, Bahrain, United Arab Emirates, Yemen, Iran and Qatar	There are alluvial soils rich in silt and desert soils, and sandy soils (Arenosols) poor in organic carbon (Omar and Shahid 2013; Shahid 2013; Abbaslou et al. 2013; EAD 2009; KISR 1999a, b)

Source FAO-ITPS (2015)

6 Facts About Soil Salinity Extent in Some MENA Region Countries

Iran—About 235,000 km^2 (or 14.2% of the total area of the country) is salt-affected, which is equivalent to about 50% of irrigated lands in Iran (Pazira 1999; Fathi and Rezaei 2013). Another estimate revealed 34 million hectares (Mha) or nearly 20% of the surface area of the country is salt-affected. This includes 25.5 Mha of slightly to moderately and 8.5 Mha of severely salt-affected soils (Cheraghi et al. 2007).

Kuwait—209,000 hectares are affected by salinity (Hamdallah 1997; Burezq et al. 2021).

UAE—In general 80% of agricultural land in Abu Dhabi Emirate is affected by salinization (EAD 2018); out of 76,858 hectares of farming area in Abu Dhabi emirate, 69,348 farmland hectares are salinized (EAD 2018) at 0–25 cm depth which is 90% of the total farmland (EAD 2018).

Oman—44% of the total geographical area is affected by varying degrees of salinity (Ahmed et al. 2013).

Egypt—Saline, saline-sodic and sodic soils have a strong presence in the Nile delta land and represent an average of 37% of the total cultivated soils. The north delta contains the highest area of saline and saline-sodic soils reaching 46% (Mohamed 2016).

Hachicha and Abdelgawed (2003) have summarized the extent of salt-affected soils in some Arab countries as below:

Syria—532,000 ha, 40% of the total irrigated areas, are salt-affected soils.
Iraq—Salt-affected soils: 1.3 Mha slightly affected, 6.7 Mha severely affected.
Saudi Arabia—about 2 Mha are sabkhas (salt scalds) and about 3,641 Mha is affected by salinity, 50,000 ha severely, 1.7 Mha moderately, 1,977 Mha slightly and 13,675 ha very slightly affected.
Qatar—70,124 ha affected, 6,517 ha slightly and the rest severely affected.
Bahrain—41,273 ha are affected, 17,540 ha slightly and 22,473 ha are severely affected.
Kuwait—85,000 ha affected and 65,827 ha slightly affected.
Oman—9,442 Mha affected, about 30% of the total area of Oman (309,500 km^2).
Yemen—483,467 ha affected.
Jordan—In the Jordan Valley, 6,500 ha affected, 1,400 ha slightly, 1,600 ha moderately, and the rest severely affected.
Libya—Salt-affected soils are about 700,700 ha: 199,300 slight, 174,400 moderate, 327,000 severe sabkhas, and sodic soils. The area affected by salinity and water logging is about 250,000 ha.
Algeria—Irrigated area is about 350,000 ha and 25% are salt-affected soils. About 8% of the irrigation waters are very saline and 21% have moderate salinity.
Morocco—Irrigated area is 1 Mha, about 21% are salt-affected and 57% of the Gharb irrigated area. Salt-affected soils are 350,000 ha. Another estimate presents, 5% of agricultural soils are affected by salinization to different degrees, reducing thus their productivity.
Mauritania—Salt-affected soils: cover 86.3 Mha (38.3%). Most of the irrigated area along the Senegal River is affected.
Tunisia—Salt-affected soils are about 1.5 Mha, 10% of the total area. Irrigated areas cover about 375,000 ha. Salinization and waterlogging affected about 50% of the areas, and 10% are severely affected.

7 Potential Threats to the Soils of the MENA Region

Globally ten threats to soils have been reported (erosion, compaction, acidification, contamination, sealing, salinization, waterlogging, nutrient imbalance, loss of organic matter and of biodiversity) (FAO-ITPS 2015). In the MENA region, both rainfed and irrigated land in use suffers from ongoing degradation caused by wind and water erosion and unsustainable farming practices. Three-quarters of the region's 30 million ha of rain-fed cropland is estimated to be degraded. In addition, soils currently used for farming are severely degraded to the point where their productivity is estimated to have been reduced by up to 30 to 35% of potential productivity. Soil degradation in rain-fed systems is caused by wind and water erosion, while in irrigated systems the farming practices themselves are responsible for soil salinity and sodicity. Losses from salinity alone across the region are estimated at US$ 1 billion annually or US$ 1,600 to US$ 2,750 per ha of affected lands. Recent studies have estimated the economic cost of land degradation in the region at US$ 9 billion each year (between 2% and 7% of individual countries' GDP).

The review of the soils of the MENA region and potential threats has revealed that the soils of the MENA region are subjected dominantly to nine threats at various locations, the exception is for acidification which is not common as the soils of arid and semi-arid regions are alkaline in reaction ($\text{pH} > 7.0$). Therefore, the soil problems in MENA region are complex and require a holistic approach for sustainable use and management, through investing in soils. The key objective should be to promote "Sustainable Soil Management" to improve soil productivity for crop intensification, provide ecosystem services, improve food and nutrition security and combat desertification towards sustainable national and regional development (Table 2).

8 The UN Sustainable Development Goal 2 in the Context of the MENA Region

Globally, there are 17 ambitious UN SDGs with 169 targets that all UN Member States have agreed to work towards achieving by the year 2030 (Pedersen 2018). Soils contribute, directly or indirectly, to a number of SDGs (numbers 2, 3, 6, 13 and 15) pertaining to hunger (SDG 2), human health through nutrition (SDG 3), clean water (SDG 6), climate change (SDG 13) and life on land (SDG 15).

The SDG 2 directly relates to agriculture, food production and soils "*To end hunger, achieve food security and improved nutrition and promote sustainable agriculture*". Among 5 targets under the SDG 2, targets 2.3 and 2.4 directly relate to food and soil quality.

> **SDG 2**—End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
> **Target 2.3**: by 2030 double the agricultural productivity and the income of small-scale food producers.
> **Target 2.4**: by 2030 ensure sustainable food production systems and implement resilient agricultural practices that progressively improve land and soil quality.

The SDG 2 and the associated targets are highly relevant to the MENA region due to continuous soil degradation and increasing water scarcity and prolonged droughts. To achieve the above-cited SDG and the activities by 2030 in the MENA region, it is essential to adopt Sustainable Soil Management (SSM) through investing in soils, especially enhancing understanding of spatial salinity distribution (salinity mapping

Table 2 Potential threats to the soils of the MENA region, influences on soils, crops and environment and management options

Kind of threats to soils	Influences	Management options
Erosion	• Loss of nutrients and organic matter • Exposure to hard pan • High inputs required • Loss of vegetation and reduced grazing capacity	• Introduce windbreakers and shelter belts around agriculture farms • Use organic fertilizers and mulch material to protect soils from erosion and conserve moisture • Soil protection from erosion through sand stabilization and fixation
Compaction	• Reduce soil porosity • Reduce moisture retention • Create resistance to plant root penetration • Reduce rhizosphere volume • Increase sheet erosion	• Diagnose reasons for compaction • Add gypsum if sodicity is a problem • Add organic amendments to increase organic matter for structure development • Avoid heavy machinery at the farm and adopt conservation agriculture (low or zero tillage) • Use mulch and grow cover crops
Sealing	• Loss of arable land • Low farm productivity • Poor farm resources management • High cost of production and low profitability	• Make an intensive soil survey of the farm, identify and map soil classes • Use marginal areas not suitable for crops to construct farm sheds, animal and poultry farms, labor camps, roads, etc • Use good quality soils for agriculture for optimum farm productivity
Salinization	• Poor soil quality • Reduces crop selection • Poor crop growth • Low water productivity • High cost of production • Poor nutrient efficiency (salinity–fertility interaction) • At very high salinity even farm is abandoned	• Leach salts through reclamation irrigation prior to seeding • Based on irrigation water salinity and expected soil salinity development, select suitable salt-tolerant crop • Use suitable agronomic and cultural practices (seeding at low salt zone on furrows) • Use modern irrigation systems based on soil types (drip, sprinkler). Avoid using a sprinkler system on fine texture soil to avoid soil crusting • Occasionally test for soil salinity at the root zone and use leaching fraction to leach access salts

(continued)

Table 2 (continued)

Kind of threats to soils	Influences	Management options
Waterlogging	• Poor soil quality • Soil salinity development • Poor plant growth • Farm abandonment	• Establish a drainage system and use drainage water for crops based on salinity level • Plant trees for biodrainage to reduce water table, e.g., *eucalyptus* if allowed for plantation in the country. • Establish fish ponds and integrate aquaculture
Nutrient imbalance	• Fertilizer unavailability when required • Excess use of fertilizers • Groundwater pollution	• Enhance extension services to educate farmers to use balanced fertilizers • Timely availability of fertilizer • Use 4R stewardship concept (Right—time, rate, place and type)
Loss of organic matter	• Poor soil structure and tilth • High vulnerability of soil to erosion • Low water permeability (fine texture) and high water permeability (coarse texture) • Low microbial activities and delayed decomposition process	• Use animal/poultry manure, compost and green manures to improve the organic matter contents of soil • Increase soil carbon sequestration • Use organic soil conditioner (biochar) for long-term effects on soil's physical and fertility properties
Loss of biodiversity	• High vulnerability of soils to erosion and degradation • Reduced microbial activities	• Use biofertilizers to improve soil microbial population and activities • Inoculate seeds for biological nitrogen fixation (BNF) • Add legume crops in the crop rotation to improve nitrogen and organic matter level of soils
Soil acidification	• Low pH • Reduced nutrients availability	• Add lime to increase soil pH • Improved nutrient use efficiency
Soil contamination	• Poor soil quality to adversely affect living organisms • Poor food quality • Low market price of the product	• Avoid using industrial water for irrigation • Treat water before use (at the production site) • Adopt phytoremediation to decontaminate soils

and regular monitoring) to create salinity-based crops zones “*that is what we must attempt to achieve in the context of MENA region affected with salinity ailment*”. Should the MENA region not address the salinity problem in irrigated agriculture holistically, there would be a danger that farm productivity will decline and that may increase food imports costing billions of dollars. This strongly suggests the need to understand the salinity impact on irrigated agriculture and assess at the national level to give national strategies to manage the salinity problem to enhance farm productivity, to increase local production and to support national food security. Therefore, it is essential to measure soil salinity to manage on scientific grounds.

9 Soil Salinity Assessment—Procedural Matters

Soil salinity can be measured in the field at different soil:water ratios (1:1, 1:2.5, 1:5), and in the laboratory by collecting extract from a saturated soil paste. The soil salinity measured at different soil:water ratios must be correlated to ECe (laboratory measurement), which is considered standard from a salinity management and crop selection point of view (Shahid 2013; Shahid et al. 2018a, b). Field measurement procedures are briefly described below:

- 10 g soil + 10 ml distilled (deionized) water (1:1)
- 10 g soil + 25 ml distilled (deionized) water (1:2.5)
- 10 g soil + 50 ml distilled (deionized) water (1:5).

There is no standard factor to convert EC (1:1, 1:2.5, 1:5) to ECe values. Table 3 provides a general guide when location and country-specific factors are not available. To be accurate it is recommended that each country in the MENA region should develop its own factors for rapid salinity assessment without sending soil samples to the laboratory, to avoid delays in decision-making. The use of a modern salinity monitoring system allows instant salinity measurement through an automated dynamic salinity logging system (Shahid et al. 2008).

9.1 Field Assessment of Soil Sodicity (Qualitative Test)

Field assessment of soil sodicity can be determined through the use of a turbidity test with soil:water (1:5) suspensions (Shahid et al. 2018a, b).

- Clear suspension—non-sodic
- Partly cloudy—medium sodicity
- Very cloudy—high sodicity.

The relative sodicity can be further assessed by placing a white plastic spoon in these suspensions.

Table 3 Conversion factor to convert EC (1:1, 1:2.5, 1:5) into ECe (Shahid et al. 2018a, b)

Relationship	Reference
ECe Vs EC 1:1	
ECe = EC1:1 × 3.03	Al-Moustafa and Al-Omran (1990) Saudi Arabia
ECe = EC1:1 × 3.35	Shahid (2013)—UAE (sandy soil)
ECe = EC1:1 × 3.00	Environment Agency Abu Dhabi (2009) Abu Dhabi Emirate (sandy soil)
ECe = EC1:1 × 1.80	EAD-MoEW (2012) Northern Emirates (UAE)
ECe = EC1:1 × 2.06	Akramkhanov et al. (2008)—Uzbekistan
ECe = EC1:1 × 2.20	Landon (1984)—Australia
ECe = EC1:1 × 1.79	Zheng et al. (2005)—Oklahoma (USA)
ECe = EC1:1 × 1.56	Hogg and Henry (1984)—Saskatchewan Canada
ECe = EC 1:1 × 2.70	USSL (1954)—USA
ECe = EC 1:1 × 2.42	Sonmez et al. (2008)—Turkey (sandy soil)
ECe = EC (1:1) × 2.06	Sonmez et al. (2008)—Turkey (loamy soil)
ECe = EC (1:1) × 1.96	Sonmez et al. (2008)—Turkey (clay soil)
ECe Vs EC 1:2.5	
ECe = EC (1:2.5) × 4.77	Shahid (2013)—UAE (sandy soil)
ECe = EC (1:2.5) × 4.41	Sonmez et al. (2008)—Turkey (sandy soil)
ECe = EC (1:2.5) × 3.96	Sonmez et al. (2008)—Turkey (loamy soil)
ECe = EC (1:2.5) × 3.75	Sonmez et al. (2008)—Turkey (clay soil)
ECe Vs EC 1:5	
ECe = EC1:5 × 7.31	Shahid (2013)—UAE (sandy soil)
ECe = EC1:5 × 7.98	Sonmez et al. (2008)—Turkey (sandy soil)
ECe = EC (1:5) × 7.62	Sonmez et al. (2008)—Turkey (loamy soil)
ECe = EC (1:5) × 7.19	Sonmez et al. (2008)—Turkey (clay soil)
ECe = EC1:5 × 6.92 (top soil)	Panah and Zehtabian (2002)—Iran
ECe = EC1:5 × 8.79 (whole profile)	Panah and Zehtabian (2002)—Iran
ECe = EC1:5 × 9.57	Al-Moustafa and Al-Omran (1990)—Saudi Arabia
ECe = EC1:5 × 6.40	Landon (1984)—Australia
ECe = EC1:5 × 6.30	Triantafilis et al. (2000)—Australia
ECe = EC1:5 × 5.6	Shirokova et al. (2000) Uzbekistan

- The spoon is clearly visible—non-sodic
- The spoon is partly visible (medium sodicity)
- The spoon is not visible (high sodicity).

9.2 Electromagnetic Induction (EMI) Characterization of Saline Soils

McNeill (1980) was among the first investigators to describe how electromagnetic induction (EMI) method can be used in assessing soil salinity. The EMI is a technique to effectively measure apparent electrical conductivity using EM38 equipment and is presented as mS/m (Cameron et al. 1981). The EM38 is specifically designed for salinity measurement in agricultural farm surveys. The EM38 measures EC for a maximum depth of 1.5 m (vertical mode) and 75 cm in horizontal mode. The salinity data can be stored in the datalogger and through integration with GIS, georeferenced salinity maps can be created, showing salinity heterogeneity in the farm or the landscape (Cook et al. 1992). The salinity map will allow farmers to develop more precise management zones and salt-tolerant crops to obtain higher yields. It should be noted that EM38 provides apparent EC (field), which must be converted to ECe (measured in the lab), therefore, a location-specific correlation between EC-EM8 and ECe is desirable for data interpretation, salinity management and crops selection, which will be location and soil type specific.

9.3 Laboratory Assessment of Soil Sodicity—Procedural Matters

Soil sodicity can be measured by analyzing extract from a saturated soil paste for Na, Ca and Mg to calculate the sodium adsorption ratio (SAR), which is then used in a standard equation to calculate the Exchangeable Sodium Percentage (ESP). The ESP can also be measured using exchangeable sodium (ES) and cation exchange capacity (CEC), both expressed in meq/100 g soil.

The Sodium Adsorption Ratio

$$\mathrm{SAR} = \mathrm{Na}/(\mathrm{Ca} + \mathrm{Mg}/2)^{0.5} \tag{1}$$

where Na, Ca and Mg are in meq/l unit.

ESP calculation by using SAR

$$ESP = [100(-0.0126 + 0.01475 * SAR)] \tag{2}$$

ESP calculation by using exchangeable sodium (ES) and cation exchange capacity (CEC)

$$\mathrm{ESP} = (\mathrm{ES}/\mathrm{CEC}) \times 100 \tag{3}$$

where ES and CEC are represented as meq/100 g or cmoles/kg.

An ESP of 15 is the threshold for designating soil as being sodic (Richards 1954). At this level, the soil structure starts degrading and negative effects on plant growth appear.

10 Soil Salinity Classification

The Soil Science Division Staff (2017) presented the latest salinity classes (Table 4), where the lowest soil salinity value is set at 2 dS/m compared to the saline soil limit set up by Richards (1954) as ECe 4 dS/m. Even though the lowest ECe limit is set at 2 dS/m, at this salinity level many salt-sensitive crops can reduce their yields (Tables 1 and 2). However, these salinity limits are appropriate for national, regional and global salinity mapping.

Regarding the soil sodicity (ESP limits to define sodic soil) there is a general consensus among global scientists to define soil as sodic when the ESP reaches 15. However, in Australia since the review by Northcote and Skene (1972), an ESP 6 had been widely used as an acritical limit for the adverse effects of sodicity.

10.1 Classification of Salt-Affected Soils (Richards 1954)

Three classes are defined to present the salinity and sodicity of the soils.

Saline soil (ECe $\geq$ 4 dS/m, ESP < 15)

Saline-sodic soil (ECe $\geq$ 4 dS/m, ESP $\geq$ 1 5)

Sodic soil (ECe < 4 dS/m, ESP $\geq$ 15)

Soil pH is not a criterion in the classification of salt-affected soils; however, at high ESP, pH is also increased which can affect nutrient availability to plants (P, and micronutrients except Mo).

Table 4 Soil salinity classes based on the EC of extract from saturated soil paste (Soil Science Division Staff 2017)

Salinity classes	Electrical conductivity of extract from saturated soil paste (ECe) in dS/m
Non-saline	<2
Very slightly saline	2 to <4
Slightly saline	4 to <8
Moderately saline	8 to <16
Strongly saline	≥16

11 Salt-Affected Soils in the Global and Regional Context

Of 310 million hectares of global irrigated areas, 20% (62 million hectares) is salt-affected, costing US$ 441 per hectare, with total economic losses of US$ 27.3 billion (Qadir et al. 2014). Further, it has been cautioned that "*Every day for more than 20 years, an average of 2,000 hectares of irrigated land in arid and semi-arid areas across 75 countries have been degraded by salt*", reported by the UNU Institute for Water, Environment and Health (https://unu.edu/media-relations/releases/world-losing-2000-hectares-of-farm-soil-daily-to-salt-induced-degradation.html). Currently 20% (62 million hectares) of 310 million hectares of irrigated lands are salt-affected. Globally, if immediate action is not taken to address salinity problems, we will lose 25% of 310 million hectares of irrigated lands by 2100, when the population will rise many folds. These figures alert us all that irrigated agriculture resources are being depleted at a rate that will certainly not allow the future population of 9.3 billion by 2050 to meet their own food demands, unless we adopt new, innovative and regenerative approaches to manage these marginal resources.

Salinity is not only neglected on irrigated agricultural farms but also in plant ecology and biogeography (Bui 2013). There is an immediate need to initiate or enhance systematic salinity research programs at national levels from assessment, to monitoring and management in agricultural farms. The most appropriate way is to delineate agricultural farms into crop zones based on groundwater and soil salinity levels and provide guidance to the farmers to grow appropriate salt-tolerant crops to improve farm productivity. This will ultimately lead to reduce the gap between local production and food import and support food security.

The food security for a growing population can only be assured if a sufficient area of fertile soil and water will be available for food production (Montanarella and Vargas 2012) and through global governance of soil resources as a necessary condition for sustainable development.

However, it has been observed that the available cropland area has decreased from 0.45 ha/person in 1960 to below 0.25 ha/person by 2008. In the regional context, recent estimates of the extent of salt-affected soils in the MENA do not exist, a few countries have assessed their soils and soil salinization levels at the national level, such as Kuwait (Shahid et al. 2002), but not in the farming areas, Abu Dhabi emirate (EAD 2009, 2018; EAD-MoEW 2012), Middle East (Hussein 2001; Shahid et al. 2010) and Oman (MAF 2012) have assessed soil salinity. However, most of these estimates are on a national level where in some countries salinization effects on agricultural farms have not been explored, and salinity concerns are not answered. Only the Abu Dhabi emirate (EAD 2018) and Oman (MAF 2012) have completed the salinity assessment of agricultural farms. Earlier, an estimated area of 209,000 hectares has been reported as being salinized in Kuwait (Hamdallah 1997), which is roughly 11.7% of the total Kuwait land area.

In recognition of the significant effects of salinity on irrigated agriculture, the UN-FAO-sponsored Global Soil Partnership (GSP) has currently published The world map of salt-affected soils (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-map-of-salt-affected-soils/en/) and assessed the current salinity extent and scale to better understand the constraints to world food security for solutions-oriented management schemes. In addition, considering the importance of salt-affected soils and their management GSP has officially launched the "International Network of Salt-Affected Soils (INSAS)" in November 2019 at the International Center for Biosaline Agriculture (ICBA first Global Forum on Innovations for Marginal Environment-GFIME) (https://www.fao.org/global-soil-partnership/insas). This international consortium also encourages the National Agricultural Research Systems (NARS) to work within their boundaries to publish geo-referenced soil salinity atlases of agriculture farms for informed decisions on crop selection to achieve higher production from the improvised farms.

12 Soil Salinity and Plant Growth

Plants are more sensitive to high salinity during seedling stages, immediately after transplanting, or at germination. As soil salinity increases, the osmotic potential is increased and the plants extract water less easily, aggravating water stress conditions. During plant growth, the water moves into plant roots by a process known as ***osmosis***, which is controlled by the level of salts in the soil water and in the water contained in the plant. If the level of salts in the soil water is too high, water may flow from the plant roots back into the soil resulting in dehydration of the plant, causing drying or even death of the plant (*Physiological drought*). The salt tolerance of a specific crop depends on its ability to extract water from salinized soils. Crop yield losses may occur even though the effects of salinity may not be obvious (*salinity is silent killer*). However, it is a general saying that "*if salinity can be measured it can be managed*".

Fig. 2 Salts secretion from mangrove leaves (Shahid 2012)

12.1 Salts Affects on Plants and Adjustments

The salts affect plants in two ways, i.e., (i) osmotic effects and (ii) specific ion effect. ***Osmotic effect***—water moves through osmosis (from higher to lower concentration), however, when salts are high in soil water, the water in the plant's cells is pulled out by the saline soil environment resulting in decreased turgor pressure in the cell leading to wilting of plants and plant death.

Specific ion effect—at higher salt levels, plant's metabolic process is decreased. This can be explained by the reduction of enzyme activities in plants.

There are three ways by which the plants adjust salts during plant growth.

(i) ***Salts excretion from leaves***—salts absorbed from the saline soil environment after passing through the plants are excreted by salt glands (e.g., saltbush—Atriplex; and halophyte grasses and mangroves) in the leaves (Fig. 2)
(ii) ***Salts exclusion at the roots level***—while plants are taking water from the soil, the salts are filtered at the roots level, thus, accumulation of salts occurs in the very near vicinity of the roots.
(iii) ***Accumulation of salts in cell vacuoles***—the salts move from the cytoplasm to the large vacuoles. The vacuoles have lower metabolism relative to the cytoplasm.

12.2 Farm's Productivity Decline Due to Salinity

The choice of crops becomes limited and yield declines linearly as salts in the irrigation water and soil increase (Shahid et al. 2018a). In Oman, farm productivity decreased due to soil salinity which has led to a significant reduction in farm profitability (MAF 2012). While the farms irrigated with fresh water make gross profits of about US$ 2,860/0.42 hectare, this falls to US$ 2,080 for low salinity water, US$ 1,222 for moderate salinity farms and only US$ 1,118 for high salinity farms (MAF 2012). Hussain (2005) reported 18.9–36.0 million US$ annual losses due to only salinity in Oman. The Oman Salinity Strategy (MAF 2012) survey data exhibit a spectrum of crops that are abandoned with the increase of salinity. Thus, for example, some vegetable crops start to be abandoned when salinity goes above 1,500 ppm. Between 3,000 and 5,000 ppm tree crops such as lemon and mango are abandoned. While even fodder crops and dates are being abandoned progressively over the salinity range 5,000 to 10,000 ppm. The main cause of abandonment was stated to be falling incomes caused by decreasing yields and product quality as the salinity of irrigation water increased. These studies (EAD 2018; MAF 2012) cautioned the effects of salinity on crops, farm abandonment, and stress to assess salinity problems at the national level if agriculture has to be sustained, such as the case of countries in the MENA region, a water and arable land scarce region.

In the Abu Dhabi Emirate (EAD 2009), an area of 35.5% (2,034,000 ha) has been depicted to be affected by varying degrees of soil salinity, where the highly saline soils on the soil salinity map are confined to the coastal land (King et al. 2013), and inland sabkha (salt scald) where the groundwater levels approach the surface, creating large areas of aquisalids at the great group level of US soil taxonomy (Soil Survey Staff 2014; Shahid et al. 2013, 2014). These estimates are mainly from general salinity assessment and do not present the salinity status of the irrigated agricultural farms. Considering the importance of salinity management in irrigated agriculture farms to enhance farms productivity and increase domestic agriculture production, the Environment Agency Abu Dhabi (EAD) conducted an Abu Dhabi emirate-wide multi-million-dollar salinity assessment of agricultural farms project (EAD 2018). After analyzing 16,000 soil samples from over 4,000 agricultural farms, it has been observed that the soil salinity of irrigated agricultural farms was significantly higher than the salinity of neighboring native soils of the same origin. Where the salinity effects are alarming, for example, over 6,000 agricultural farms have been abandoned in the Abu Dhabi emirate alone, due to the salinity problem, thus reducing the national capacity of domestic food production. The survey showed about 90% of the irrigated farmland was affected by soil salinity of varying degrees (EAD 2018). Such agriculture farm-based salinity information is not known in most of the MENA region countries, but the situation may be alarming.

In the case of Kuwait, the country-wide soil/water salinity status of agricultural farms is not known (Al-Menaie et al. 2018), but soil salinity has been indicated (Al-Rashed and Al-Senafy 2004) in Abdali farms ranging from 5 to 25 dS/m levels, imposing serious constraint to crop production in Kuwait cultivated land and in general it is reported as an early warning of land degradation (Shahid et al. 1998). Later, Al-Rashed and Al-Senafy (2004) clearly stated that since the establishment of Abdali farms, there was a clear increase in soil salinity levels. In the same study in Abdali, groundwater Total Dissolved Solids (TDS) were reported to range between 5,700 and 14,900 mg/l during summer and between 5,200 and 17,500 mg/l in winter. While interpreting soil survey data, Shahid et al. (2002) concluded that in Kuwait an area of 12.1% was affected by varying degrees of salinity, this salinized area does not include agriculture farms. Therefore, the farmers are not aware of the salinity levels of their farm soils and irrigation waters and continue farming various crops without knowing their salt-tolerance levels, and are likely to have low crop productivity. If, however, the farmers select crops based on the salinity tolerance levels, maximum production can be achieved.

12.3 General Guideline About the Crop Response to Root Zone Soil Salinity

No effect of soil salinity on crop yield declines until soil salinity (ECe) reaches a threshold level (ECt). Above this, there is a linear decline in crop yield "slope" (s) as soil salinity increases (Maas and Grattan 1999). To understand the possibility of expected crop yield decline at certain soil salinity (ECe) levels relative to yield from normal soil, the following relationship is globally used:

$$\mathrm{Yr} = 100 - \mathrm{s}(\mathrm{ECe}—\mathrm{ECt}) \tag{4}$$

where Yr is yield under saline soil environment relative to non-saline environment, i.e., at or below ECt level; s = is the slope (% linear decline in yield with each unit increase of soil salinity (ECe) above ECt; ECe = Average root zone soil salinity during crop season; ECt = threshold soil salinity of crop.

The above equation can be explained by giving the following example.

Example: Average soil salinity (ECe) of irrigated field is 8 dS/m. What are the relative yields of barley (forage) and alfalfa crops?

Barley *(Hordeum vulgare)*

ECe (8 dS/m); ECt (8 dS/m); S (5%) Barley yield relative to non-saline soil = 100%

Alfalfa *(Medicago sativa)*

ECe (8dS/m); ECt (2 dS/m); S (7.3%) Alfalfa yield relative to non-saline soil = 56.2%

Conclusion: Farmer should grow barley for higher yield and profitability. If he grows alfalfa farmer is likely to lose 43.8% yield.

13 Facts About Soil Salinity, Crop Salt-tolerance and Management

Crop selection based on the expected root zone soil salinity during crop season is the best choice to moderate salt effects. Extra leaching has to be accomplished in access to crop water requirements to keep the root zone salinity at an acceptable level (threshold salinity). Plants are sensitive to salinity at an early stage, the mature plants are more tolerant to salts. Salt tolerance in general increases from *Fruits* → *vegetables* → *field crops* → *forage crops*. Regular monitoring of root zone salinity is a must to take necessary action to maintain soil salinity at a safe limit.

14 A Paradigm Shift in the Classification of Salt-Affected Soils in Relation to Crop Types

The most used classification of salt-affected soil is the one published in 1954 by US Salinity Lab Staff (1954) and later in 2017 (Soil Science Division Staff 2017). In the former classification, saline soil presents electrical conductivity of extract from saturated soil paste (ECe) more than or equal to 4 dS/m (ECe $\geq$ 4 dS/m). This limit was set up with the understanding that at this level, salinity starts showing its impact on soil properties and plant growth. However, it is not true for salt-sensitive crops, such as, maize, broccoli, tomato, cucumber, spinach, celery, cabbage, potato, pepper, lettuce, radish, onion, carrot etc., these crops start showing effects of soil salinity on plant growth even at less than ECe 2 dS/m. The Soil Science Division Staff (2017) classify soils with ECe < 2 dS/m as non-saline, even though salt-sensitive crops show yield decrease in this range. These definitions (Richards 1954; Soil Science Division Staff 2017) are creating confusion among scientists and farmers, in the sense that how a non-saline soil can cause a significant effect on plant growth. The authors of this chapter believe that the level of soil salinity in the context of its impact on crops to be set up at the salinity threshold level of the specific crop. If this paradigm shift in understanding the effects of salinity to crop is well received and appreciated specifically in the MENA region, and in general globally, this will lead to enlighten the gray area (between salinity thresholds of crops below ECe 4 dS/m) and provide more insights to the salinity problems and their objective-oriented long-lasting management through the selection of salinity level oriented appropriate salt-tolerant crops. To guide the researchers, extension workers and farmers, a comprehensive information is prepared (Tables 5 and 6) showing the crops in relation to salinity threshold level (t), slope (s) and the minimum (ECe) and maximum (ECe) salinity levels for each crop, with explanation as a footnote, relative reduction of crop yield in saline soils compared to non-saline soil and comprehensive salinity/sodicity management practices. All these crops (Table 5) show significant crop yield reduction at ECe 4 dS/m (a level considered non-saline soil). Therefore, the saline soil definition (EC $\geq$ 4 dS/m) of Richards (1954) should be considered very general, perhaps suitable for regional and global soil salinity mapping, but not from the crop point of view of crop selection considering the salinity level is safe for crops.

Table 5 List of crops with salinity thresholds (ECe) less than 4 dS/m

Crop	Botanical name	ECt	Slope	Yield reduction at ECe 4 dS/m	Minimum ECe	Maximum ECe
		dS/m	%	%	dS/m	dS/m
Maize	*Zea mays*	1.7	12.0	27.60	1.7	10.0
Alfalafa	*Medicago sativa*	2.0	7.3	14.60	2.0	16.0
Broccoli	*Brassica oleracea botrytis*	2.8	9.2	11.04	2.8	14.0
Tomato	*Lycopersicon esculantum*	2.5	9.9	14.85	2.5	13.0
Cucumber	*Cucumis sativus*	2.5	13.0	19.50	2.5	10.0
Spinach	*Spinacia oleracea*	2.0	7.6	15.20	2.0	15.0
Celery	*Apium graveolens*	1.8	6.2	13.64	1.8	18.0
Cabbage	*Brassica oleracea capitate*	1.8	9.7	21.34	1.8	12.0
Potato	*Solanum tuberosum*	1.7	12.0	27.60	1.7	10.0
Pepper	*Capsicum annuum*	1.5	14.0	35.00	1.5	8.5
Lettuce	*Latuca sativa*	1.3	13.0	35.10	1.3	9.0
Radish	*Raphanus sativus*	1.2	13.0	36.40	1.2	8.9
Onion	*Allium cepa*	1.2	16.0	44.80	1.2	7.4
Carrot	*Daucus carota*	1.0	14.0	42.00	1.0	8.1
Beans	*Phaseolus vulgaris*	1.0	19.0	57.00	1.0	6.3
Orange	*Citrus sinensis*	1.7	16.0	36.80	1.8	8.0
Peach	*Prunus persica*	1.7	21.0	48.30	1.7	6.5
Apricot	*Prunus armeniaca*	1.6	24.0	57.60	1.6	5.8
Grape	*Vitus. sp*	1.5	9.6	24.00	1.5	12.0
Almond	*Prunus dulcis*	1.5	19.0	47.50	1.5	6.8

(continued)

Table 5 (continued)

Crop	Botanical name	ECt	Slope	Yield reduction at ECe 4 dS/m	Minimum ECe	Maximum ECe
		dS/m	%	%	dS/m	dS/m
Plum	*Prunus domestica*	1.5	18.0	45.00	1.5	7.1
Blackberry	*Rubus sp.*	1.5	22.0	55.00	1.5	6.0
Strawberry	*Fragaria sp.*	1.0	33.0	99.00	1.0	4.0

Adapted from Ayers and Westcot (1994); Maas (1990), Maas and Hoffman (1977); Zaman et al. (2018a, b); ECt = Threshold salinity where yield of crop is not reduced; Slope = % decrease in yield by 1 unit increase in ECe above ECt; Minimum ECe = ECe level where yield does not reduce (threshold salinity); Maximum ECe = ECe level where crop yield reduces to zero

Table 6 Relative yield reduction of important field, vegetables, forage and fruit crops as affected by soil salinity (ECe) (Ayers and Westcot 1994)

Crops ↓	Percent yield reduction at different soil salinity levels			
	0%	10%	25%	50%
Root zone Salinity →	ECe dS/m	ECe dS/m	ECe dS/m	ECe dS/m
A. Important field crops—Relative yield decrease				
Barley	8.0	10.0	13.0	18.0
Sugar beet	7.0	8.7	11.0	15.0
Safflower	5.3	6.2	7.6	9.9
Soybean	5.0	5.5	6.3	7.5
Maize	1.7	2.5	3.8	5.9
Cowpea	1.3	2.0	3.1	4.9
B. Important vegetable crops—Relative yield decrease				
Beets, red	4.0	5.1	6.8	9.6
Broccoli	2.8	3.9	5.5	8.2
Tomato	2.5	3.5	5.0	7.6
Cucumber	2.5	3.3	4.4	6.3
Spinach	2.0	3.3	5.3	8.6
Celery	1.8	3.4	5.8	9.9
Cabbage	1.8	2.8	4.4	7.0
Potato	1.7	2.5	3.8	5.9
Pepper	1.5	2.2	3.3	5.1
Lettuce	1.3	2.1	3.2	5.1
Radish	1.2	2.0	3.1	5.0
Onion	1.2	1.8	2.8	4.3

(continued)

Table 6 (continued)

Crops ↓	Percent yield reduction at different soil salinity levels			
	0%	10%	25%	50%
Root zone Salinity →	ECe dS/m	ECe dS/m	ECe dS/m	ECe dS/m
Carrot	1.0	1.7	2.8	4.6
Beans	1.0	1.5	2.3	3.6
C. Important forage crops—Relative yield decrease				
Wheatgrass, tall	7.5	9.9	13.0	19.0
Wheatgrass, crested	7.5	9.0	11.0	15.0
Bermuda grass	6.9	8.5	11.0	15.0
Barley, hay	6.0	7.4	9.5	13.0
Ryegrass, perennial	5.6	6.9	8.9	12.0
Vetch, common	3.0	3.9	5.3	7.6
Sudan grass	2.8	5.1	8.6	14.0
Cowpea	2.5	3.4	4.8	7.1
Sesbania	2.3	3.7	5.9	9.4
Alfalfa	2.0	3.4	5.4	8.8
Love grass	2.0	3.2	5.0	8.0
Corn fodder	1.8	3.2	5.2	8.6
Berseem, clover	1.5	3.2	5.9	10.0
Clover	1.5	2.3	3.6	5.7
D. Important fruit crops—Relative yield decrease				
Date palm	4.0	6.8	11.0	18.0
Fig, Olive	2.7	3.8	5.5	8.4
Grapefruit	1.8	2.4	3.4	4.9

(continued)

Table 6 (continued)

Crops ↓	Percent yield reduction at different soil salinity levels			
	0%	10%	25%	50%
Root zone Salinity →	ECe dS/m	ECe dS/m	ECe dS/m	ECe dS/m
Orange	1.7	2.3	3.3	4.8
Lemon, Apple	1.7	2.3	3.3	4.8
Peach	1.7	2.2	2.9	4.1
Apricot	1.6	2.0	2.6	3.7
Grape	1.5	2.5	4.1	6.7
Almond	1.5	2.0	2.8	4.1
Plum, prune	1.5	2.1	2.9	4.3
Strawberry	1.0	1.3	1.8	2.5

15 Soil and Salinity Management Options in the MENA Region

Due to the complexity of soil, water and environmental problems in the MENA region, sustainable soil management requires a mix of best soil management practices tested and proved successful under local conditions or on similar soils and environmental conditions for adoption. In summary, it requires proper tillage to conserve soil moisture and organic carbon, efficient nutrient and water management, crop residue management to transform to compost, organic and biofertilizers, irrigation and weed management as well as crop rotation by including crops having the character of biological nitrogen fixation (BNF) to maintain soil fertility. Negligence of any of the above may reduce soil's capability to produce to its full capacity and compromise soil quality and crop performance as well as lead to soil and groundwater pollution. In addition, due to differences in climatic conditions (temperature, rainfall), soil parent material, intensity of soil formation factors and processes, the soils within the national boundaries and across the region are of different types (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/). The groundwater used for irrigation is not of the same quality, but possess heterogeneous levels of salinity and sodicity, thus the vulnerability of the irrigated lands to salinity/sodicity is different. This led to the conclusion that there is no single or combination of techniques universally applicable to manage soil salinity in the MENA region. Therefore, the salinity management in irrigated agriculture should be diagnostics-based, crop and location-specific. In this context, a comprehensive analysis is made to come up with potential salinity/sodicity problems in the region, their influences and objective-oriented management solutions are enlisted (Table 7). This comprehensive table provides all types of problems in the countries of the MENA region and the suggested mitigation options, these are not specific for any country but can be used on a case by case basis based on diagnostics of the problems.

Table 7 Salinity and sodicity-related problems, their influences and potential management solutions

	Influence on soil and plant growth	Potential management options
A. Water-related problem		
Saline water	• No effect on soil structure of coarse-textured soils • In fine texture soils, the effect of saline water can be observed after rain, when dilution of salts can cause soil dispersion, and translocation of colloidal (clay) particles to the subsurface where the conducting pores can be blocked, affecting water infiltration and root growth • Osmotic pressure will be increased and the plants will not be able to abstract water from soil, which may cause physiological drought	• Laser land leveling is recommended for the uniform distribution of water in irrigated agriculture fields • The level of organic matter is recommended to be maintained at a suitable level to reduce soil dispersion and to enact the soil (aggregation) to hold nutrients and water. Green manuring is recommended as a part of soil management • Based on the salinity level of the irrigation water and the potential of soil salinity development ($ECe = ECiw \times 1.1$ for coarse texture soils, and $ECe = ECiw \times 1.5$ for fine texture soil), selection of salt-tolerant crops is recommended which has market values • Saline water can be blended with fresh water (if available) to achieve desired salinity level with respect to the selection of the crop. Reducing water salinity increases the choices of crops • Cyclic use of water is recommended, fresh water is used at early stage of plant growth and saline water at the advanced stage of plant growth • Modern irrigation system (drip) can be used to irrigate crops along with suitable leaching fractions to leach salts and to maintain rootzone salinity to an appropriate level (below the threshold level of a specific crop)
		• Suitable cultural practices are used to place seeds on the furrow where low level of salt build may be expected (furrow irrigation) • The surface salt built up can be removed through scraping • If affordable, the farmers are recommended to use small-scale Reverse Osmosis (RO) unit to desalinate highly saline water, to be used on cash crops (high-value vegetables) and the brine is either used for salt-tolerant crops or collected in properly sealed evaporation ponds, where fish farming can be a profitable business, or at very high salts levels, salts may be harvested, which can be exploited for multiple uses (domestic and industrial) after proper treatment

(continued)

Table 7 (continued)

	Influence on soil and plant growth	Potential management options
Saline-sodic water	• Can cause salinity, and specific ion (Na, Cl) effects on crops • Can cause soil dispersion at high sodicity (SAR > 10 mmoles/l)$^{0.5}$ and low salinity levels • High salinity and low sodicity water is likely to maintain soil structure (flocculation) • Plants will not be able to abstract water from soil at high salinity levels. Prolonged and hiked saline conditions may cause physiological drought that may lead to complete plant death	• Laser land leveling is recommended for the uniform distribution of water in irrigated agriculture fields • Based on the irrigation water salinity and projected soil salinity development suitable salt- tolerant crops are recommended • Blending with fresh water, and cyclic use is recommended • Gypsum stones are to be placed in the water basins (collecting water from tube wells) or in the water channels transporting water to irrigated agriculture fields where saline-sodic water is used to irrigate crops (Shahid et al. 2018b) • The saline-sodic water is to be analyzed in the laboratory for gypsum requirement to reduce water sodicity (Residual Sodium Carbonates-RSC) to a desirable level • RO units are recommended with proper management of brine • A suitable quantity of organic matter (farm yard manure, organic matter, compost, green manuring) is to be maintained to avoid soil structure breakdown
Sodic water	• Can cause soil dispersion/structure breakdown and seal the soil subsurface (fine-textured soils) • The sodic water effects are minimal in coarse-texture soils (sandy soils) • Can cause a specific ion effect (Na) on plants	• Laser land leveling is recommended for the uniform distribution of water in irrigated agriculture fields • Dilute with saline water to reduce sodicity (SAR) below 10 (mmoles/l)$^{0.5}$, but maintain the water salinity desirable for the selected crop • Use saline water for irrigation along with growing salt-tolerant crops. This will improve soil flocculation, CO_2 released by plant roots will mobilize Ca from $CaCO_3$ equivalents from soil and improve water sodicity • Increase organic matter contents of soil to maintain soil structure • Use mulch material to control raindrop splash impact on fine texture soils, which may lead to soil surface sealing and crusting • Analyze the water in the laboratory to determine gypsum requirements to offset the water sodicity

(continued)

Table 7 (continued)

	Influence on soil and plant growth	Potential management options
B. Soil-related problems		
Saline soils	• Reduce crop selection based on soil salinity and quality of irrigation water • No soil structure breakdown in sandy soil; however, in fine-textured soil, the impact can be maximum during and after rain (due to raindrop splash action) and dilution of salts in the soil • Osmotic pressure will be increased and the plants will not be able to abstract water from soil, which may cause physiological drought • Specific ion effects (Na, Cl) on crops	• Laser land leveling is recommended for the uniform distribution of water in irrigated agriculture fields • The level of organic matter is recommended to be maintained at a suitable level to reduce soil dispersion and to enact the soil (aggregation) to hold nutrients and water. Green manuring is recommended as a part of soil management • Based on the expected soil salinity level in relation to irrigation water salinity, select suitable salt-tolerant crops with market value • Use reclamation irrigation prior to seeding/transplantation to reduce rootzone soil salinity to improve seed germination • If available, use fresh water for irrigation (river/canal water) • Use drip/sprinkler irrigation systems • Suitable cultural practices are used to place seeds on the furrow where low levels of salt build may be expected (furrow irrigation) • The surface salt built up can be removed through scraping • Depending on the affordability by the farmers, small Reverse Osmosis (RO) units are recommended to desalinate highly saline water, to be used on cash crops (high-value vegetables) and brine is either used for salt-tolerant crops or collected in properly sealed evaporation ponds, where fish farming can be a profitable business, or at very high salts levels, salts may be harvested, which can be exploited for multiple uses (domestic and industrial) after proper treatment

(continued)

Table 7 (continued)

	Influence on soil and plant growth	Potential management options
Saline-sodic soils	• Reduce crop selection based on soil salinity and quality of irrigation water • No soil structure breakdown in sandy soil, but fine-textured soils are highly vulnerable to raindrop splash impact causing surface sealing and crusting • Osmotic pressure will be increased and the plants will not be able to abstract water from soil, which may cause a physiological drought • Very high salinity will lead to uneconomical farm production and lead to farm abandonment	• Laser land leveling is recommended for the uniform distribution of water in irrigated agriculture fields • Adopt management practices as described for saline soil. In addition to the following for saline-sodic soils, where appropriate: • Analyze soil for soil sodicity (exchangeable sodium percentage) and gypsum requirement • Based on the gypsum requirement, add gypsum to the soil and mix it properly with soil. Make bunds around the field and apply water to pond for few days to dissolve gypsum and react with exchangeable sodium • The ponded water with sodium released from soil can be drained to side channels and safely disposed • Where soils are underlain with clay pan due to translocation of dispersed sodium, it must be shattered through subsoiling to increase the drainage capacity of the soils • 10 mesh-sized gypsum (2 mm) is recommended for cost-efective and high-efficiency reclaimation of saline-sodic or sodic soil
Sodic soils	• Cause soil structure breakdown, disperse clay, and translocate to subsurface where clay particles are lodged on the conducting pores and seal the subsurface • Can create soil surface sealing and crusting and reduce seed germination (Shahid and Jenkins 1992b) • Restricts water movement in soil and can cause ponding • Can create clay pan at deeper layers • Soil hardness, can cause difficulty for the farm machinery operation • Cause-specific ion effect (Na) on crops	• Use saline water of desirable salinity based on the crop to be grown. Increased salinity will maintain soil structure by increasing soil flocculation • Break the hard/clay pan at deeper layers through chiseling or subsoiling as appropriate to increase water absorption and soil drainage capacity • Analyze soil for ESP and gypsum requirement • Make bunds around the field, add gypsum and add water to the pond for a few days, drain the water to side channels and dispose of safely • 10 mesh-sized gypsum (2 mm) is recommended for high-efficiency reclaiming saline-sodic or sodic soil

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Chapter 3
Innovation and Practical Experience of Using Saline Water at the Farm Level in Tunisia

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Abstract Tunisia is confronted, like several other countries, with water scarcity and salinity challenges. For salinity management, some activities are carried out. An alternative saline farming system is tried to find based to change the extensive rainfall crop system to a semi-intensive saline irrigated farming system, introduce new crops/cultivars, use localized irrigation, and develop more adapted farmer' practices. Concerning the adapted irrigation system under saline conditions, subsurface drip irrigation showed an improvement in water efficiency and a reduction in salt stress for different tomato varieties. Compatible organic molecular proline was tested to improve crop salinity tolerance. Foliar exogenous application of proline showed an increase in fruit yield. A new study has been carried out to evaluate the effect of the electromagnetic treatment (ET) of saline water on several aspects which as salts leaching, and duration of ET on the characteristics of drainage water and soil. The volume and the salts concentrations of drainage water were significantly higher under irrigation with electromagnetically treated saline water. This result was manifested by the improvement of salt leaching and the elimination of salt far from the root zone. The soil showed an increase in EC. The ET duration effect was also tested. The results indicated an increase in the volume and the salinity of drainage water when increasing the ET duration. The ET duration had also a significant effect on soil salinity which decreased under ET.

Keywords Salinity · Water · Management · Tunisia · Cultural practices

1 Introduction

Arid and semi-arid regions are characterized by scarcity of precipitation where evapotranspiration exceeds precipitation during the largest part of the year. Therefore, crop production is dependent on irrigation to achieve satisfactory yields. At the same time, one of the major constraints for environmental, social, and economic development

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in these regions is the shortage of freshwater resources (Bedbabis et al. 2014). The intensification of water scarcity is expected with rapid industrialization, fast population growth rates, and increased demand from the agricultural sector. Competition among user sectors will reduce the amount of freshwater allocated for crop production which, therefore, limits agricultural development. Consequently, there has been a growing interest in the use of nonconventional water, as alternative sources, such as agricultural drainage water, brackish water, or municipal and industrial effluent to meet its greater demands (Oron et al. 2002; Bixio et al. 2006; Khaskhoussy et al. 2019).

Although the use of saline water for irrigation is a strategy to mitigate water shortage, poor saline water management for irrigation has resulted in secondary salinization and a series of environmental problems (Kumar et al. 2015; Li et al. 2015). These problems will aggravate under climate change, unfavorable soil, overexploitation of groundwater, improper cropping patterns, and sea-water intrusion conditions (Heydari 2019).

Irrigation with saline water under strong evaporation, without taking into consideration the adequate application of water or conservation of the productive capacity of the soils, and associated with the absence of an efficient drainage system or the use of excessive amounts of fertilizers, leads to salt accumulation in the soil (Hue and Silva 2000; Wang and Qui 2004; Guilherme et al. 2019), salt accumulation in the upper soil layer negatively affects the soil properties. Indeed, high concentrations of sodium, calcium, and magnesium ions can affect the dispersion of clay particles, hydraulic conductivity, porosity, and soil aggregate stability (Guilherme et al. 2019). Therefore, the soil becomes degraded by salinization (Shrivastava and Kumar 2015). Consequently, soil salinization results in significant limitations to agricultural crop production which, in turn, negatively affects food security (FAO 2018).

High soil salinity levels decrease the osmotic potential of the soil, which results in the onset and the development of salinity stress at the whole plant level leading to reduced plant growth and finally biological or economic yield reduction (Dong 2012). Under osmotic stress conditions, various morphological, physiological, and biochemical changes in plants are mostly identical to drought (Munns 2002; Tang et al. 2007). Both drought and salinity stresses cause biochemical changes including inhibition of enzyme activities in metabolic pathways and accumulation of reactive species that play an important role in inhibiting plant growth and development (Nxele et al. 2017). Generally, salinity affects plants' growth, development, and survival in different ways such as water stress, specific-ion toxicity, oxidative stress, nutritional disorders, alteration of metabolic processes, reduction of cell division and expansion and genotoxicity (Munns 2002; Zhu 2007; Carillo et al. 2011).

Tunisia is among the semi-arid regions that face serious problems of salinization and water scarcity. Nowadays, about 10% of the national territory is affected by different degrees of salinity and about 25% of water resources have salt concentrations exceeding 3 g l^{-1}. As a result, about 50% of the total irrigated areas are considered at high risk of salinization. In this context, many experiences have taken place, since the sixties, in irrigated areas of Tunisia Center and at the experimental site of National Institute of Rural Engineering Water and Forests to evaluate the performance of different management practices including proper irrigation scheduling, drainage efficiency, appropriate irrigation systems, physical and chemical techniques (leveling, plowing, planting techniques, optimizers, etc.), soil amendments and introduction of salt-tolerant crops varieties and species for the sustainability of irrigated agriculture under salinity pressure were investigated.

To avoid such damage caused by these stresses and increase food production, it is necessary to develop innovative adaptation practices and different reclamation approaches including changes in crop management practices, agricultural water management strategies, and the adoption of new agricultural technology (Thong et al. 2019). In this context, farmers also play a crucial role, not only as receivers of innovations but also as producers and holders of knowledge (Goulet and Le Velly 2013; Tambo and Wunscher 2017).

As mentioned, various technological and biotechnological crop-soil–water salinity management practices, such as better water management, the introduction of alternatives crops, salt-tolerant plants, organic substances, and adoption of new irrigation practices at the field level, including methods for water use efficiency and innovative technologies for saline water treatment (Hanson et al. 2007; Pereira et al. 2002, 2009) were suggested.

There is a wide range of alternative crops for industrial, energy, and alimentation usages that can be used in salinity management which adapt well to arid and semi-arid region's climates and when using high salinity water for irrigation. These crops are generally salt-tolerant or/and well adapted to drought conditions. It has been reported that the yield of some salt-tolerant crops under saline water irrigation is similar to that under freshwater irrigation (Wan et al. 2010; Singh and Panda 2012). A variety of plants that seem to be well adapted to arid and semi-arid regions (Ashton et al. 2008) can be energetic, pseudo-cereal, cosmetic, etc., with high economic value (Gantait et al. 2014; Kaya and Attila 2015). Moreover, it has been reported that is possible to improve crop salinity tolerance by organic substances application, such as proline (Kahlaoui et al. 2016).

Proper choice of irrigation methods should create and maintain favorable salt and water regimes in the root zone such that water is readily available to plants for their growth and without any damage to yield (Minhas et al. 2020). In addition, it should ensure uniform distribution of water. Micro (Drip) irrigation methods are regarded as superior in improving efficiency and crop production under saline conditions (Hanson et al. 2008; Minhas et al. 2020).

Recently, new innovative practices, such as magnetic/electromagnetic treatment of saline water have gained greater importance. This physical treatment of water is an innovative approach that affects the behavior of inorganic and organic materials in water, including crystallization and biological processes, which, consequently, can positively influence the growth parameters of many crops (Selim and El-Nady 2011).

Considering these management strategies, many research studies have been done to develop appropriate management suitable for cropping with poor-quality waters under semi-arid Tunisian conditions, where salt-tolerant fruit trees, medicinal, aromatic, and other high-value crops are tested, and innovative technology systems were used.

This paper is an overview of the results of experiments conducted by the team of the Research Laboratory Valorization of Non-Conventional Waters, National Institute of Rural Engineering, Waters and Forests, Tunisia. An innovation represents “an idea, practice, or object that is perceived as new” and includes new agricultural technology and many other processes or the application of a new learning and teaching method (Spielman et al. 2011). Many research projects are conducted on salinity and efficient use of saline water issues under Tunisian climatic conditions by adapting innovative management practices that improve the efficient use of saline soil. The practices include new crops/varieties; new systems of irrigation; new technologies and more adapted farmer practices.

2 Selection of Salt-Tolerant Crops and Varieties

2.1 New Varieties of Olive Trees

Olive is a major tree crop in the Mediterranean region of which more than 90% of the world’s olive oil is produced. In Tunisia, olive is the most representative, cultivated with about 1835 thousand hectares cultivated in a large agricultural area and there are approximately 82 million trees covering the land (DGPA, 2015). *Chemlali* is the major Tunisian cultivar that covers 2/3 of the Tunisian olive grove and contributes more than 60% of the national production of olive oil (Khlif et al. 2002; Ben Rouina et al. 2002). In comparison to other Mediterranean fruit trees, olive is considered to be a moderately salt-tolerant plant and the tolerance level depends on plant age and cultivar (Chartzoulakis 2011; Erel et al. 2019). It is suggested that olives can be irrigated with water with electrical conductivity (ECw) between 3 and 6 dS m^{-1} causing no effect on growth or yields, and irrigation water with 8 g l^{-1} NaCl has been found to be the tolerance limit for olive trees (Ayers and Westcot 1985; Chartzoulakis 2011). Mechanisms of salinity tolerance in olive trees include a strong ability to exclude potentially toxic ions such as Na^+ and Cl^- ions from aboveground tissues and its retention in roots (Chartzoulakis et al. 2002; Kchaou et al. 2010). To investigate and compare the effect of salinity on two olive trees cultivars, a field experiment was conducted, at the North of Bouhajla village located at the South of Kairouan city. This region has a typical Mediterranean semi-arid climate with an annual average precipitation of about 250 mm. Two olive trees cultivars: *Arbequina,* a Spanish cultivar, and *Chemlali,* a Tunisian cultivar, were used and a total of 120 olive trees were planted in the plot. Olive trees were irrigated with well water where TDS, EC, and SAR reached 3.7 g l^{-1}, 5.1 dS m^{-1}, and 11.4, respectively. The soil is characterized by a silty clay texture with about 50% of smectites, less than 1% of organic matter, 32% of total lime, 20% of active lime, pH of about 8.3, and a high initial salinity of about 5.0 dS m^{-1} in the surface layer and 6.5 dS m^{-1} at a depth of 1.5 m. Yield production and oil quality were evaluated after 6 years of planting. *Arbaquina* cultivar had a fruit yield (12 kg/tree) significantly higher than *Chemlali* cultivar (2 kg/tree). Fruit weight was significantly higher with the *Arbaquina* tree than with the *Chemlali* tree and this was mainly due to an increase in the olive weight. There were no differences among cultivars in acidy of oil, where acidy was about 2.64 and 2.71 for *Chemlali* and *Arbaquina,* respectively. According to this result, the oil of both cultivars looks to be regular virgin olive oil, which may be due to the collection, storage, and extraction of oil conditions. Oil fatty acid composition of these olives showed to conform with the International Olive Oil Council Standards (2019), except for two acids for *Arbaquina* cultivar and one acid for *Chemlali* that exceeded these criteria. It was found that *Arbaquina* oil absorption of UV radiation was more conforming to standard than *Chemlali* oil. Furthermore, *Arbaquina* cultivar looks to be a more salt-tolerant tree than the *Chemlali* Cultivar.

2.2 Energetic Plant: Jatropha

Jatropha curcas L. is a member of the spurge family (Euphorbiaceae), native to South America but now thrives in many parts of the tropics and subtropics in Africa and Asia (Kumar and Sharma 2008; Niu et al. 2012). It has emerged, among the species used to produce biodiesel from the oil extracted from their seeds, as one of the candidates with the greatest potential. It has increased in popularity in recent years due to its high ecological adaptability which allows it to thrive in a wide range of environmental conditions (Kheira and Atta 2009; Dorta-Santos et al., 2014). Jatropha is reported to be drought resistant due to its ability to grow under arid and semi-arid climates and without irrigation in a region where average rainfall does not exceed 300 mm $year^{-1}$ (Nui et al. 2012; Dorta-Santos et al. 2014). However, there is little information on its salt tolerance and no threshold has been assessed. While a number of researchers reported that Jatropha could successfully be irrigated with levels of salinity of up to 12 dS m^{-1}. FAO classified Jatropha as a sensitive crop (Dagar et al. 2006).

A greenhouse experiment was conducted to evaluate the growth responses of Jatropha to a range of salt concentrations. Jatropha was cultivated in three Tunisian soil types (clay loam, sandy loam, and medium textures) and irrigated with drinking water ($C0 = 1.5$ dS m^{-1}), saline water of 7.5 dS m^{-1} (C1) and saline water of 10.0 dS m^{-1} (C2). Stem length, diameter and number of leaves were recorded. Jatropha growth was significantly influenced both by water quality and soil texture (Fig. 1).

Indeed, the highest dry weights, d leaf areas, and stem lengths were observed in the sandy-loam soil under drinking water irrigation (Fig. 2).

Significant growth reduction observed in plants irrigated with saline soil could be due to the increase in Na^+ in different parts of the plant and especially in leaf tissues.

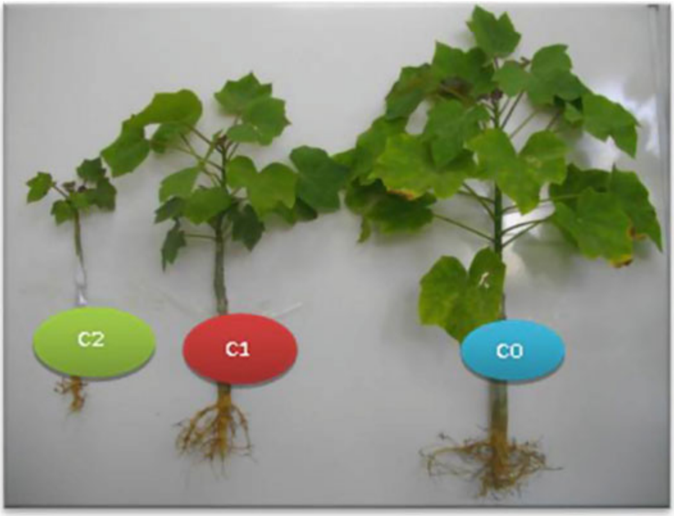


Fig. 1 Effect of saline water irrigation of different salinity levels on Jatropha growth. C0: Control; C1: 7.5 dSm^{-1}; C2: 10 S m^{-1}

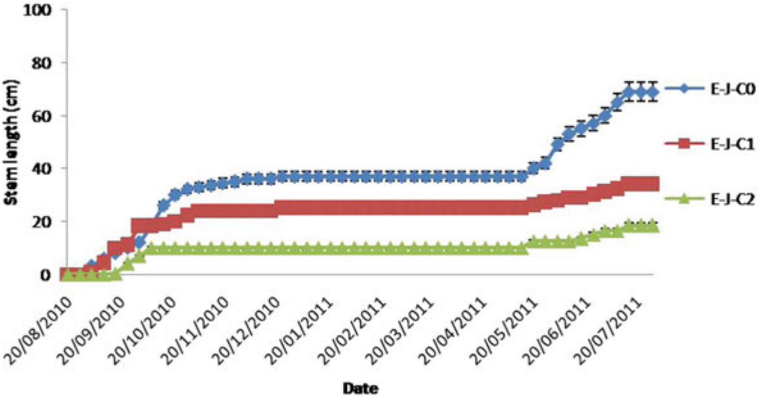


Fig. 2 Effect of saline water irrigation on stem length of Jatropha. C0: Control; C1: 7.5 dS m^{-1}; C2: 10 dS m^{-1}

Based on this finding, Jatropha cannot be considered a tolerant plant to salinity where its yield would be reduced when grown in a salt-affected area. This suggests that energy plants can only be adopted in areas with a shortage of water resources.

2.3 Pseudo-Cereal: Quinoa

Chenopodium quinoa Willd is an Andean species that shows a potential to enhance farm-level productivity and livelihoods in drought- and salt-prone areas. Quinoa is a salt-tolerant seed crop widely investigated due to its nutritional composition and gluten-free seeds (Kaya and Attila 2015). Field experiments (Rjeibi et al. 2015) were conducted to evaluate the response of quinoa, at different growth stages from seedling to maturity, to water deficit, and salinity stress under the Tunisian climate. The study highlighted the effect of irrigation with saline water at different salinity levels (1.25, 10, 25, and 40 dS m^{-1}) on morphological and physiological parameters of quinoa such as germination rate, length, diameter, leaf area, number of spikes, chlorophyll, and mineral element content. Stress conditions allow this plant to develop resistance mechanisms to water stress and grow under optimal conditions with a very limited quantity of water irrigation (250 mm). Quinoa also showed a tolerance for salinity with a seedling reduction of about 9% at 25 dS m^{-1}. Quinoa irrigated with saline water at a level of 10 dS m^{-1} showed the highest length, width, leaf area, number of branches, and weight. Moreover, the highest mineral contents were especially observed in leaves.

A germination test of quinoa seeds was performed for five varieties from the International Center for Biosaline Agriculture and from the University of Santiago of Chile. Among quinoa varieties, AMES 13,761 and *Ch.q. Willd* have the highest germination rates and consequently are more tolerant to salinity than other varieties. After the seed germination test, a field trial (Fig. 3) was carried out in the Cherfech research station to evaluate the response of quinoa to irrigation with saline water of two salt concentrations (6 and 12 g l^{-1}) and fresh water.

Fig. 3 Field experiment for quinoa seeds crop at Cherfech research station (north of Tunis City)

Growth parameters suggested a good adaptation of quinoa to drought stress. Results indicated also an increase of root biomass under deficit irrigation levels of 50% and 75% compared to full irrigation. The highest yield production was recorded under deficit irrigation levels of 75%, whereas, the lowest was recorded under the level of 100%. Generally, the highest yield production to the lowest were ranked as follows75% > 50% > 100. A comparison was performed on some growth parameters, such as shoot length and root biomass of plants irrigated with saline water of salt concentration 6 g l^{-1} and plants irrigated with deionized water (salt concentration = 0 g l^{-1}). Results suggested a good adaptation of Quinoa to salinity stress. The nutritional advantages of quinoa seeds and antioxidant components such as polyphenols are also evaluated, and the result showed that quinoa seeds cultivated under saline water irrigation (6 g l^{-1}) had the highest amount of proteins and polyphenols.

2.4 Medicinal and Cosmetic Plant: Aloe Vera

Aloe vera is a tropical, drought-resistant succulent plant of the Liliaceae family. *Aloe vera* (*Aloe barbadensis* M.), the most popular *Aloe* variety, has been cultivated for its beneficial properties, finding application in a wide range of medical and health products. It originates from the Mediterranean region, Eastern Africa, the Arabian Peninsula, India, and China. *A. vera* is a xerophyte with a strong drought resistance ascribable to its use of crassulacean acid metabolism photosynthesis, and a certain degree of tolerance to salt stress. It is highly appreciated due to its short growth period and its high economic value (Gantait et al. 2014). *A. vera* is a short-stemmed perennial that reaches a height of 60–100 cm. This succulent has elongated leaves that store large amounts of water. The leaf extracts latex and gel are the primary products used in *A. vera* industry. The original commercial use of the *Aloe vera* plant was in the production of a latex substance called Aloin, a yellow sap used for many years as a laxative ingredient. Later the gel, stabilized and marketed, gained respect as a product used as a base for nutritional drinks and as a healing agent. This gel has a complex chemical composition: amino acids, minerals, vitamins, enzymes, proteins, polysaccharides, and biological stimulators. The rich chemical composition of the plant depends, essentially, on the type of the aloe's species, conditions of cultivation, climate, harvest time, and the method utilized in harvesting (Giannakoudakis et al. 2018). It is attributable to its importance in the medical and healthcare fields, food industry, cosmetology, and nanotechnology (Soltanizadeh and Ghiasi-Esfahani 2015; Balaji et al. 2015; Rahman et al. 2015).

A. vera is being considered as an alternative crop for industrial applications in arid and semi-arid areas, where drought and salinization are preponderant. This suitable and environmentally safe solution shows an ability to survive in xerophytic conditions of the tropical, and subtropical regions as well as a salt tolerance even in infertile saline soils of coastal zones, although it is not usually taken as a halophyte (Zheng et al. 2009). Several experiments have been carried out for the assessment of growth, cations distribution, gel yield, and Aloin contents under different environmental conditions (Murillo-Amador et al. 2014). Many of these studies emphasized the beneficial role of moderate salinity stress for good growth, high yield of Aloe gel, and aloin content (Rahi et al. 2013).

Ascribed to its high market demand and export potential, *A. vera* farming is being encouraged by the Tunisian government. In order to occupy unproductive lands and preserve the water of good quality for domestic purposes, research was focused on either the Aloe cultivation in salt-affected soils or its irrigation with brackish water. In this context, an experiment has been conducted in the Kalaât Landelous region under hydromorphic and extreme saline conditions. The soil of the study area is distinguished by a high salinity level (16–24 dS m^{-1}) characterized by dominant Na and Cl ions. This salinity is mainly related to the presence of a shallow and highly saline water table. In fact, the water table depth is about 30 cm deep in the rainy seasons, and 142 cm in the dry seasons, and the salinity may reach 10.9 dS m^{-1}. Irrigations have been only performed during the summer season. Despite the elevation of the soil 1 m above the surface reducing as a result the effect of salinity in the topsoil, the soil remained very strongly saline with a genotoxic potential. *Aloe* plants showed an inability to resist the natural conditions prevailing in the study region. During the two years of monitoring, plants showed slow growth and low production (less than 12 leaves per plant) with signs of dryness (Souguir et al. 2013).

Simultaneously, the ability of *A. vera* to withstand salinity was tested under controlled conditions. Plants were cultivated in slightly alkaline (pH = 7.6) soil with low salinity (ECe = 1.1 dS m^{-1}). Salt stress was applied by NaCl addition in irrigation water: two salinity levels have been chosen: a moderate (EC = 3.5 dS m^{-1}) and a high (EC = 12.0 dS m^{-1}) level of NaCl. Irrigation frequency varied according to the season, and the cumulative water intake was about 1782 mm for each plant. 14 months of irrigation with saline water strikingly increased the soil salinity even under drinking water (Table 1). The most typical symptom of saline injury to plants is the reduction of growth. High concentration of salt significantly reduced growth parameters in terms of leaf number and length and fresh and dry matters with no significant modification in their water and gel contents. Growth changes occurred as a result of the Na accumulation in the leaf tissues, consequently dropping the K/Na and Ca/Na ratios when compared to plants irrigated with drinking water (Table 1). In addition, *A. vera* was a seat of high production of hydrogen peroxide (H_2O_2), a reactive oxygen species, generally associated, at a high level, with the development of the oxidative injury and the disruption of the metabolic functions in plants.

Malondialdehyde (MDA), a reliable indicator of oxidative injury and membrane lipid deterioration, also exhibited an enhancement of its content, proportionally to the toxic ion accumulation and/or H_2O_2 production (Table 1). In order to reduce oxidative damage, *Aloe* leaves have increased phenolic compounds biosynthesis (Table 1), which are the most abundant secondary metabolites in plants and play an important role in scavenging the free radicals (Mohamed and Aly 2008). On the basis of overall growth assessment and metabolic response at different salinity levels, *A. vera*, planted in soil affected by at least moderate salinity or irrigated with moderate salt water, can be attractive for industrial production in arid and semi-arid areas. High salinity negatively affects plant growth and its productivity.

Table 1 The salinity effects on the soil and on the *Aloe* plants. Irrigations were performed with different water qualities: drinking water (EC: 1.25 dS m^{-1}), moderate salinity (EC: 3.50 dS m^{-1}) and high salinity (EC: 12.00 dS m^{-1})

	Irrigation water quality		
	Drinking Water (EC: 1.25 dS m^{-1})	Moderate salinity (EC: 3.50 dS m^{-1})	High salinity (EC: 12.00 dS m^{-1})
Soil salinity-ECe (dS m^{-1})	5.77 ± 2.16a	11.4 ± 6.90b	20.55 ± 8.85c
Growth parameters			
Leaf number	14.45 ± 0.85b	12.91 ± 1.50b	9.09 ± 1.57a
Leaf length (cm)	30.46 ± 2.89b	29.76 ± 2.22b	22.22 ± 3.15a
Fresh weight (g)	369.16 ± 13.05c	255.22 ± 16.82b	163.26 ± 19.3a
Dry weight (g)	16.3 ± 1.23c	12.2 ± 0.05b	9.4 ± 1.67a
Water–gel content (%)	95.58 ± 1.92a	95.21 ± 1.18a	94.21 ± 1.45a
Cation content			
Na (%)	1.29 ± 0.04a	1.79 ± 0.09b	3.75 ± 0.22c
K/Na	1.04 ± 0.04c	0.72 ± 0.2b	0.47 ± 0.18a
Ca/Na	2.87 ± 0.10c	1.29 ± 0.40b	1.25 ± 0.09a
Oxidative stress-H_20_2 content (µmol g^{-1})	30.90 ± 12.96a	79.39 ± 42.48b	97.87 ± 14.12c
Lipid peroxidation-MDA content (nmol g^{-1} FW)[a]	6.41 ± 3.87a	12.96 ± 2.70b	31.54 ± 1.55c
Total phenolic compounds (U)[b]	1.22 ± 0.22a	2.68 ± 0.10b	4.30 ± 0.95c

Values represent means ± SE of triplicates

In each line, values followed by different letters are significantly different at $P < 0.05$ according to Tukey's test

EC lectrical conductivity of water, *ECe* electrical conductivity of the saturated soil-extract paste, H_2O_2 hydrogen peroxide, *MDA* malondialdehyde

[a] Fresh Weight

[b] Unit

2.5 Forage Legume: Sesbania

In order to find new crops tolerant to saline conditions and with high economic values, we were interested in *Sesbania aculeata*, a forage plant less studied in Tunisia. It is a leguminous shrub that belongs to the Fabaceae family and is one of the most potential legume fodder crops grown on saline and/or alkaline soils due to its halophytic nature (Parveen and Rauf 2008). Indeed, it can tolerate salinity up to 10 dS m^{-1} (Juzdan 2014). This plant plays an important role in the long-term maintenance of soil productivity because of its high nitrogen-fixing capacity. It can produce between

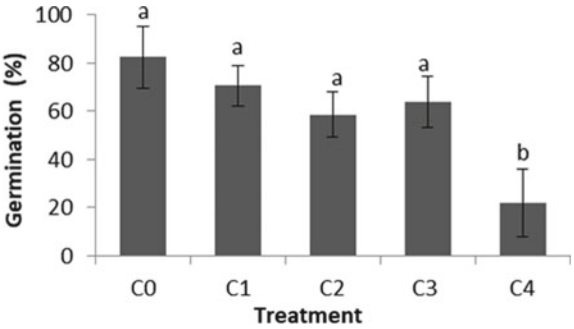


Fig. 4 Final percentage of germination of seeds of *S. aculeata* under salt stress (C0: distilled water; C1: 6 dS m^{-1}; C2: 12 dS m^{-1}; C3: 18 dS m^{-1} and C4: 24 dS m^{-1})

5.00 and 5.25 T ha^{-1} per year of dry matter and fix between 500 to 600 kg ha^{-1} of nitrogen per year.

Our study concerned the germination, the growth of this plant in a greenhouse and in the open field, and the effect of irrigation with saline water on the plant. In the first test, we tested the germination capacity of the seeds by applying different salt concentrations (6, 12, 18, and 24 dS m^{-1}) and we found that these seeds have a germination capacity of over 60% with irrigation water of up to 18 dS m^{-1}. Beyond this concentration, germination decreased significantly compared to the control seeds (Fig. 4).

Taking these results into account, a second test was carried out using only the concentrations 6, 12, and 18 dS m^{-1}. The test was carried out in pots and on loamy clay soil. In this soil, *Sesbania aculeata* was able to survive but with a significant decrease in growth especially under 18 dS m^{-1} (C3). This concentration affected the length of the plants and the fresh and dry matter of the roots and stems. The increase in salinity has no negative effect on the fresh and dry matter of *Sesbania* leaves (Table 2).

Based on the results obtained in this test, another experiment was conducted in the field using the concentrations 6 and 12 dS m^{-1}. Irrigation with saline water and even with drinking water has caused an increase in soil salinity with an accumulation of salts, especially in the deep layers (210 cm deep). The accumulation of salts in the soil seems to modify some growth parameters of the plants of *Sesbania aculeata.* In fact, salinity has no significant effect on the above and below-ground biomass (Table 3) as well as on the growth in length and diameter of the Sesbania stems (Fig. 5). These results do not agree with the results obtained by Mahmood et al. (2008) who showed that the fresh and dry biomass of the stems and roots of *Sesbania sesban* gradually decreased with increasing levels of salinity. However, Ben Naceur et al. (2001) show that irrigation of wheat varieties with 4 g l^{-1} saline water does not significantly affect height growth.

The root part seems to be the most affected by salinity with a significant decrease in lateral branching (Fig. 6) and the inhibition of the formation of nodules fixing atmospheric nitrogen at 12 dS m^{-1} (Fig. 7).

Tests of *S.aculeata* under salinity conditions showed a particular resistance at the germinative stage rather than at the growth stage. Two uses of *Sesbania aculeata* can

Table 2 Growth parameters of *S. aculeata* under salt irrigation. In addition to the control (C0), C1, C2, and C3, respectively represent the Electrical conductivity of irrigation water: 6 dS m^{-1}, 12 dS m^{-1} and 18 dS m^{-1}

	C0	C1	C2	C3
Fresh matter (g)				
Roots	5.49 ± 1.72a	4.06 ± 2.04a	3.06 ± 1.28ab	1.28 ± 0.72b
Stems	4.95 ± 2.40a	7.03 ± 3.57ab	5.42 ± 2.86a	2.24 ± 1.32b
Leaves	5.54 ± 1.70a	7.78 ± 3.43a	6.08 ± 3.27a	3.93 ± 1.02a
Drymatter (g)				
Roots	0.83 ± 0.23a	0.88 ± 0.37ab	0.76 ± 0.36a	0.35 ± 0.18b
Stems	1.57 ± 0.62a	2.14 ± 1.06ab	1.63 ± 0.82a	0.71 ± 0.45b
Leaves	1.84 ± 0.52a	2.27 ± 1.06a	1.7 ± 0.86a	1.05 ± 0.32a
Number of leaves	14.82 ± 2.89a	20.17 ± 5.20b	16.38 ± 5.12ab	14.43 ± 3.01a
Length of the aerial part (cm)	28.79 ± 4.94a	27.26 ± 4.69a	19.59 ± 5.07b	14.08 ± 3.41c

For each plant part (line), the different letters indicate significant differences by the Tukey test at $P < 0.05$

Table 3 Variation of fresh and dry matter of *S. aculeata* under irrigation with saline water. C0: 1.5 dS m^{-1}; C1: 6 dS m^{-1} and C2: 12 dS m^{-1}

	C0	C1	C2
Fresh matter (g)			
Roots	136.02 ± 38.97a	110.51 ± 57.66a	70.91 ± 20.50a
Stems	307.45 ± 101.92a	306.18 ± 94.64a	228.58 ± 103.87a
Leaves	49.63 ± 2.31a	28.78 ± 21.31a	24.95 ± 12.96a
Dry matter (g)			
Roots	48.06 ± 16.10a	52.333 ± 28.716a	38.35 ± 3.19a
Stems	193.10 ± 62.98a	152.30 ± 52.24a	111.64 ± 41.74a
Leaves	15.47 ± 0.64a	18.03 ± 16.06a	12.17 ± 9.31a

For each plant part (line), the different letters indicate significant differences by the Tukey test at $P < 0.05$

be considered. The aerial part can be used as fodder during the summer period. In this sense, *Sesbania* can also be irrigated with water having a salinity of up to 12 dS m^{-1}. In order to increase the productivity of crops and for nitrogen enrichment of the soil, *Sesbania* can be irrigated with water having a salinity of 6 dS m^{-1}. So, cultivating the Fabaceae *Sesbania aculeata* during the summer season is a better option than bare fallow to maintain the soil nitrogen reserve and decrease nitrogen fertilization rates, not only in arid and semi-arid countries but also worldwide.

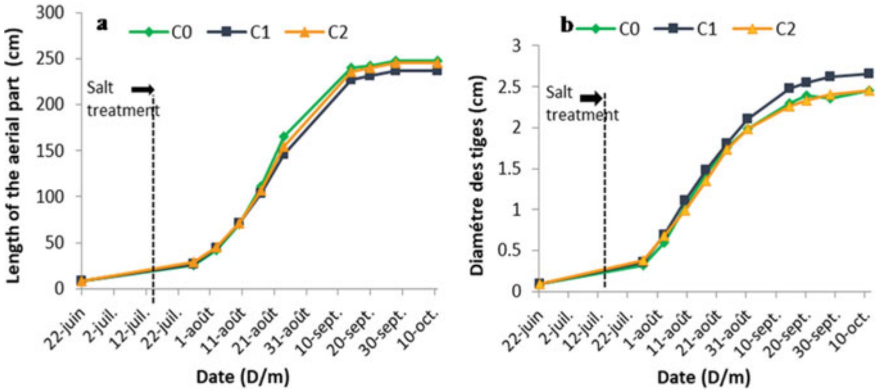


Fig. 5 Evolution of the growth (a: length; b: diameter) of the aerial parts of *Sesbania aculeata*. C0: 1.5 dS m^{-1}, C1: 6 dS m^{-1} and C2: 12 dS m^{-1}

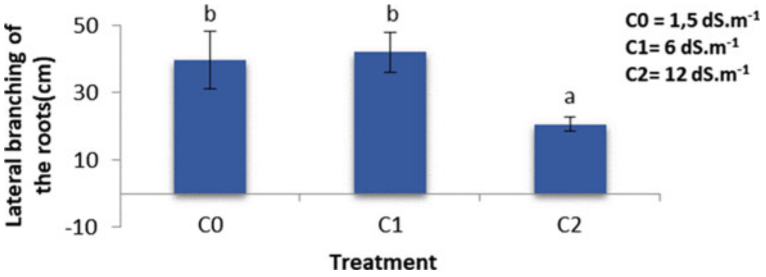


Fig. 6 Lateral branching of the roots of *Sesbania aculeate*

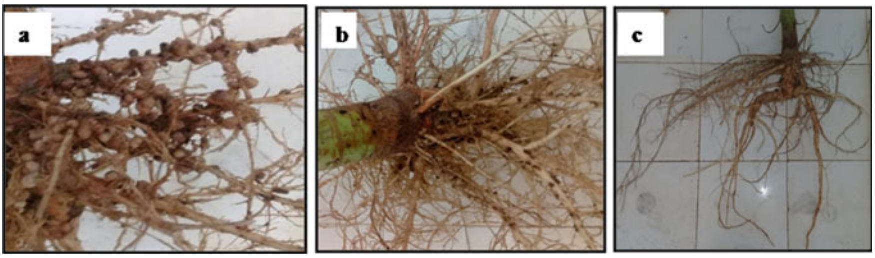


Fig. 7 Nodules on the roots of *Sesbania aculeata*. The roots show an abundance of nodules in the control C0 (**a**), a low number of nodules in C1 (**b**) and an absence of nodules in C2 (**c**). C0: 1.5 dS m^{-1}, C1: 6 dS m^{-1} and C2: 12 dS m^{-1}

3 Adapted Irrigation System Under Saline Condition

Water irrigation management is based on reducing salt accumulation in the active root zone and therefore the elimination of salt stress, especially during the critical growth stages of the plants (Minhas et al. 2020). To ensure proper water management, water distribution on irrigated land should be uniform by using the proper method of irrigation. Drip irrigation methods are regarded as superior in improving efficiency and crop production under saline conditions (Hanson et al. 2008; Minhas et al. 2020). With the purpose of improving salinity management and water use efficiency, an experiment (Kahlaoui et al. 2014) was conducted to study the effect of surface drip irrigation (DI) and subsurface drip irrigation (SDI) on three cultivars of tomato crop: Rio grande, Rio Tinto and Nemador under deficit irrigation levels of 85% and 70% and full irrigation. An increase in salinity was recorded under deficit irrigation levels of 70%. Results showed also a significant difference in the crop response to different treatments. Irrigation method with saline water affected the tomato growth (Fig. 8) of Rio Tinto and Nemador cultivars, in particular leaf area, dry and fresh matter, as well as chlorophyll contents and the mineral composition of leaves, stems, and roots. However, the effect on fruit quality was not manifested.

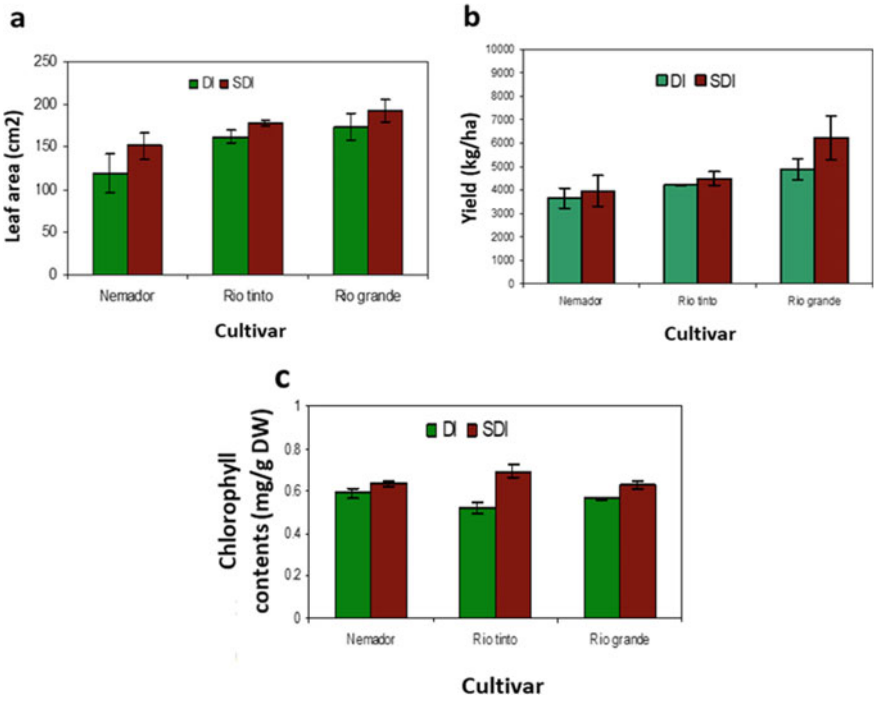


Fig. 8 Growth parameters variation among tomato cultivar and irrigation method (**a**: leaf area; **b**: yield production; **c**: chlorophyll content)

The accumulation of Na^+ and Cl^- was associated with a decrease in the contents of Ca^{2+}, K^+ and Mg^{2+} under DI irrigation treatment. The nutrient uptake, which affected by Na^+ and Cl^- accumulation, depends on mineral elements and tomato cultivar. Rio grande cultivar seems to be more suitable for water deficit under SDI. The more sensitive cultivar (Nemador) showed a low decrease in yield by SDI as a consequence of water efficiency improvement and saline stress reduction under using SDI.

4 Improving Crop Salinity Tolerance by Organic Substances: Proline

Proline (Pro) is an organic compound synthesized and accumulated in the cytosol and organelles of plants in response to salinity stress (Ashraf and Harris 2004; Sairam et al. 2006). It is also called a "compatible osmolyte" due to its accumulation in the plant without perturbing intracellular biochemistry (Sairam et al. 2006; Kahlaoui et al. 2016). Proline accumulation is considered as one of the adaptive plant mechanisms in response to salt stress and water deficit (Kumar et al. 2000; Ramajulu and Sudkakar 2000). Therefore, proline accumulation may be used as a clue for salt stress tolerance (Ramajulu and Sudkakar 2000). It has been reported that proline accumulation protects macromolecules against denaturation, contributes to osmotic adjustment, reduces cell acidity, acts as a storage compound and nitrogen source for an after-stress rapid growth, and protects plants against free radical-induced damage by quenching the oxygen single (Singh et al. 1973; Schobert and Tschesche 1978; Venkamp et al. 1989; Aziz et al. 1999; Teixeira and Fidalgo 2009).

Considering these findings, an experiment was conducted at Cherfech Station to investigate the effect of the exogenous application of two concentrations of proline on the physiological and biochemical responses of two cultivars of tomato irrigated and saline water ($EC = 6.57$ dS m^{-1}, $SAR = 12.8$) using subsurface drip irrigation (SDI) (Kahlaoui et al. 2012). The experiment was carried out, according to a randomized design with two factors (cultivar and Pro concentration), during the summer of 2009 (from 02/05 to 27/09). Two tomato cultivars (Solanum lycopersicum) were used: a salinity-tolerant cultivar, Rio Grande (Kahlaoui et al. 2011) and a salinity-sensitive cultivar, Heinz-2274 (Kahlaoui et al. 2012). Treatments were two exogenous applications of Pro (10 and 20 mg l^{-1}) and a control (without proline application) for each cultivar. Proline spraying was performed 6 times from 30% of the flowering state in June. It was shown that exogenous application of 10 mg l^{-1} of Pro was the most effective in promoting growth and productivity of both cultivars of tomato crops (Fig. 9) by increasing fresh and dry weight, leaf area, chlorophyll content, and improving mineral nutrition.

Exogenous applications increased proline accumulation, total soluble protein content, Guanine nucleotide-binding proteins (GS), and Guanylate kinase (GK) activities and decreased Proline Oxidase (PROX) activity. The increase due to proline

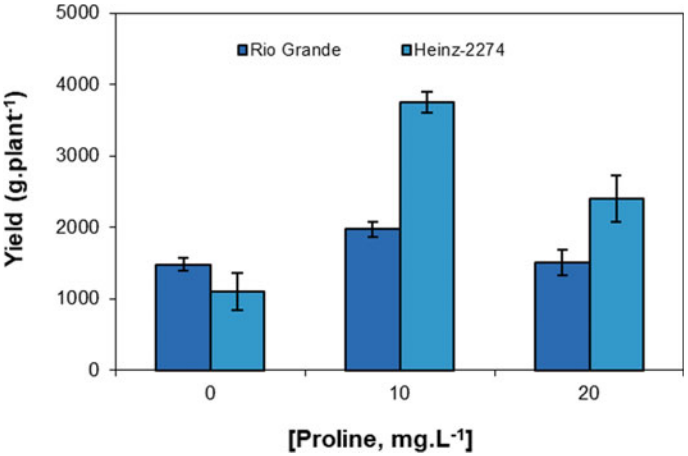


Fig. 9 Effect of the exogenous application of proline on tomato crop yield of two cultivars

accumulation was accompanied by a significant decrease in sodium and chlorine and the symptom of blossom-end rot. The increase of this physiological disease was the highest in the Heinz cultivar with a high concentration of Proline (20 g l^{-1}). With regard to the fruit quality, spraying with proline had no significant effect on acidity and on the total dissolved solids amount. In turn, the acidity raised in Heinz cultivar fruit at a high concentration of proline (20 g l^{-1}).

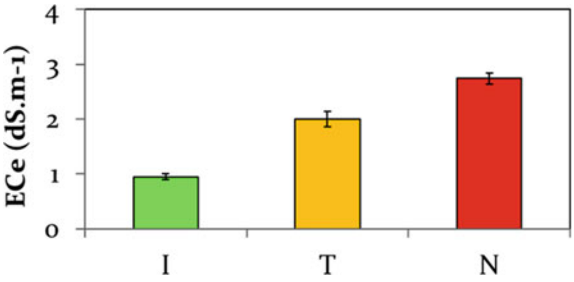
5 Reducing Water Salinity Effect by Electromagnetic Treatment

In order to improve yield production and manage low-quality soil and water, farmers of arid and semi-arid regions have been forced to implement innovative approaches. Among these approaches, some research studies have shown that magnetic/electromagnetic treatment (ET) of water can positively influence the growth parameters of various plant species and the soil properties (Esitken and Turan 2004; Turker et al. 2007; Selim and El-Nady 2011). The technology of water physical treatment by a magnetic/electromagnetic device that works with very low frequency and very low intensities permits to recreate a structure of natural and optimized water in its ability to dissolve and transport minerals (Hachicha et al. 2016).

In Tunisia, many electromagnetic and magnetic systems have been used by farmers for years, but research results on beneficial effects are still few. In this context, some studies were carried out, to evaluate the effects of the ET with Aqua-4D (Fig. 10) technology of saline water on the response of potato and tomato crops irrigated with saline water. Aqua-4D is a physical water treatment technology that acts on the structure of water, giving it properties that create a better dissolution and distribution

Fig. 10 Aqua-4D system used for experiments

Fig. 11 Effect of ET-treated water on soil salinity. I: initial; T: treated water; N: non treated water



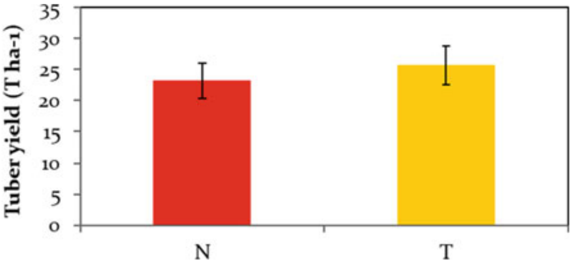
of minerals in the water, better water retention in the soil, and better adsorption of minerals by plants without destroying the bacterial soil life and promoting a balance between the different elements of the living soil (Hachicha et al. 2016).

The first experiment was conducted under greenhouse conditions and repeated for two seasons (Autumn 2011 and Spring 2012). Potatoes "*Spunta*" crops were cultivated and irrigated by water characterized by a salinity level of about 4 dS m^{-1} (3 g l^{-1}), pH of 8.4 and SAR of 7.4. At the end of the irrigation cycle, soil irrigated with electromagnetic-treated water showed a significant decrease in its salinity level (Fig. 11).

ET of saline water increased yield production (25.7 T ha^{-1}) by about 11% as compared to untreated water (23.2 T ha^{-1}), with a slight improvement in the commercial volume (45 mm) (Fig. 12). Result showed also a slight increase on tuber caliber (>45 mm).

To test the performance of ET on water quality a pot experiment was carried out in a greenhouse. Soil was irrigated with saline water, treated, and non-treated at different salinity levels (1, 4.5, 9, 13.5 and 18 dS m^{-1}). After one irrigation cycle, volume and electrical conductivity salinity of drained water were measured. As presented in Fig. 13, the volume and salinity of drained water from treated water showed to be higher than the volume of drained and salinity water from untreated water.

Fig. 12 Effects of electromagnetic treatment of saline water on tubers yield of potato. N: non-treated water; T: treated water



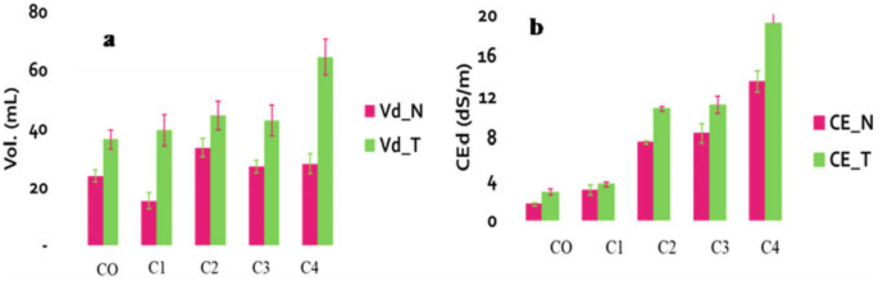


Fig. 13 Variation of volume (vol. a) and electrical conductivity (CEd, b) of drained water under electromagnetic treatment of saline water (CO: 1 dS m^{-1}; C1: 4.5 dS m^{-1}; C2: 9 dS m^{-1}; C3: 13.5 dS m^{-1} and C4: 18 dS m^{-1})

ET of saline irrigation water can be considered an effective method for soil desalinization. It has been reported that magnetic treatment of water decreases the hydration of salt ions and colloids, has a positive effect on salt solubility, and accelerates coagulation and salt crystallization (Hillal and Hillal 2000). It, consequently, increased the leaching of excess soluble salts, lowered soil alkalinity, and dissolved slightly soluble salts (Abedinpour and Rohani 2017). In this experiment soil water content and salinity were evaluated to test the beneficial effect of ET saline water on soil properties.

Soil irrigated with ET saline water showed a significant increase in its moisture (Fig. 14).

According to Surendran et al. (2016), irrigation with magnetized irrigation water caused higher soil moisture compared with the control for different solutions of saline and hard water.

The soil electrical conductivity (ECe) decrease was significant under irrigation with ET saline water as compared to non-treated water (Fig. 15).

Results revealed that the ET duration had also a significant effect on soil salinity (Fig. 16). Indeed, it helps to reduce salt accumulation and improve soil conditions around the plant's roots. The total removal of salts from the soil with electromagnetic water was greater than from untreated water.

ET water removes excess soluble salts and leaches salts further than the root zone (Aloutifi 2013; Mahmoud et al. 2019).

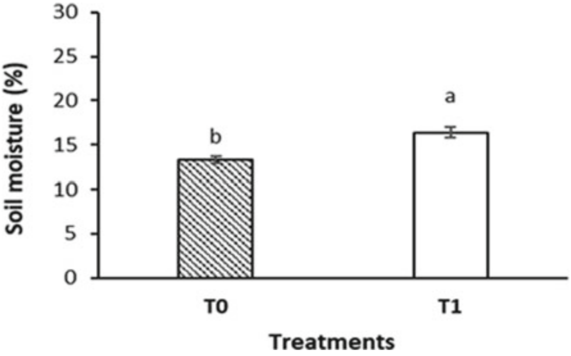


Fig. 14 Variation of the soil moisture (%) according to the treatment of irrigation water. T_0: untreated irrigation water; T_1: electromagnetically treated irrigation water

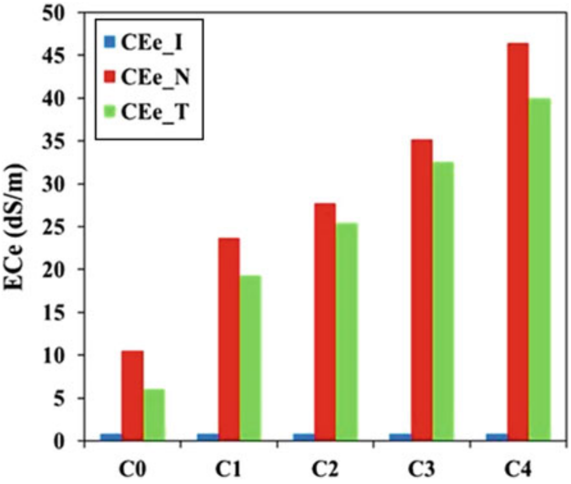


Fig. 15 Effect of electromagnetic treatment of saline water on soil electrical conductivity (ECe). CEe_I: initial soil salinity; CEe_N: Salinity of soil irrigated with nontreated water and CEe_T: Salinity of soil irrigated with treated water

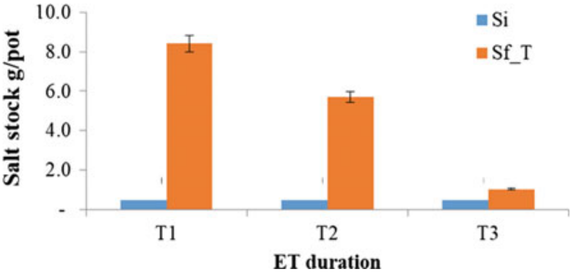


Fig. 16 Variation of salt stocks according to the duration of the ET. T1: water treatment duration of 5 min; T2: water treatment duration of 15 min; T3: water treatment duration of 30 min; SI: initial salt stocks; Sf_T: salt stocks after treatment

6 Conclusion

Water and soil salinity are the major factors limiting crop production and natural resources sustainability, especially in arid semi-arid regions including Tunisia. Based on the importance of facing salinity problems, many research projects covering some Tunisian regions are conducted to evaluate different adopted management strategies and performances in improving crop production under salt and drought conditions. Research studies related to soil salinity control (1) cultivation of alternative and tolerant-salt varieties such as new cultivars of the olive tree, Quinoa, Jatropha, *Sesbania,* and *Aloe vera*, (2) irrigation water management by using DI and SDI, (3) improvement of crop tolerance to salinity by exogenous application of proline substances and (4) the use of innovative technology systems such as Aqua4-D for ET of saline water. The results indicated the beneficial effects of different management strategies on the growth and yield of crops, on soil and water properties, and the tolerance of the majority of alternative crops to salinity and drought conditions, which confirmed the possibility of using low-quality water for agriculture. Further studies are required for more salinity assessment by the development of new tools, and more adaptation of biotechnology techniques in order to limit the salt stress effect and it will be important to better understand the mechanism of the magnetic field in order to turn it into a technology for sustainable farming.

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Chapter 4
Soil and Nutrient Management Under Saline Conditions

Munir Jamil Rusan

Abstract Salt-affected soils are common in arid and semiarid environment and in irrigated agriculture. Soil salts have detrimental adverse impacts on soil's physical, chemical, and biological properties. Plants grown on salt-affected soils usually suffer from water shortage and nutrient deficiencies rendering them to grow under drought, low fertility, salinity, and ions-specific toxicity stresses. Salt-affected soils are very vulnerable and susceptible to climate change and environmental stresses, therefore, proper and integrated management of agricultural inputs including soil and nutrients is crucial for developing a sustainable and efficient farming system. Integrated soil and plant nutrient management combines both 4R nutrient stewardship, which is defined as the application of the right source, right rate, right time, and right place of nutrient application and conservation practices and is considered the most appropriate strategy for developing a sustainable farming system in salt-affected soils. Soil and nutrient management of salt-affected soils includes both reclamation processes and adaption of best agricultural management practices such as leaching of salts, replacing exchangeable Na with exchangeable Ca, maintaining mulch cover on the soil surface to reducing evaporation and limiting the capillary rise of saline water from the water table, use appropriate leaching requirement, irrigation scheduling, method of irrigation, quality of irrigation water, salt-tolerant crop/variety, and bed shape. Organic amendments also improve soil structure and facilitate salt leaching.

Keywords Salinity · Soil management · Nutrient management · 4R nutrient stewardship

1 Introduction

Soil salinity is a common term referring to the accumulated soluble salts in the soil and/or to the relative increase in the exchangeable sodium compared to calcium and magnesium at the exchange sites of the soil. It is more accurate to refer to the

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soils affected by these salts as ‘salt-affected’ soils, which are further categorized and classified into saline soils, sodic soils, and saline-sodic soils (Table 1). The saline soils are characterized by high concentrations of soluble salts, sodic soils are characterized by a high percentage of sodium adsorption ratio (SAR), while the saline-sodic soils are characterized by high levels of both soluble salts and sodium.

The sources of Salts and Salinization Processes include (Havlin et al. 1999):

- Old geologic saline layers: Naturally occurring processes: salt lakes, Dead Sea
- Mineral weathering without leaching
- Rising water table infuses the root zone with salts:
    - Plant water uptake will move and accumulate salts near surface
    - Upward movement with capillary water from groundwater
- Irrigation with saline water—Irrigation salinity
- Improper Management of Irrigation and Fertilization.

Salt-affected soils are common and are a widely recognized problem in arid and semiarid environments and in irrigated agriculture and they have become the most severe problem facing the world agriculture production system (Rus and Guerrier 1994; Rusan et al. 2003). The scarcity of water resources in most countries of the arid and semiarid regions has led many farmers to use poor-quality water for irrigation. Considerable amounts of such marginal water are available and can be successfully used for irrigation under proper management (Rusan 2018). However, using such marginal water for irrigation became an additional cause for the salinization of soil in these countries. Moreover, soils developed under arid and semiarid conditions are generally low in organic matter, alkaline in reaction, mostly calcareous, and in many cases saline and/or sodic (Rusan et al. 2003). This makes these soils very vulnerable and susceptible to climate change and environmental stresses (Rusan 2018). Therefore, proper and integrated management of agricultural inputs including soil and nutrients under saline conditions is crucial for developing a sustainable and efficient farming system (Rusan 2011).

Soil salts have a detrimental adverse impact on soil’s physical, chemical, and biological properties (Rusan et al. 2003). High concentration of soluble salts can reduce the availability of soil water and nutrients and severely inhibits their uptake by the plant. Moreover, the high percentage of exchangeable soil sodium has a detrimental impact on the soil’s physical properties and causes soil dispersion. This leads

Table 1 Classification of salt-affected soils and their main properties (Havlin et al. 1999)

Classification	EC (dS/m)	Soil pH	SAR (% Exch. Na)	Physical conditions
Saline	>4	<8.5	<15	Normal
Sodic	<4	>8.5	>15	Poor
Saline-Sodic	>4	<8.5	>15	Normal

to poor soil structure, poor water permeability, and infiltration in the soil (Arunin and Pongwichian 2015).

Plants grown on salt-affected soils usually suffer from water shortage and nutrient deficiencies rendering them to grow under drought, low fertility, salinity, and ions-specific toxicity stresses (Rusan et al. 2003). This comprises the main damaging impact of salinity on plant growth. In addition, the accumulation of toxic levels of various ions within the plants, even when the total concentration of salts is low can be detrimental to plant growth. It has been reported that the damaging effects of salinity on plant growth happen through physiological water availability (Al Karaki 2000; Lloyd et al. 1987) and the accumulation of toxic levels of various ions within the plants (Ali et al. 1993). A linear decrease in tomato plant dry matter production and total water content was reported by Al-Rawahy et al. (1992) with increased salinity.

Excess salts reduce nutrient availability and cause nutrient deficiency. A high concentration of salts in the soil solution increases the ionic strength of the soil solution. This will lead to higher and strong interaction among nutrients which will lower nutrient availability, such as the interaction between Cl and NO_3, P and micronutrients (Fe, Zn, Mn), K and Ca and Mg (Rusan 2018; Rusan 2017a, 2017b).

Nutrient uptake is actually a function of ion or nutrient activity in the soil solution and not of its concentration, which can be demonstrated by the following relationships (Havlin et al. 1999) and as shown in Fig. 1:

$$a_i = \Upsilon_* C_i \tag{1}$$

$$\mu = 1/2 \sum_i^n C_i Z_i^2 \tag{2}$$

$$Log\gamma_i = -AZi^2\left[\frac{\sqrt{\mu}}{1+\sqrt{\mu}} - 0.3\mu\right] \tag{3}$$

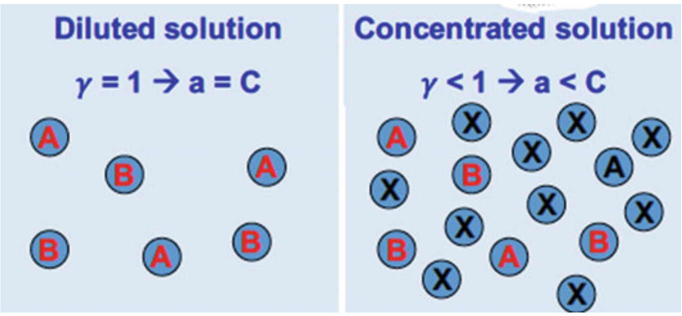


Fig. 1 Nutrient interaction in root zone

where a = activity; c = concentration; γ = activity coefficient; μ = ionic strength; z = ion charge; A = constant.

According to these relationships, the activity of the nutrient will be equal to its concentration only in diluted solution where the activity coefficient (γ) will equal one and thus a = c. Under normal field conditions, the soil solution will have some salts dissolved in it. The higher the salt concentration the lower the activity coefficient and thus the lower the availability of the nutrient to the plant.

However, plants differ in their tolerance to soil salinity, whereas tolerant crops have developed physiological and biochemical mechanisms for salt tolerance. Plants grown under saline conditions cope with salinity through several mechanisms, which have been proposed to improve salt tolerance in sensitive plants (Abdelrahman et al. 2005; Cano et al. 1996; Gisbert et al. 2000; Rus et al. 1999). These mechanisms involve the accumulation of solutes to balance osmotic adjustment and/or osmoprotection of intracellular components (osmotic adjustment and ion compartmentalization and/or biosynthesis of compatible solutes). These include betaine (Pan et al. 1991), free amino acids (Cano et al. 1996), soluble carbohydrates (Qaryouti 2001), and proline (Al Karaki et al. 1996; Huang et al. 2009; James et al. 2008). Osmotic adjustment in the cell lines occurred as a result of the accumulation of Na^+ and Cl^- with the maintenance of adequate intracellular levels of K^+. The maintenance of adequate intracellular K^+ levels is indicative that K^+ deficiency is not responsible for the inhibition of cell expansion and may indicate that membrane K^+ /Na^+ selectivity adaptations have occurred in the salt-adapted cells to facilitate K^+ uptake (Cramer et al. 1985). It is well documented that salt stress causes, at least in part, some of the cellular oxidative damage. Osmotic adjustment in the cell lines may occur as a result of the accumulation of Na^+ and Cl^- with the maintenance of adequate intracellular levels of K^+ (Rusan et al. 2003).

Tomato shoot and fruit physiological responses to salt stress conditions have been extensively investigated (Cruz et al. 1990; Mitchell et al. 1991; Niedziela et al. 1993). However, information on the effect of salinity on root growth is limited (Snapp and Shennan 1994). Studying the salinity effect on root growth and senescence in tomatoes, Snapp and Shennan stated that conventional observations of root length are not adequate and observing root system architecture should be considered. Root morphology parameters are important criteria for crop growth and responses to water and salt stress conditions. However, these parameters are often not determined due to difficulties associated with their measurements. Better methods for measuring root morphology parameters (root length, root surface area root diameter) are needed (Baker 1989). In this study, edge discrimination analysis using the desktop scanner was used to measure the root morphology (Pan et al. 1991). The objective of this study was to evaluate the root and shoot response of tomatoes to salt stress conditions under different levels of P nutrition.

Salt-affected soils are very vulnerable and susceptible to climate change and environmental stresses, therefore, proper and integrated management of agricultural inputs including soil and nutrients is crucial for developing a sustainable and efficient farming system (Rusan 2018). Integrated soil and plant nutrient management combines both 4R nutrient stewardship and conservation practices and is considered the most appropriate strategy for developing a sustainable farming system in salt-affected soils (Rusan 2018).

General requirements for soil and nutrient management of salt-affected soils include the following implementation of the reclamation processes and adaption of best agricultural management practices (Rusan 2017a, 2017b; Samuel et al. 1993):

- Leaching of soluble salts out of the root zone
- Replacing exchangeable Na with exchangeable Ca by adding gypsum (Gharaibeh et al. 2014)
- Maintaining mulch cover on soil surface to reduce evaporation and limit capillary rise of saline water from the water table
- In lowland areas, leveling the land to reduce ponding
- Use appropriate leaching requirements, irrigation scheduling, method of irrigation, quality of irrigation water, salt-tolerant crop/variety, bed shape
- Apply organic amendments to improve soil structure and facilitate salt leaching
- Supplying Ca and Mg to improve soil structure
- Adapt the 4R Nutrient Stewardship approach for nutrient management, that is apply the right source, rate, time, and placement of nutrient application (IPNI 2013)
- Phosphorus has been recognized to enhance root growth (Samuel et al. 1993) and it was found that plant root growth under drought conditions was stimulated by localizing the P fertilizers in the root zone (Rusan et al. 1998). This effect on root growth may enhance the performance of crops grown in saline conditions.

2 Management of Salt-Affected Soil

An integrated management approach should be adopted for sustainable management salt-affected soil. The approach includes both conservation practices and 4R nutrient stewardship to optimize effectiveness of the farming system (Fig. 2).

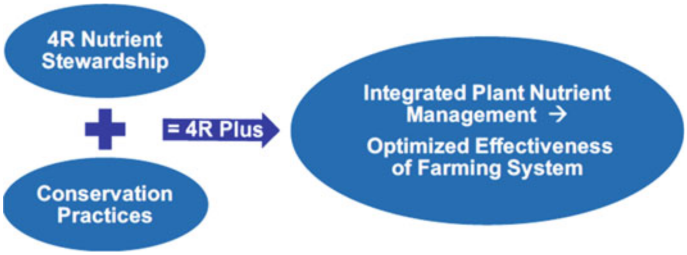


Fig. 2 Integrated management approach

Salt-affected soils can be managed by getting rid of the salt from the soil and leach them down from the soil profile (or at least from the root zone). This can be achieved through amelioration or reclamation of the salt-affected soil (Havlin et al. 1999). In the case of saline soil, this can be achieved through leaching the salts by application good quality water in an amount to leach the salt below the root zone. In case of the sodic soil and saline-sodic soil this can be achieved by fort replacing Na from the soil exchange sites with Ca by applying the gypsum ($CaSO_4$) and then leaching them with good quality water: Na-Soil + $CaSO_4 \rightarrow$ Ca-Soil + $Na^+ + SO_4^{2-}$ (Havlin et al. 1999). If the soils are calcareous, then Na can be replaced by Ca by the application of elemental sulfur which will form $CaSO_4$ by reacting with the indigenous $CaCO_3$ as shown in the following reactions (Gharaibeh et al. 2014):

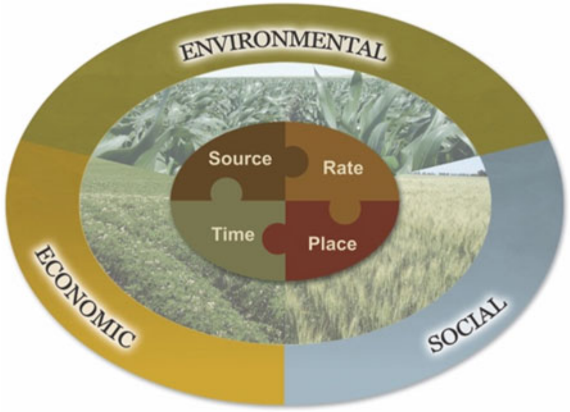
$$2S + 3O_2 + 2\,H_2O = 2\,H_2SO_4$$
$$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$$
$$2\text{Na-Soil} + CaSO_4 \rightarrow \text{Ca-Soil} + Na_2SO_4$$

One should be careful not to leach or irrigate the saline-sodic soil with good quality water before getting rid of sodium as this will result in forming a sodic soil which will be more difficult to reclaim.

Another approach to manage salt-affected soils is to adopt the best agricultural management practices, which include soil management, nutrient management crop management, and nutrient management (Rusan 2018; IPNI 2013). The following practices are recommended for managing such soils (Havlin et al. 1999; Rusan 2017a, 2017b):

- Keep good soil structure with appropriate tillage and organic amendments
- Subsoiling and Deep tillage: Deep tillage interrupts capillary rise from groundwater
- Mulching: Cropping cover and Plastic cover (Picture 1)
- Phytoremediation: crops with shallow and deep roots, crops with high capacity to absorb salt
- Appropriate planting geometry and bed shape
- Salt accumulation depends on bed shape and irrigation method.
- Adaption of Integrated Plant Nutrient Management, which includes both the 4R Nutrient Stewardship approach and conservation practices (Rusan 2018; Rusan 2017a, 2017b; IPNI 2013).

Picture 1 Mulching by plastic cover



Picture 2 Logo of the 4R Nutrient stewardship

3 4R Nutrient Stewardship for Nutrient Management Under Saline Conditions

The 4R Nutrient Stewardship approach implies the application of nutrients using the right sources, at the right rate, at the right time, and in the right place and meets the goals of sustainability (IPNI 2013) (Picture 2).

3.1 Selecting the Right Source of Nutrients Under Saline Conditions

Selecting the right source of nutrients under saline conditions should consider the following: Firstly, one should use fertilizers with low salt index: (Table 2).

- Use of slow-release fertilizers → has a lower salt effect

Table 2 Salt index of fertilizers

Material and analysis	Salt index (sodium nitrate = 100)	
	Per equal weights of material	Per unit (lb) of plant nutrients
Nitrogen		
Ammonium nitrate, 34% N	105	3
Ammonium sulfate, 21.2% N	69	3.3
Calcium nitrate, comm. grade, 15.5% N	65	4.2
Sodium nitrate, 16.5% N	100	6.1
Urea, 46.6% N	75	1.6
Nitrate of Soda Potash, 15% N, 14% K_2O	92	3.2
Natural organic, 5% N	4	0.7
Phosphate		
Normal Superphosphate, 20% P_2O_5	8	0.4
Concentrated Superphosphate, 45% P_2O_5	10	0.2
Concentrated Superphosphate, 48% P_2O_5	10	0.2
Monoammonium phosphate, 12% N, 62% P_2O_5	30	0.4
Diammonium phosphate, 18% N, 46% P_2O_5	34	0.5
Potash		
Potassium chloride, 60% K_2O	116	1.9
Potassium nitrate 13% N, 46% K_2O	74	1.2
Potassium sulfate, 46% K_2O	46	0.9
Monopotassium Phosphate, 52% P_2O_5, 34%K_2O	8	0.1
Sulfate of potash-magnesia, 22% K_2O	43	2

Note N and K fertilizers have a higher salt index than P fertilizers, so salt damage is more likely when using these fertilizer formulations

- Use Organic Fertilizers
    - o Organic fertilization enhances soil fertility and OM:
    - o OM Mineralization releases humic substances, which:

        Improve soil phosphates and micronutrients availability due to acidification, chelation and
        prevent adsorption by coating calcite surface (Rusan et al. 2003)

    - o OM increases CEC which increases exchangeable-K^+, which is a competitor of Na^+, thus, preventing Na + into the exchange complex. Besides, K^+ is important to maintain turgor pressure of plants under salinity stress (Rusan et al. 2003; Rusan 2011; Rusan 2017a, 2017b)
    - o OM is a slow release of nutrients
    - o OM improves physical and microbiological properties of the soil
    - o OM supplies proline which enhances plant tolerance to salinity
    - o Growing legumes and using green manure has a similar effect as organic manure.
- Use Biofertilizers / Bioremediation. For example, the application of the Mycorrhizal inoculum will (Rusan 2018):
    - o Enhance plant survival stress condition
    - o Act as bioremediation and/or phytoremediation
    - o Enhance nutrient uptake efficiency by enhancing the plant to uptake nutrients from soil solution even when their concentrations are very low. This can be shown by decreasing the Cmin and Km which are the two parameters in the kinetic of nutrient absorption according to the Michalis and Menten equation (Fig. 3)
    - o Note that, Cmin refers to the minimum concentration below which no absorption, while Km refers to the concentration in the solution at 50% of the maximum velocity of absorption.

3.2 Selecting the Rate and Time of Nutrient Application Under Saline Conditions

It is important to apply the right rate of nutrient application to make sure the crop is receiving the required amount of nutrients, while avoiding excess. The right rate is necessary to avoid the application of excess fertilizer at one time which may cause salt damage, unnecessary fertilizer cost, reduce profitability and adverse impacts on natural resources, and accumulation of nutrients in agricultural products above acceptable levels.

Timing nutrient application when the nutrients are needed by the crop is critical to maximizing nutrient uptake and recovery efficiency and minimize nutrient losses

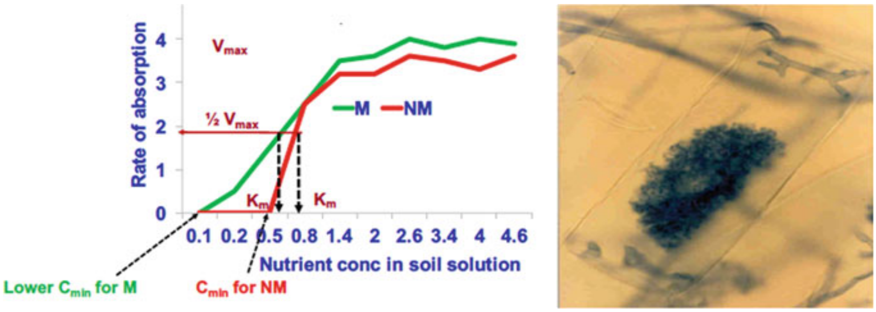


Fig. 3. Absorption of P from mycorrhizal and non-mycorrhizal plant under P-deficient soil (The photo, courtesy Rusan 2018, shows the arbuscular, which is a mycorrhizal organ developed inside the cell and acts as an exchange site for nutrients and assimilates between the host and the mycorrhizae) (Rusan 2003; Rusan 2017a, 2017b)

to the environment. Selecting the right time is a crop and site-specific management practice and depends on the local soil and climatic conditions, and on the type of crops and cropping system. For example, in coarse-textured soils, the nutrients are applied more frequently and in small doses to minimize losses by leaching. Phosphorus demand is high during the early growth stages and therefore, farmers should ensure the P is available during early growth stages. For most of the annual crops, highest nutrient uptake occurs during the flowering stage. For example, the highest uptake by a tomato crop occurs during the late vegetative and flowering stages. The uptake of nitrogen and potassium is initially slow, followed by a rapid increase during the flowering stage. Potassium uptake peaks during fruit development. The uptake rate of phosphorus and secondary nutrients (Ca and Mg) is relatively constant during the growing season for the tomato crop.

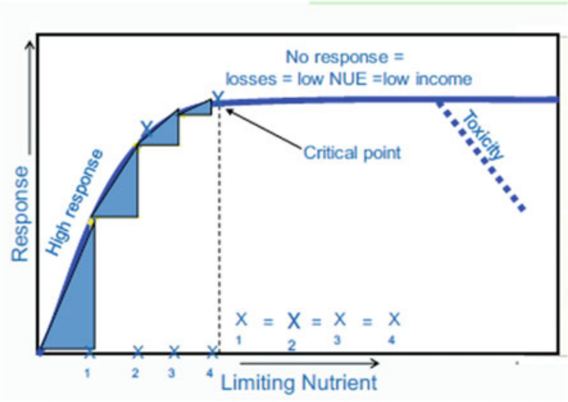
In general, the following should be considered when selecting the right rate and time of nutrient application.

- Consider Crop Characteristics and crop nutrient requirements for each growth stage
- Consider the rate that achieves the Maximum economic and ecological yield following the law of the diminishing return (Fig. 4)
- Consider the Right Frequency of Fertilization under irrigation, that is consider the right rate and right time of application of both water and nutrients (Rusan 2018). As shown in Fig. 5, if irrigation water was applied without fertilizer application, then the salinity level will remain about the EC of the irrigation water or 1 dS/m. If we fertigate in each irrigation, then the application of nutrients will raise the EC to 2 dS/m, and thus the EC in the root zone will be about 2 dS/m, or 4 dS/m if we fertigate on every second irrigation. In the following irrigation, there will be no fertilizer application and thus the EC would be the same as the EC of the irrigation water, which is 1 dS/m. In another case where the farmer needs to fertigate every 4th irrigation, then the fluctuation in the EC of the irrigation water and therefore the EC in the root zone will vary from 1 dS/m during the first three irrigation

events and 7 dS/m during the 4th irrigation event where the nutrient application rate will be 4 times more compared to the rate with every irrigation. It is well known that most crops grown under saline conditions tend to physiologically adjust to high levels of salinity (Physiological adjustment). However, in the case of low fertigation frequency such as fertigation with each 4th irrigation, the crops will be subjected to salt shocks by exposing them to very high salinity levels (7 dS/m). This will interrupt the process of physiological adjustment by, and cause salt damage to, the crop.

- Consider the right management of irrigation, that is select the right method of irrigation, the right quality of irrigation water (IW), the right irrigation scheduling/frequency, and the right leaching fraction. The salinity can be controlled by using the right leaching fraction (LF) (Samuel et al. 1993), which can be estimated for a particular crop using the LF equation:

Fig. 4. Law of the diminishing return



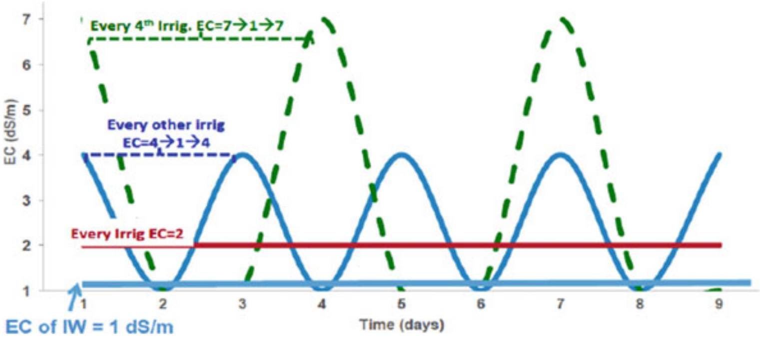


Fig. 5. Frequency of application of irrigation war and fertilizers under saline conditions (Rusan 2018)

$$LF = \frac{EC_w}{5(EC_e) - EC_w}$$

where;

LF = Min. LF needed to control salts within the crop tolerance (EC_e).
EC_w = Salinity of the IW in dS/m.
EC_e = Soil salinity of saturated extract tolerated by the crop.

Crop management under saline conditions should include the following:

- Select the salt-tolerant crops (species, varieties, cultivars)
- Select the crops with a high capacity to absorb and accumulate salts (Phytoremediation)
- Selecting the right plant geometry where growers should place the seeds or seedlings in the soil parts away from salt accumulation.
- Alternate planting deep and shallow root crops.

3.3 Selecting the Right Place for Nutrient Application

Proper placement of fertilizer has several benefits such as enhancing fertilizer use efficiency, reducing losses, enhancing seed germination and emergence, improving plant establishment, increasing yields, and improving the quality of crop production. Selecting the right place for fertilizer application plays a major role in enhancing the positional availability of the applied nutrients and in nutrient uptake. This is of more importance in the soil where the potentials for nutrient fixation, leaching, and volatilization are high. In fertigation, it is the wetted soil zone where the roots are most active and fertilizers must be placed within this small wetted soil volume to avoid being placed in dry soil and not available by plant roots.

Applied fertilizers are placed close to the roots, therefore, application of higher than recommended rates might induce a fertilizer burn and potentially inhibit root growth especially under saline conditions (Rusan 2018). Thus, one should consider placing the fertilizer at a rate not harmful to the root zone as such a zone is very small under drip irrigation, which is the common method of irrigation under saline conditions (Fig. 6). In other words, if the nutrient is located in a place where the roots cannot reach, or they are too far to be transported by mass flow, diffusion, or interception, then this nutrient is considered positionally not available and not bioavailable. This clearly illustrates the importance of the right place for fertilizer best management practices. In general, for selecting the right place for nutrient application growers should consider the method of irrigation, type, and geometry of the root system, soil physical and chemical properties, dynamic of nutrients in the soil, mechanisms of nutrient movement, and as well as the source, rate and time of nutrient application (Rusan 2018).

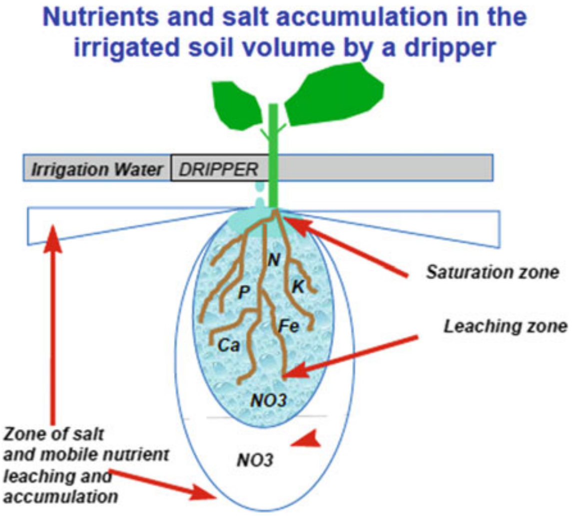


Fig. 6. Nutrient and salt accumulation in the irrigated soil volume by a dripper (Rusan 2018)

4 Conclusion

To properly and sustainably manage salt-affected soils and sustainable farming system, one should adopt the integrated management approach of agricultural inputs in particular the application of irrigation water and fertilizer. Such an approach will also integrate the 4R nutrient stewardship and conservation practices. The selection of the right source of irrigation water and of fertilizers in the right combination with the right selection of the right rate of application, and right time of application will ensure the sustainable management of salt-affected soils. Parallel to this approach, pressurized and localized irrigation methods should be adopted to minimize the negative impact of soil salinity. Such a method facilitates localized leaching of the salts from the root zone during the growing season, which is a practical approach to leach salt in areas of scarcity of water resources such as those that prevailed in the arid and semiarid regions. In the case of sodic soil, the replacement of exchangeable sodium with calcium is a prerequisite for the successful reclamation of sodic soil. To meet the main objective of farmers, it is highly recommended to grow salt-tolerant crops to ensure an acceptable level of income for the farmers. Since reclamation of salt-affected soils is in many cases expensive, the government should be involved either in subsidizing the farmers' plan for reclamation of their salt-affected soil or taking this task by itself.

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Chapter 5
Prospects of Alternative Agricultural Systems to Improve the Productivity of Marginal Lands in Ethiopia

Asad Sarwar Qureshi, Tesfaye Ertebo Mohammad, and Melese Minaleshoa

Abstract Agriculture is an essential sector in Ethiopia, like in many other sub-Saharan African countries. The agriculture sector in Ethiopia supports 80% of the workforce, whereas 85% of the total population is directly or indirectly attached to agricultural activities to earn their living. Ethiopia's 7 million smallholder farmers are responsible for producing more than 95% of the total agricultural outputs, including food crops, cereals, oilseeds, and pulses. Cotton and sugarcane are mainly grown in state-owned large-scale enterprises. Ethiopia also has significant livestock capital, i.e., cattle, sheep, goats, and camels. Despite this high biodiversity and distinctive ecosystems, food shortages are widespread, and there have been recurrent droughts and subsequent food crises since the 1970s. Today, Ethiopia stands first in Africa in the magnitude of salt-affected soils due to human-induced and natural causes. Current estimates imply that 11 million ha are exposed to salinity and sodicity. Therefore, restoration and rehabilitation of these soils are of critical importance to ensure food security. The restoration of salt-affected soils through engineering techniques such as installing drainage systems is costly and time-consuming. Therefore, the 'biosaline approach' could be an effective and economical approach to tackle this problem. The Biosaline approach is based on adaptable technology packages composed of salt-tolerant fodders and halophytes integrated with livestock and appropriate management systems (on-farm irrigation, soil fertility, etc.). These integrated crop and forage-livestock feeding systems have the capacity to increase the resilience of small-scale crop-livestock farms. This chapter discusses the causes and extent of salinity development and its socio-economic impacts on the livelihood of people in Ethiopia. Furthermore, this chapter recommends a wide variety of salt-tolerant crops that can be used to improve the agricultural productivity of salt-affected lands. The adoption of these feed and fodder species can be a game-changer for improving the livelihood of smallholder farmers living in the marginal lands of Ethiopia.

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Keywords Salt-affected lands · Biosaline approach · Salt-tolerant species · Environment · Smallholder farmers

1 Introduction

Irrigated agriculture is challenged by increasing soil salinity problems (Ventura and Sagi 2013; Hasanuzzaman et al. 2014). According to recent estimates, about one billion ha (Bha) land is salinized, which is about 7% of the earth's land surface (Table 1). Currently, about 33% of the irrigated area (76 Mha) is affected by soil salinization, and more than 50% of the farms around the world are expected to be salinized by 2050 (Jamil et al. 2011; Kumar and Shrivastava 2015). Salt-affected soils are increasing at the rate of 1.0–2.0 Mha per year (Omuto et al. 2020). The lack of good-quality irrigation water exacerbates soil degradation in many arid regions (Hopmans et al. 2021).

The soil salinity problems in semi-arid and arid regions are caused by low rainfall and lack of irrigation water, which restricts the leaching of salts. Salt-affected soils are more widespread in northern Africa, South Africa, Botswana, and tropical Africa (Senegal, Mauritania, Upper Volta, Chad, north of Cameron, Swaziland, Malawi, Kenya, Zambia, southern Angola, and southern Mozambique) (Tully et al. 2015) (Table 2). Some countries such as Zaire, Congo, Gabon, Ivory Coast, and Liberia are virtually free of saline soils.

An estimated 11 million hectares in Ethiopia are salinized (Kidane et al. 2006; Gedion 2009; Frew 2012; Ashenafi and Bedadi 2016) (Table 2). This relates to 9% of the total land area and 13% of the irrigated area of Ethiopia (Birhane 2017). Most of these salt-affected soils are in the Rift Valley, Wabi Shebelle River Basin, the Denakil Plains, and other lowlands and valleys, which are home to 9% of the total population (Sileshi 2016).

The primary sources of salts in the rift valley are the gradual rise of the groundwater table caused by the development of large irrigation schemes in the Awash Valley

Table 1 Distribution of salt-affected soils in different regions of the world

Continent/region	Area (Mha)		
	Saline	Sodic/Alkali	Total
North America	6.2	9.6	15.82
Mexico and Central America	2.0	–	2.0
South America	69.5	59.8	129.2
Africa	122.9	86.7	209.6
South Asia	83.3	1.8	85.1
North and Central Asia	91.6	120.0	211.6
Southeast Asia	20.0	–	20.0
Australia	17.6	340	357.6
Total	413.1	617.9	1,031

Table 2 Salt-affected soils in the top 10 African countries (1,000 ha)

Countries	Saline	Sodic	Total
Algeria	3,201	129	3,150
Botswana	5,009	670	5,679
Chad	2,417	5,850	8,267
Egypt	7,360	–	7,360
Ethiopia	10,608	425	11,033
Kenya	4,410	448	4,858
Libya	2,457	–	2,457
Mali	2,770	–	2,770
Nigeria	665	5,837	6,502
Somalia	1,569	4,033	5,602

without appropriate drainage systems. The high evapotranspiration rates are another reason for salinity development in these areas (Frew 2012). The increasing salinity problems in Ethiopia are causing substantial crop losses and the abandonment of farmlands in many regions (Gebremeskel et al. 2018).

The increasing demand for food in Ethiopia is pressing to take contingent measures to rehabilitate and manage saline soils. In Ethiopia, minimal data and information are available on salt-affected soils' causes, extent, and spatial distribution. This chapter presents the available information on salt-affected soils, which can help develop workable strategies for rehabilitating and managing saline soils in Ethiopia.

2 Sources, Causes, and Distribution of Salt-Affected Soils

2.1 *Characterization of Salt-Affected Soils*

The build-up of soluble salts is the most critical factor in forming saline soils in areas where evaporation exceeds precipitation (Cooke et al. 1993). The sources of salts include saline parent materials, fossil salts of former marine and lacustrine deposits, atmospheric deposition, collection of saline sediments in catchment areas, irrigation waters, and fertilization. However, an excessive salt build-up occurs due to the evaporation of irrigation water from the surface and the shallow depths of soils, leaving the salt behind. Based on the USDA classification (US Salinity Laboratory Staff 1954) saline soils are categorized into three main classes, i.e., saline, saline-sodic, and sodic (Table 3).

Saline Soils: Saline soils are more common in irrigated areas of arid and semi-arid regions, where precipitation is much lower than annual evapotranspiration. In humid environments, soluble salts are washed down by percolating rainwater and irrigation water. Saline soils contain excessive sodium chloride (NaCl) and sodium sulfate (Na_2SO_4), which restrict the capacity of roots to extract water from soil resulting in

Table 3 Summary of classification of salt-affected soils

Category	Electrical conductivity of saturation extracts (ECe) (dS m^{-1})	Exchangeable sodium percentage (ESP)	pH
Saline soils	≥ 4.0	<15	<8.5
Saline-sodic soils	≥ 4.0	≥ 15	<8.5
Sodic soils	<4.0	≥ 15	8.5–10
Non-saline non-sodic soils	<4.0	<15	$\approx$ Neutral

poor crop growth. The presence of white crusts on the soil surface is an indication of saline soils. Saline soils are usually flocculated, well-structured, and well-permeable. The saline soils contain large amounts of Na^+, Ca^{2+}, Mg^{2+} ions, and small amounts of NO_3^- and HCO_3^-. The soluble Na^+ is much lower than the sum of other cations and is thus not adsorbed in the soil.

Saline-sodic soils: These soils have excessive exchangeable sodium (Na^+) that can be detrimental to plant growth and soil structure. Saline-sodic soils hold both saline and sodic soils properties and are described by subsoils impervious to water. The dispersing effect of exchangeable Na^+ may be counterbalanced by the coagulating effect of the soluble salts (electrolyte effect) present in the soil. The saline-sodic soils are generally well-structured and permeable. This is true if soil ECe is higher than 10 dS m^{-1} and ESP is greater than 20. However, if ECe is low and ESP is high (ECe $= 6$; ESP > 25), saline-sodic soils also act like sodic soil. Therefore, the removal of excess soluble salts from saline-sodic soils by leaching changes them to sodic soils. As a result, the soil becomes strongly alkaline (pH > 8.5), soil particles swell and disperse and translocate to subsoils where they are lodged in conducting pores, restricting the movement of water and air.

Sodic soils: These soils have excessive quantities of exchangeable sodium, destroying the soil structure with subsequent adverse effects on plant growth. They are low in salts but contain large amounts of sodium carbonate (Na_2CO_3), which disperses clay particles in soils or deflocculates by ion exchange processes, resulting in poor soil structure. Sodic soils consist mainly of the anions Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}. The surface horizons of sodic soils are exceptionally compact and cemented, and puddles of water on these soils are usually turbid, brownish-black in color (Na-humus), and a shiny black crust of film of dry colloidal substance develops on the dry soil surface. The presence of dispersed colloidal clays of smectites group of clay minerals causes soil swelling resulting in low permeability, making tillage operations difficult. Irrigated sodic soils are impervious to water. Since clay soils are sensitive to Na, ESP values as low as 5–10 may reduce infiltration, particularly with good-quality water and swelling clays.

2.2 Causes of Soil Salinity Development in Ethiopia

The natural cause of soil salinity is the weathering process of the parent material of the soil. The salts are brought in by streams draining into the basins. Dissolved sodium accumulates as exchangeable sodium in the B horizon due to vertical or horizontal leaching in humid regions. The salt-affected soils in Ethiopia are affected by climate, soil, and water management practices, and irrigation methods. Low annual rainfall, high temperatures, and shallow groundwater tables in irrigated areas have also added to existing salinity problems. From the very scattered information on the extent and characteristics of salt-affected soils, salinity and sodicity in the region are rapidly increasing, both in irrigated and non-irrigated areas. Four primary sources of the constituents of soil salinity and sodicity {Na^+, Ca^{2+}, Mg^{2+}, K^+ (common metals) and SO_4^{2-}, Cl^-, HCO_3^-, NO_3^- (common ligands)} are (a) mineral weathering (Na rich feldspars), (b) precipitation or rainfall, (c) fossil salts (marine or lacustrine deposits) and (d) collection of saline sediments in catchment areas. Salts are added through irrigation water or because of fertilization.

In the absence of effective surface irrigation systems, the availability of water for irrigation remains a challenge. For this reason, farmers in many areas have developed a flood-based farming system called ‘spate irrigation.’ This system is beneficial in mountain catchment border lowlands, where farmers can use short-duration floods to irrigate their lands. However, crop productivity is severely affected as water often comes long before or late after the cropping season. The success of spate irrigation depends on the availability of good infrastructure and the cooperation of farmers. In the arid lowlands of the country, conventional irrigation is limited due to the perennial nature of most rivers.

Development of soil salinity in Kewet and Efratana Gidim areas is associated with the use of poor-quality water for irrigation during the dry season when freshwater availability from the river is insufficient to meet irrigation requirements. The water quality of dug wells is only marginally fit for irrigation (Yonas 2005). In many other lowlands, there is considerable groundwater potential. However, it is challenging to exploit this water source due to its presence at deeper depths, lack of drilling facilities, and associated costs. In other lowlands, the poor quality of groundwater restricts its use for agriculture.

Waterlogging and salinity problems have been exacerbated due to poor drainage facilities and on-farm water management practices. The widespread waterlogging and salinity problems are the major constraint for crop production in Zeway Dugda around Lake Zeway, farms around Gerjele, and Tumuga swampy area, irrigated farm areas of Abaya and Arbaminch. Farmers in these areas tend to over-irrigate their crops (whenever water is available), which results in excessive seepage and rising groundwater levels. Most farmers use flooding and basin irrigation methods on poorly leveled fields, which results in uneven distribution of irrigation water and salts within the same area. Due to technical and financial constraints, the use of soil amendments, the required amounts of fertilizers, and other soil management techniques is limited.

2.3 Effects of Soil Salinity on Soil and Plants

Saline soils negatively affect plant growth due to excessive soluble salts, exchangeable sodium, or both. Plants in saline soils of arid regions grow in a delicate balance because the amount of soluble salts and exchangeable sodium present in these soils is sufficient to produce harmful effects on plant growth. This requires proper management to avoid reduced crop production or, in severe cases, complete crop failure followed by a decline in land value and subsequently abandoned for agricultural use (FAO 1989). When soluble salts occur in excess soil, they limit the availability of water to plants by reducing the osmotic or water potential of the soil. Moreover, soluble salts increase the concentration of specific ions that have toxic effects on plant metabolism.

The sodicity problem is more permanent than the salinity problem because exchangeable sodium remains in the soil profile even after the salts are removed by leaching. The adverse effects of excessive salts and exchangeable sodium on plant and soil properties are summarized in Table 4 (US Salinity Laboratory Staff 1954):

- Excessive salt concentration in soils inhibits plants from extracting water from the soil for their growth due to increased osmotic tension of the soil.
- Specific ions such as boron, chlorine, and sodium affect plant physiological processes.
- The presence of excessive accumulations of specific ions and salts such as Na^+, HCO_3^-, CO_3^{2-}, SiO_3^{2-}, or NaCl and Na_2SO_4 can cause nutritional disorders.
- Changes in soil physical properties finally inhibit water infiltration and movement, air movement, root penetration, and seedling emergence problems.

Salinity threshold: This is the maximum level of soil salinity that does not reduce the potential yield of a specific crop, or it is the salinity (ECe) value where crop yield decline begins. The tolerance levels of salinity and yield reduction of different crops vary according to their physiology. For instance, *Hordeum vulgare* (barley) is salt-tolerant, while *Phaseolus vulgaris* (beans) is highly sensitive to salinity. Differences in salt tolerance exist between crops and different varieties of the same crop.

Table 4 Response of plants to soil salinity at different ECe values

ECe (dS m^{-1})	Plant response
0–2	Negligible salinity effects
2–4	Yields of sensitive crops (Beans, Carrot, Lemon, Orange, Avocado, Pineapple, Peach, Strawberry, Onion, Rose) may be decreased
4–8	Yield of many crops is restricted
8–16	Tolerant crops (Wheat, Grapes, Sorghum, Oats, Mandarin, Soybean, Clover, Sudan grass, Wild rye, Safflower) will survive
>16	Only highly tolerant crops (Barley, Sugar beet, Bermuda grass, Alkali grass, Saltgrass, Cotton, Wheatgrass) will yield satisfactorily

In salty soils, the roots of plants cannot absorb enough water. Thus, as the growth rates of their cells are limited, they have small leaves and closed stomata resulting in low CO_2 fixation (i.e., reduced photosynthesis). However, wilting is often not seen due to the build-up of non-toxic and osmotic substances. Bresler et al. (1982) have described that these plants also show marked differences in their tolerance to exchangeable sodium contents (Table 5).

Crop tolerance to boron: Plants vary in their tolerance to the level of boron in soils. The tolerable boron concentration in different crops is given in Table 6.

Table 5 ESP tolerance of various crops under non-saline conditions

Tolerance to ESP	Crops	Growth (field) response
Extremely sensitive (ESP = 2–10)	Deciduous fruits, Nuts, Citrus (*Citrus spp.*), Avocado (*Persea americana*)	Na^+ toxicity symptoms even at low ESP values
Sensitive (ESP = 10–20)	Beans (*Phaseolus vulgaris*)	Stunted growth at low ESP
Moderately tolerant (ESP = 20–40)	Clover (*Trifolium spp.*), Oats (*Auena sativa*), Tall fescue (*Festuca arundinacea*), Rice (*Oryza sativa*)	Stunted growth due to adverse soil conditions
Tolerant (ESP = 40–60)	Wheat, Cotton, Alfalfa, Barley, Tomatoes, Beets	Stunted growth
Most tolerant (ESP > 60)	Crested and Fairway Wheatgrass, Tall Wheatgrass, Rhodes grass	Stunted growth due to poor soil conditions

Table 6 Crop tolerance limits for Boron in saturation extracts of soil

Tolerant plants	Semi tolerant plants	Sensitive plants
4.0 ppm of Boron	2.0 ppm of Boron	1.0 ppm of Boron
Athel (*Tamarix aphylla*)	Sunflower (*Hellanthus annus*)	Plum (*Prunus domestica*)
Palm (*Phoenix conariensis*)	Potato (*Solanum tuberosum L.*)	Pea (*Pyrus communis*)
Date palm (*P. dactylifera*)	Cotton (*Gossypium hirsutum*)	Apple (*Malus sylvestris*)
Sugar beet (*Beta vulgaris*)	Tomato (*L. esculentum*)	Grape (*Vitis spp.*)
Alfalfa (*Medicago sativa*)	Radish (*Rapharus sativus L.*)	Cherry (*Prunus spp.*)
Broad bean (*Vicia faba L.*)	Field pea (*Pisum sativum*)	Peach (*Prunus persica)*
Onion (*Allium cepa L.*)	Barley (*Hordeum vulgare*)	Orange (*Citrus sinensis*)
Turnip (*Brassica rapa L.*)	Wheat (*Triticum aestivum*)	Avocado (*Persea americana*)
Cabbage (*Brassica oleracea*)	Corn (*Zea mays*)	Grapefruit (*Citrus P. macfafad*)
Lettuce (*Lactuca sativa L.*)	Sorghum (*Sorghum bicolor*)	Lemon (*Citrus lemon*)
Carrot (*Daucus carota L.*)	Oat (*Avena sativa*)	Apricot (*Prunns americana*)
	Pumpkin (*Cucurbita spp.*)	Navy bean (*Phaseolus vulgaris*)
	Pepper (*Caspsinum annum*)	
	Sweet Potato (*Ipomoea batatas*)	

2.4 Extent and Distribution of Saline Soils in Ethiopia

The majority of salt-affected soils are concentrated in the Rift Valley System and Somali lowlands in the Wabi Shebelle River Basin and the Denakil Plains (Mesfin 2001; Heluf and Mishra 2005). The source of salts in the Rift Valley system is weathering. These parent materials undergo intensive disintegration and decomposition when exposed to natural waters. However, the processes liable for salinization and sodication of soils in Ethiopia are more diverse and complicated (Heluf 1985, 1987, 1995; Heluf and Mishra 2005).

It is estimated that the area covered by saline soils in the former Hararghe Administrative Region (eastern region) is 1,159,300 ha, which is 13% of the region's total land area (Girma and Fentaw 1996). Out of 4,000 ha of irrigated lands at Melka Sedi, 40% is saline, 17% is saline-sodic, and only 0.02% is sodic. There is also evidence that farmers have abandoned a large land area due to increasing salinity. Furthermore, about 39% of the Abaya State Farm is also salt-affected.

The Rift Valley Zones and the south-eastern (Somali) country's lowlands are the most valuable agricultural lands as they offer vast potential for multiple cropping. Most of the irrigated State Farms where export crops (i.e., cotton, sugarcane, and fruits) are being grown, are also located in the Rift Valley Zone. However, due to the absence of adequate drainage systems, a substantial proportion of the areas of this zone are turning into saline and saline-sodic soils annually (Heluf and Mishra 2005). Preliminary soil surveys have shown massive salt build-up in the soils of the lower Wabi Shebelle basin of Gode (Somali Region), where small-scale irrigation systems by taking water from the Shebelle River have been introduced. This implies that the development of large-scale irrigation projects in the Wabi Shebelle and other river basins without proper drainage will rapidly expand soil salinity and sodicity problems. A map of soil groups in different parts of Ethiopia is shown in Fig. 1.

2.5 Spatial Distribution of Soil Salinity in Different Regions of Ethiopia

The International Center for Biosaline Agriculture (ICBA) has conducted a detailed survey in the different regions of Ethiopia to characterize salt-affected soils (Qureshi et al. 2021). The spatial variability of soil salinity (ECe) was assessed using the geostatistical technique. The survey data developed soil characterization, and surface salinity (0–30 cm depth) maps for Afar, Oromia, Amhara, and Tigray regions. The surface salinity was classified as non-saline (<2 dS m^{-1}), low saline (2–5 dS m^{-1}), medium saline (5–10 dS m^{-1}), high saline (10–15 dS m^{-1}) and extreme saline (> 15 dS m^{-1}). The soils were classified according to FAO (2014) soil correlation/classification system and mapped at 1:500,000 scale at the reference group level. The data was also used to develop surface salinity maps.

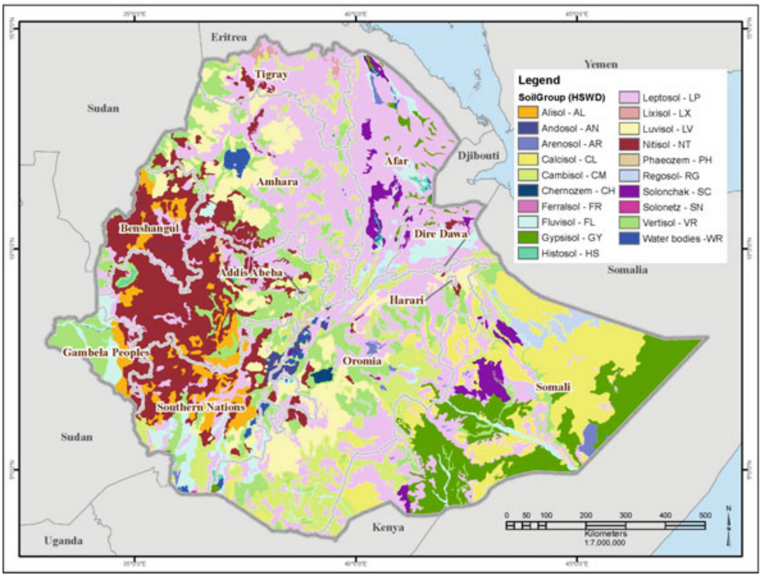

Fig. 1 Soil groups in different regions of Ethiopia

Highly saline soil

Moderately saline and sodic soil

Low salinity and highly sodic soil

Highly sodic soil

Table 7 Area covered by different RSGs in the Afar region

No.	Soil Types	Area		No	Soil Types	Area	
		km^2	%			km^2	%
1	Leptosols	29,821	30.68	9	Gypsisols	2,882	2.96
2	Rockoutcrop/Lava	14,541	14.96	10	Solonetz	2,544	2.62
3	Cambisols	11,108	11.43	11	Calcisols	2,221	2.28
4	Fluvisols	7,870	8.10	12	Luvisols	1,670	1.72
5	Solonchaks	6,882	7.08	13	Durisols	699	0.72
6	Regosols	6,829	7.02	14	Andosols	362	0.37
7	Arenosols	5,108	5.25	15	Water Body	143	0.15
8	Vertisols	4,523	4.65	16	Acrisols	2.38	0.002
Total						97,205	100

Afar region: Sixteen Reference Soil Groups (RSGs) were identified for the Afar region, covering 82% of the area as given in Table 7. The primary identified RSGs include Leptosols (30.68%), Cambisols (11.43), whereas, Fluvisols (8.15), Solonchaks (7.08%), Regosols (7.02%), Arensosols (5.25%), Vertisols (4.65%), Gypsisols (2.96%), Solonetz (2.62%), and Calcisols (2.28%) are minor groups.

The spatial distribution of different soil types is shown in Fig. 2.

The ECe of the surface soils (0–30 cm) in the Afar region ranges from non-saline (<2 dS m^{-1}) to extremely saline (>15 dS m^{-1}). In the Afar region, about 58% of the soils are affected by different salinity levels (Table 8). Low and medium surface soil salinity classes cover 38% of the area and are found in the region's central and southern parts. High and highly saline surface salinity levels cover 20% of the region and spatially cover the northeastern part of the region (Fig. 3). The severity and spatial coverage of subsurface soil salinity are presumed to be higher than the upper 30 cm soil layer. Therefore, it is recommended to properly conduct deep soil profile salinity analysis to select salt-tolerant species for these regions.

Amhara region: Eighteen Reference Soil Groups (RSG) have been identified in the Amhara region, covering 96.6% of the area. The area covered by each RGS is shown in Table 9. Leptosols (38.2%) are dominant in the region followed by vertisols, cambisols, and luvisols.

The surface salinity (0–30 cm) in the Amhara region ranges from non-saline (<2 dS m^{-1}) to extremely saline (>15 dS m^{-1}). About 12% of soils are saline to various degrees. Low and medium surface salinity classes cover 11% of the region and are found in the central, south, southwest, and eastern part of the region. High and extreme soil salinity levels cover only 1% of the area and spatially cover the south and south-eastern part of the region (Fig. 4). Table 10 shows the surface salinity (0–30 cm depth). The surface salinity map of the Amhara region is shown in Fig. 5.

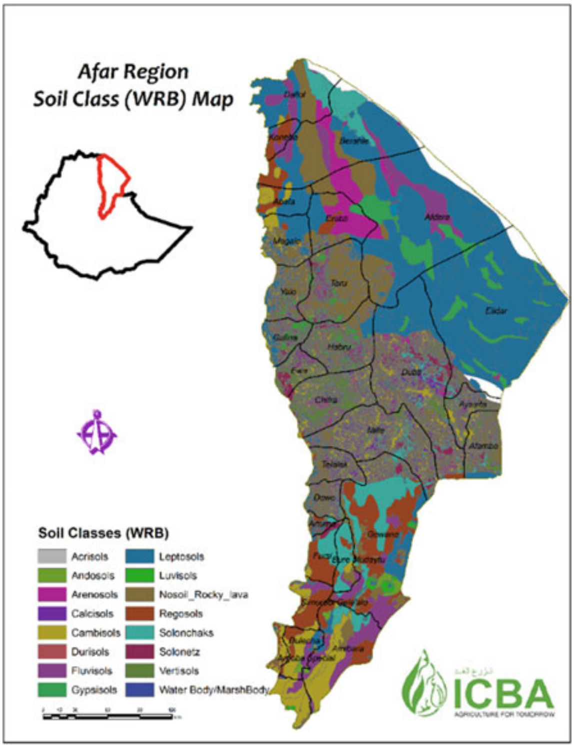

Fig. 2 Dominant RSGs in the Afar region

Table 8 Surface (0–30 cm) soil salinity levels in the Afar region

Soil salinity levels	Area	
	km^2	%
Non-saline/Waterbody/Rockoutcrop (<2 dS m^{-1})	40,787	42
Low saline (2–5 dS m^{-1})	26,916	28
Medium saline (5–10 dS m^{-1})	9,798	10
High saline (10–15 dS m^{-1})	5,618	5
Extremely saline (>15 dS m^{-1})	14,085	15
Total	97,204	100

Oromia region: Fourteen Reference Soil Groups (RSG) have been identified in the Oromia region, covering about 96.55% of the area (Table 11; Fig. 6). The soil survey results indicate that the soil surface salinity (0–30 cm) in the Mahara region ranges from none-saline (<2 dS m^{-1}) to extremely saline (>15 dS m^{-1}). It is estimated that 11.33% of the soils in the region are under various degrees of salinity levels (Table 12). Low (5.33%) and medium (5.29%) surface soil salinity classes cover 10.62% of the region and are in the central, south, and central-eastern parts of

Fig. 3 Surface salinity map of the Afar region

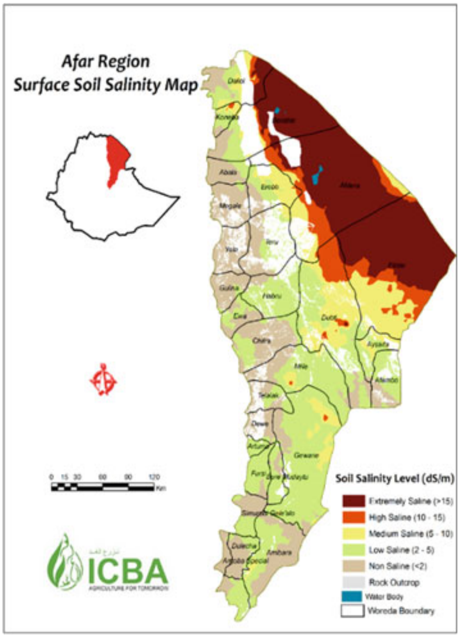

Table 9 Area covered by different RSGs in the Amhara region

No.	Soil Types	Area		No.	Soil Types	Area	
		km^2	%			km^2	%
1	Leptosols	59,635	38.32	10	Fluvisols	908	0.58
2	Vertisols	30,444	19.56	11	Arenosols	472	0.30
3	Cambisols	18,258	11.73	12	Acrisols	431	0.28
4	Luvisols	15,972	10.26	13	Andosols	223	0.14
5	Alisols	12,320	7.92	14	Umbrisols	38	0.02
6	Regosols	5,926	3.81	15	Solonetz	36	0.02
7	Calcisols	4,068	2.61	16	Lava/Rock	34	0.02
8	Nitisols	3,683	2.37	17	Chernozems	8	0.01
9	Water Body	3,180	2.04	18	Gleysols	0.9	0.0006
				19	Phaeozems	0.4	0.0003
Total						155,638	100

the area. Highly saline soils cover only 0.71% of the region (0.49% high and 0.22% extremely saline levels) and spatially cover the south and south-eastern part of the region. Figure 7 shows surface soil salinity ECe (0–30 cm depth) in the Oromia region.

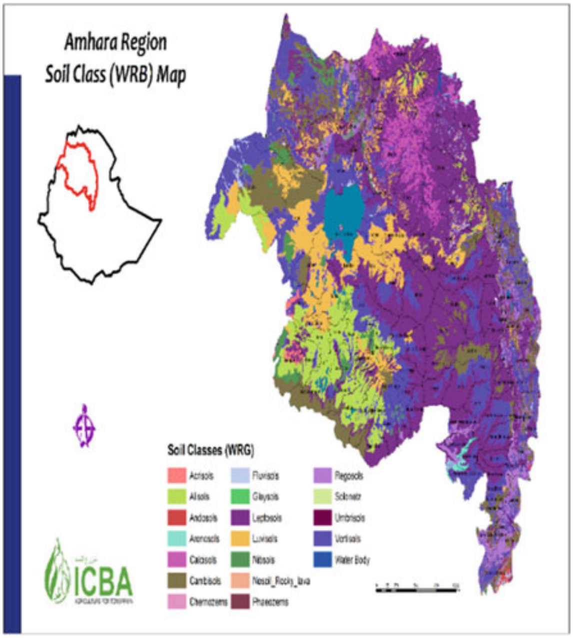

Fig. 4 Dominant RSGs in the Amhara region

Table 10 Surface soil salinity (0-30 cm) in the Amhara region

Soil salinity levels	Area	
	km^2	%
Non-saline/Waterbody/Rockoutcrop (<2)	137,428	88
Low saline (2–5 dS m^{-1})	4,903	3
Medium saline (5–10 dS m^{-1})	11,892	8
High saline (10–15 dS m^{-1})	1,230	0.8
Extremely saline (>15 dS m^{-1})	202	0.2
Total	155,648	100

Tigray region: Eleven Reference Soil Groups (RSG) were identified for the Tigray region covering about 94% of the area. The major groups are leptosols, cambisols, and vertisols (Table 13; Fig. 8). The results of the soil survey indicate that ECe of the surface soils (0–30 cm) ranges from none-saline (<2 dS m^{-1}) to extremely saline (>15 dS m^{-1}). It is estimated that 2.71% of the soils of the region are medium saline and are present in the central, southwest, and eastern parts of the area (Table 14). Figure 9 shows the surface soil salinity classes (0–30 cm) in the Tigray region. The salinity of the deeper layers may be higher due to variations in soil properties.

Fig. 5 Surface salinity in the Amhara region

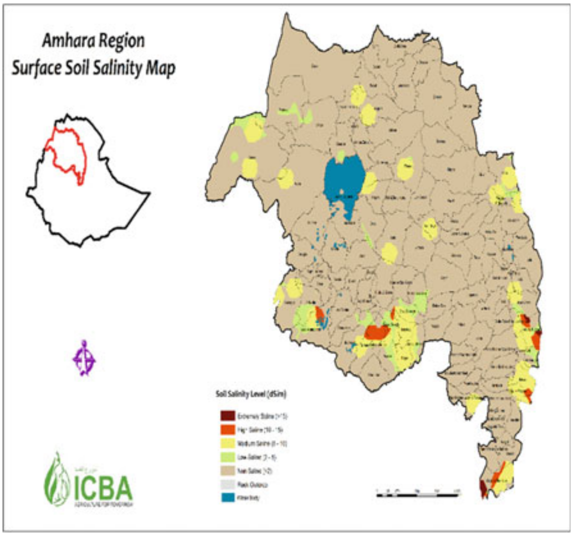

Table 11 Area covered by each RGS in the Oromia region

No.	Soil types	Area		No.	Soil types	Area	
		km²	%			km²	%
1	Cambisols	68,891	21.23	13	Regosols	2,388	0.74
2	Leptosols	51,113	15.75	14	Solonchaks	1,854	0.57
3	Nitisols	46,363	14.29	15	Chernozems	1,612	0.50
4	Vertisols	43,883	13.53	16	Phaeozems	1,400	0.43
5	Luvisols	36,091	11.12	17	NosoilRockylava	1,051	0.32
6	Alisols	15,508	4.78	13	Solonetz	982	0.30
7	Fluvisols	12,523	3.86	14	Gypsisols	595	0.18
8	Acrisols	9,504	2.93	15	Planosols	576	0.18
9	Lixisols	6,184	1.91	16	Water Body	456	0.14
10	Calcisols	5,649	1.74	17	Plinthosols	192	0.06
11	Gleysols	5,379	1.66	18	Lake	79	0.02
12	Andosols	5,319	1.64				
Total						324,429	100

Therefore, it is suggested to do a detailed subsurface salinity analysis before offering the best cropping systems for these areas.

Causes of Salinity Development in Ethiopia.

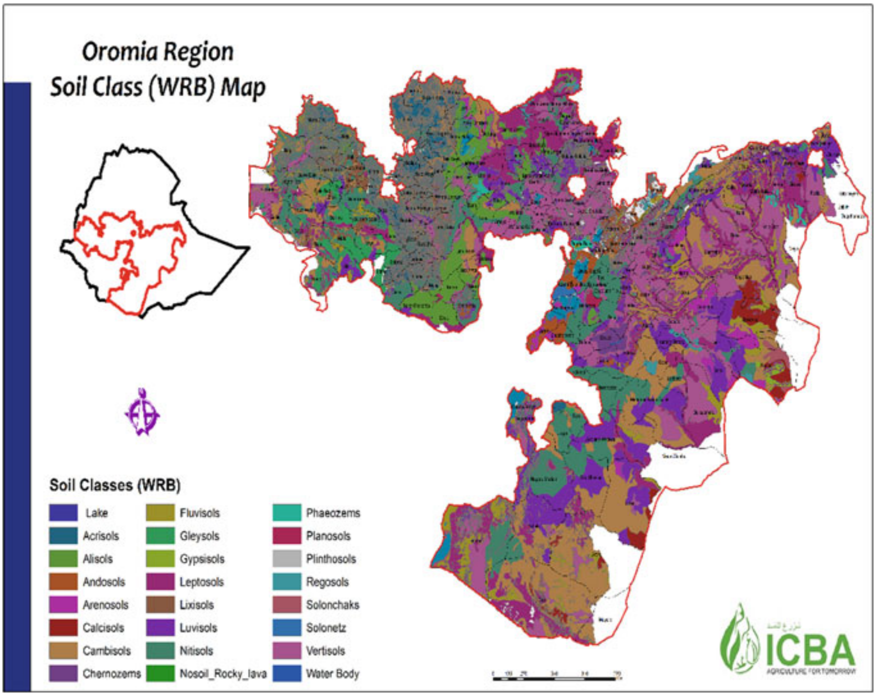

Fig. 6 Soil group types in the Oromia region

Table 12 Surface (0–30 cm) soil salinity in the Oromia region

Soil salinity levels	Area	
	km^2	%
Non-saline/Waterbody/Rock out crop (<2 dS m^{-1})	28,7768.25	88.70
Low saline (2–5 dS m^{-1})	17,292.05	5.33
Medium saline (5–10 dS m^{-1})	17,152.54	5.29
High saline (10–15 dS m^{-1})	1,576.72	0.49
Extremely saline (>15 dS m^{-1})	713.74	0.22
Total	324,428.69	100

2.6 *Water Shortage for Irrigation*

Ethiopia receives an annual rainfall of 850 mm, or the equivalent of 940 km^3 per year. About 13% of total rainfall is diverted into so-called blue water (river flows and fresh water in lakes). Only 3% is used for rainfed agricultural production, covering 15% of Ethiopia’s land area. Regardless of the overall resource potential, the county faces severe water scarcity in the eastern, south-eastern, and north-eastern parts where little

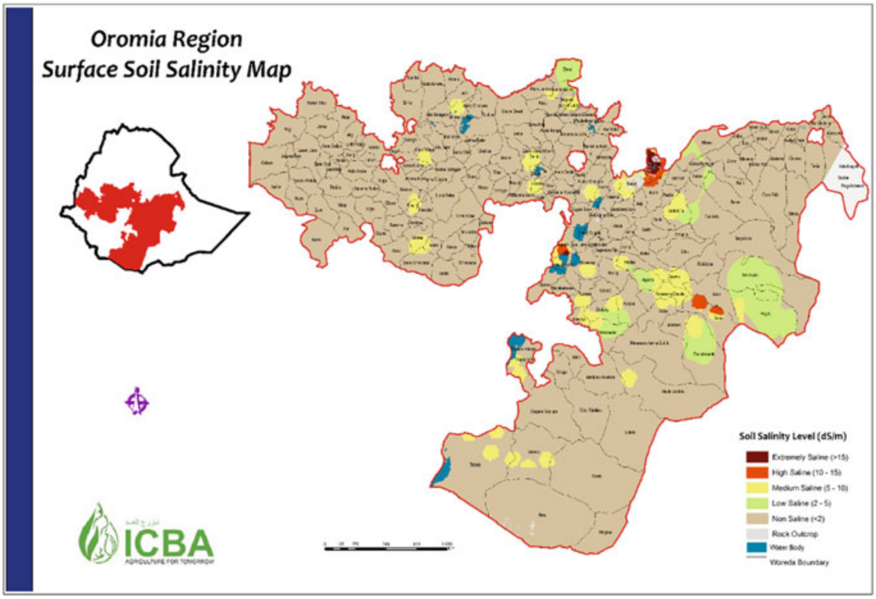

Fig. 7 Surface soil salinity (0–30 cm) map of the Oromia region

Table 13 Area covered by each RGS in the Tigray region

No.	Soil types	Area		No.	Soil types	Area	
		km^2	%			km^2	%
1	Leptosols	28,490	58	8	Calcisols	422	0.85
2	Cambisols	9,307	19	9	Fluvisols	67	0.14
3	Vertisols	7,120	14	10	Regosols	47	0.10
4	Luvisols	1,673	3	11	Rocky Surface	44	0.09
5	Alisols	980	2	12	Nitisols	34	0.07
6	Arenosols	626	1	13	WaterBody/Marsh Land	23	0.04
7	Lixisols	572	1				
Total						49,406	100.00

or no surface water is available. Due to increasing drought incidences, on average, more than four million people face food shortages and need relief assistance in any given year. The development and management of water resources face multiple challenges.

In Ethiopia, about 90% of the crop production is rainfed. The high degree of rainfall variability often creates water scarcity, causing massive damage to productivity in rainfed systems. Therefore, irrigation is vital for sustainable crop production in these

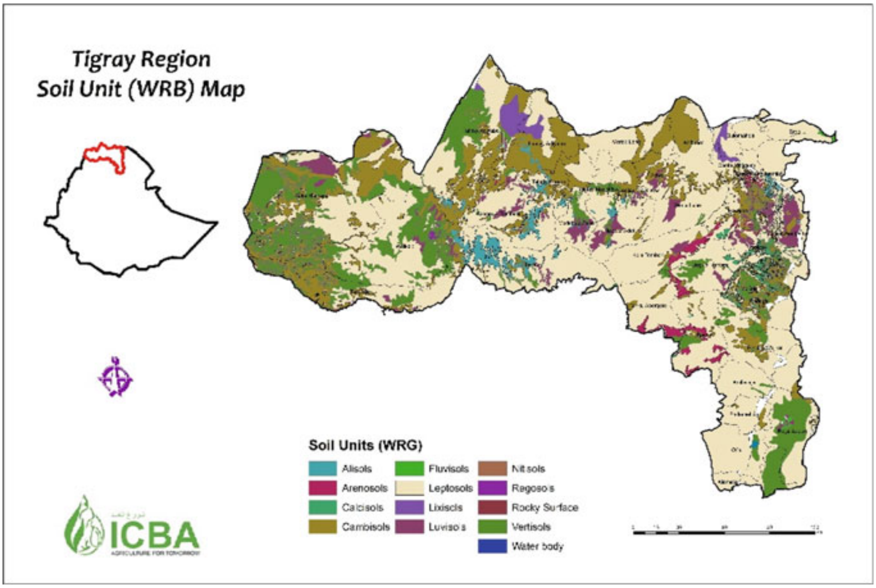

Fig. 8 Soil group types in the Tigray region

Table 14 Distribution of suface (0–30) soil salinity in the Tigray region

Soil salinity levels	Area	
	km^2	%
Non-saline/Waterbody/Rock outcrop (<2)	48,067	97.29
Low Saline (2–5)	0	0
Medium saline (5–10)	1,339	2.71
High saline (10–15)	0	0
Extremely saline (>15)	0	0
Total	49,406	100

areas. Due to multi-faceted and complex issues associated with water resource development, Ethiopia has done little to utilize its water resources. Therefore in Ethiopia, water availability is a limiting factor rather than land to expand irrigated agriculture. The surface irrigation potential of Ethiopia is estimated at 3.7 million ha (Awulachew 2010). However, this focuses on large and medium-scale irrigation developments and does not address the potential effects of small-scale irrigation, including minor river diversions, groundwater irrigation, and rainwater harvesting. An additional one million ha of land can be irrigated from groundwater and 0.5 million ha from rainwater harvesting. The total irrigation potential, thus, was estimated to be about 5.3 million ha (Awulachew and Ayana 2011).

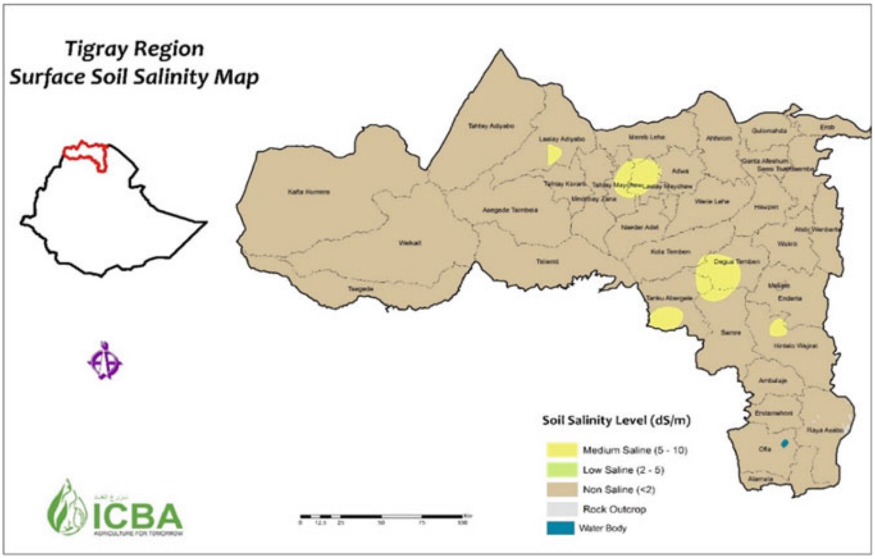

Fig. 9 Surface soil salinity (0–30 cm) map of the Tigray region

2.7 *Declining Irrigation Water Quality*

Salt-affected soils should be irrigated with good-quality water to avoid salt build-up to the extent that it becomes harmful to plant growth. The soils of Gergera Watershed, Atsbi-Wonberta, Tigray, and Northern Ethiopia have shown signs of increasing sodicity due to excessive use of poor-quality water for irrigation (Fig. 10). Therefore, it is proposed to adopt advanced crop and water management practices for sustaining crop productivity in these areas (Yeshitela et al. 2012). The use of poor-quality groundwater for irrigation has also increased the salinity problems in the Central Rift valley. The small-scale irrigated farms of Kewet and Efratana Gidim areas also face widespread salinity problems (Tilaye and Mekonen 2002) due to the use of poor-quality water for irrigation from dug wells during the dry season. The water quality of these dug wells is marginally fit for irrigation (Yonas 2005). The declining water quality of tributaries of the Awash River is also becoming a serious concern because this water is used for more than 3000 ha of farmland along the River Basin (EIAR 2015).

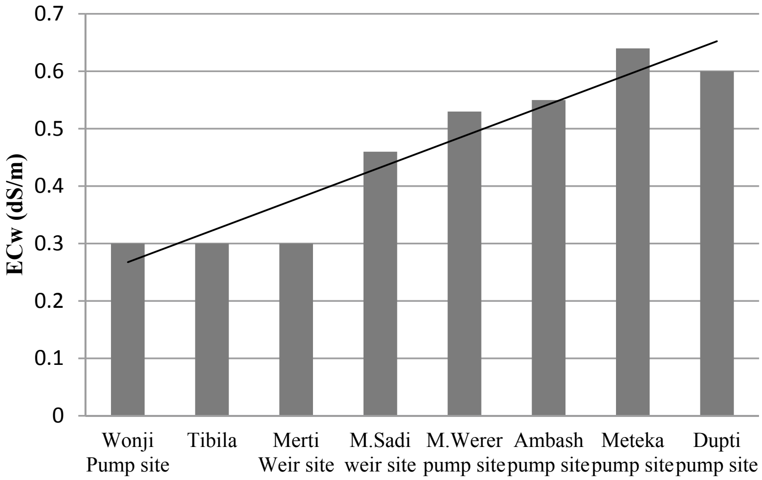

Fig. 10 Surface water quality along the Awash River (from upstream to downstream)

2.8 Waterlogging and Soil Salinization Problems

The increasing soil salinity and waterlogging problems have forced farmers to abandon their agricultural lands and migrate to nearby cities to seek off-farm jobs. This situation has reduced crop production and increased household poverty, which has affected the country's overall economy. The case is more alarming in arid and semi-arid regions. High salinity and sodicity levels from rising groundwater levels threaten irrigated agriculture's sustainability in many parts of the country (Kidane 2003). The waterlogging problems are associated with the lack of drainage facilities and poor on-farm irrigation practices. The Zeway Dugda, irrigated areas of Gerjele and Tumuga swampy area, and farm areas of Abaya and Arbaminch are the most affected areas. Many agricultural farms in these areas have gone out of production, reducing farm incomes and increasing poverty. Therefore, to produce sufficient food for the increasing population and ensure sustainable economic development of the country, these salt-affected lands need to be reclaimed.

2.9 Problems in Traditional Reclamation

The rehabilitation of salt-affected lands by installing appropriate drainage systems and chemical amendments is a costly, time-consuming, and laborious task. Under the current socio-economic conditions of the country, this doesn't seem practical in the near future. In addition, the reclamation of these soils is beyond the technical and financial capacity of smallholder farmers. They need external input and guidance on salinity management strategies and access to salt-tolerant crops. Therefore the adoption of the ‘biosaline approach’ would be an attractive solution. This approach involves growing salt-tolerant food and feed crops irrigated with marginal quality water integrated with livestock and suitable crop management systems. These integrated crop-livestock systems can increase the resilience of farmers who are dependent on the livestock sector development.

3 Potential Alternative Crops for Salt-Affected Soils in Ethiopia

The soil salinity problem in Ethiopia has been causing devastating effects on farms in Ethiopia. Farmers are experiencing substantial crop losses, while many farms have gone out of production over the last decades. The salinity problems in Ethiopia are spread over a range of landscapes, irrigated lands, rainfed farming areas, and rangelands in the country. In Ethiopia, the arid and semi-arid agro-ecologies, which account for nearly 50% of the country’s land area, are considered marginal environments (Qureshi 2018). While soil salinity levels are steadily increasing, the lack of awareness by the farmers on the causes and remedies to the problem is regarded as one of the crucial factors for uncontrolled expansion. The growing salinity problems will have severe consequences on the country’s economic development and food security.

Farmers of rainfed areas in Ethiopia are looking for alternate cropping systems to improve the productivity of their lands due to the unpredictable nature of rainfall (Tesfaye and Fassil 2011). Due to widespread salinity problems in irrigated and rainfed areas, land availability in Ethiopia has reduced to 0.2 ha per capita (Spielman et al. 2011). As the development of new agricultural lands will be difficult, owing to economic constraints, increasing the productivity of existing lands to ensure future security for the increasing population will be a potential option (Ringheim et al. 2009). This requires proper education to smallholder farmers about advanced water and salt management strategies and the provision of salt-tolerant crops. The potential alternative crops suitable for salt-affected lands of Ethiopia are summarized below.

3.1 Salt Tolerant Field Crops

The excess salts in the soil cause poor and spotty stands of crops, uneven and stunted growth, and poor yields. The primary effect of salinity is that it reduces water available to plants through roots as a result of the increased osmotic pressure of the soil solution. In addition, excessive concentration and absorption of individual ions may cause toxicity to the plants and restrict the absorption of other plant nutrients (FAO 1988). There is no crucial point of salinity where plants fail to grow. With the increase in salinity, plant growth decreases until plants become chlorotic and die. On the other hand, plants differ widely in their ability of salt tolerance. Salt tolerance of plants is based on yield reduction on salt-affected soils compared with yields on similar non-saline soils (FAO 1988). Under field conditions, saline soils can be recognized by the spotty growth of crops and often by white salt crusts on the surface.

Knowing the relative tolerance of crops to soil salinity is of paramount importance in selecting appropriate cropping patterns under different salinity environments. In highly saline areas where the growth of regular crops is restricted, salt-tolerant crops and halophytes can be potentially grown. This salinity management approach is called *Biosaline agriculture*. This approach is especially suitable for smallholder farmers as they cannot afford costly reclamation measures. The success of this approach lies in the appropriate selection of salt-tolerant crops that can grow under highly saline or sodic soil conditions.

The crops with diverse genetic diversity that can grow satisfactorily under saline soil conditions include barley, sorghum, wheat, mustard, and oilseeds. Barley is a widely grown cereal crop in the highlands of Ethiopia and is now expanding to mid-altitude areas. However, its use in marginal environments is still not very common. For instance, farmers in the Zeway Dugda area replaced barley with maize and other horticultural crops when the soil got more salinized. Over the past three decades, several salt-tolerant genotypes of barley have been developed that can be successfully grown in various environmental conditions. Studies have shown that sunflower cultivars can be grown up to a salinity level of 19 dS/m with a 50% decrease in growth. Similarly, safflower is an essential multi-purpose oilseed crop with great potential to grow under saline conditions. A study of 52 genotypes using marginal-quality water has shown that safflower is moderately salt-tolerant (ICBA 2014).

To increase the salt tolerance of field crops such as barley, wheat, sorghum, and oilseed, intra-specific variation and screening out resistant varieties that suit saline areas are needed. Therefore, more research is required to develop genetic diversity for barley, sorghum, and oilseed crops since Ethiopia is a large country with diversified climatic conditions. The introduction and adoption of modified genotypes of food crops that best suits salinity stress conditions can help increase crop production in marginal areas, raise farm incomes, and reduce household poverty. This will have a direct impact on the economic development of the country.

3.2 Salt-Tolerant Legumes and Forage Grasses

Ethiopia has extensive livestock resources, including cattle, sheep, goats, and camels. However, it faces an acute shortage of fodder resulting in low livestock productivity. There is little use of improved varieties to increase fodder production in the country. There is a strong need for modified forage varieties resistant to common diseases to improve livestock productivity. Planting salt-tolerant forage grasses and legume crops are more practical in highly saline areas. Studies done in Ethiopia have shown that Karnal grass (*Diplachne fusca*), Rhodes grass (*Chloris gayana*), Para grass

(*Brachiaria mutica*), and Bermuda grass (*Cynodon dactylon*) can be successfully grown in highly saline and sodic soils. Even when no amendments are applied, the Karnal grass grows exceptionally well in sodic soils having ESP up to 80. The dry matter yields of 7.5 tons per ha for Karnal grass have been reported in Pakistan (Chang et al. 1994). In Saudi Arabia, Rhodes grass produced 8.9 tons per ha of dry matter in 188 days; this was more than double the production of any other fodder species (Rozema et al. 2013).

Ethiopia's studies have shown promising results in salinity tolerance and biomass yield for four forage species, i.e., *Cinchrus spp., Panicum antidotal, Sudangrass, Chloris gayana*, and three legume species*; Desmodium triflorum, Sesbania sesban, and Medicago sativa (Alfalfa). Cinchrus Spp, Panicum antidotale, Sudangrass, and Chloris gayana* were subjected to salt stress levels of 8.2, 10.4, 12.7, and 17.9 dS/m, respectively. The biomass yields obtained under saline soil conditions were compared with those obtained under normal soil conditions (Fig. 11) (EIAR 2015). *Chloris gayana* (Rhodes grass) gave the highest fresh biomass yield (127 tons/ha/yr), followed by *Cinchrus* spp. (118 ton/ha/yr).

The Chloris gayana was less affected by salinity compared to *Cinchrus grass* under high salinity conditions. The dry matter yield reductions were 15% and 9% for *Cinchrus and Chloris gayana*, respectively. On the other hand, dry matter yields of *Panicum antidotale* and *Sudangrass* were reduced to almost half under similar salinity conditions. Therefore, Chloris gayana is the most suitable salt-tolerant forage crop for Ethiopian salt-affected areas compared to other grass species. These findings agree with Deifel et al. (2006), who reported that *Chloris gayana* is the most salt-tolerant grass. Studies in the United Arab Emirates also showed that *Chloris gayana* produced

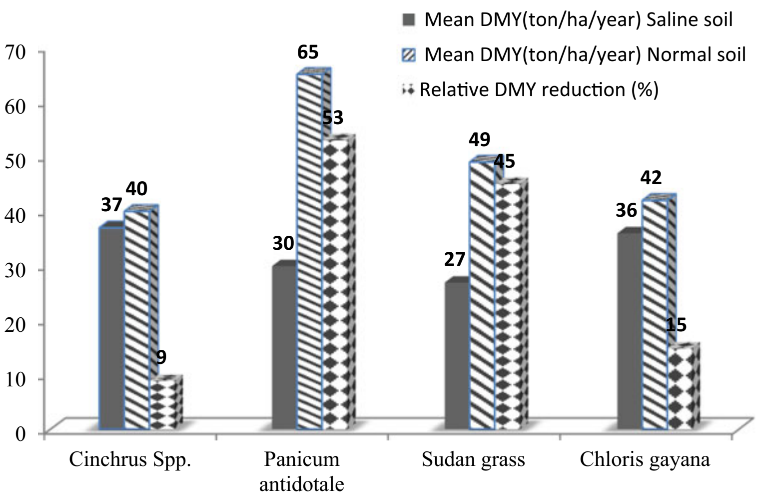

Fig. 11 Comparison of mean dry matter yield for different grass species under saline and normal soil conditions

high dry matter yields when water up to 23 dS m^{-1} was applied for irrigation (ICBA 2014).

These grasses also significantly improve the pH and bulk density of the soil. The surface soil salinity was decreased in all grass treatments from a mean ECe value of 12.3–3.7 dS m^{-1}. Rhodes grass (*Chloris gayana*) and *Panicum antidotale* have also shown promising results for sodic soils (Akhter et al. 2003). This indicates that growing these salt-loving grasses can help increase forage production, improve soil permeability, and enhance native-soil solubility $CaCO_3$, resulting in enhanced leaching of salts to deeper layers and decrease salt accumulation in the upper soil layers.

The forage legume species *sesbania susban* showed excellent salinity tolerance, moisture stress, biomass yield, and high water use efficiency. The *sesbania susban* can be used as a feed and firewood. This makes it the most favorable forage for marginal-quality soil and water resources. Other grasses such as alfalfa have also shown tolerance against salinity with excellent biomass yield. Since alfalfa is a water-demanding grass with a deep rooting system, it is more suitable for areas where soil salinity and high groundwater table due to canal seepage are a problem.

3.3 Bio-Drainage to Control Waterlogging

Most of the major irrigation schemes in Ethiopia face waterlogging problems due to over-irrigation and a lack of appropriate drainage systems. Over the last three decades, tree plantation for bio-drainage has got the attention of the farming community. This technique is suitable in areas where the installation of drainage systems to control groundwater table are not viable due to economic and technical reasons. For bio-drainage, trees with high evapotranspiration rates are selected. The excessive use of water by these trees restricts groundwater table rise to a critical depth, which is harmful to crop growth (Qureshi 2016). Plant species such as *Eucalyptus hybrid*, *Prosopis juliflora*, and *Acacia nilotica* have shown the potential for bio-drainage purposes as their annual discharge rate is equal to or exceeds the rate of recharge to groundwater. The tree plantation for bio-drainage is also economically beneficial for farmers.

In many areas of the world, this technique has successfully been used for lowering groundwater tables. In the Rajasthan region of India, the annual evapotranspiration from eucalyptus trees with a density of 1900 trees/ha was estimated to be 3446 mm (Dagar 2009). The annual water use of the eucalyptus forest was two times higher than that of crops such as finger millet. Calder (1994) have also shown that the fully-developed *Eucalyptus Camaldulensis*, *Acacia nilotica*, and *Prosopis Cineraria* plants, with a tree density of 1100 trees/ha, can transpire water equal to annual Class A Pan evaporation. In marginal environments where land productivity is low due to soil salinity and waterlogging, tree plantation is a potential option because it helps soil reclamation and generates economic benefits for the farming communities. Bio-drainage is an environment-friendly and cost-effective technique to overcome the problems of waterlogging (Qureshi 2017). However, long-term objectives need to be combined with short-term incentives to make it attractive for farmers.

3.4 Halophytes Plantation for Highly Salt-Affected Lands

Halophytes can be successfully planted in marshes, estuaries, cliffs, and dunes because they can tolerate high soil and water salinity. They help protect habitat, maintain ecological stability, carbon dioxide sequestering, and reclamation of salt-affected soils (Sardo 2005). Halophytes tend to remove salts from soils through salt excluding, excreting, or accumulating by their morphological and physiological adaptations at their cellular level (Michalk et al. 2013). They are suitable for coastal and inland soils of arid and semi-arid areas where evapotranspiration exceeds precipitation. The productivity of salt-affected lands can be maintained up to a salinity level of 70 dS m^{-1} by planting halophytes if root zone salinity is maintained through effective leaching (ICBA 2014).

Halophytes have been tested as a vegetable, forage, and oilseed crops in field trials. The oilseed halophyte, *Salicornia bigelovii*, yields 2 tons/ha of seed and contains 28% oil and 31% protein, like soybean yield and seed quality (Girma and Awulachew 2007). Halophytic forage and seed products have been used to replace conventional ingredients in animal feeding systems. However, there are certain restrictions on their use because they contain high salt content and anti-nutritional compounds (Khan and Duke 2001).

The facultative halophytic species such as Quinoa can successfully be grown in salt-affected lands. Quinoa (*Chenopodium quinoa* Willd.) is an edible seed species with rich proteins, fiber and fat, and gluten-free characteristics. It has substantial resistance to drought, frost, and salinity. Quinoa has got global attention as an agro-industrial crop that can succeed in highly saline areas and poor-quality irrigation water (ICBA 2014).

Selecting salt-resistant plants is essential for sustainable agricultural production in saline lands (Flowers and Muscolo 2015). Soil reclamation through the plantation of halophyte plants in pasture and fodder production is a beneficial strategy (Khan and Duke 2001). Halophytic plants such as *Atriplex* can successfully be used to improve soil salinity. Studies have shown that *Atriplex* treatment improved soil salinity by 40% for a one-year experiment and is considered a high-protein animal feed (ICBA 2014).

4 Conclusions and Recommendations

Despite vast salt-affected areas, research and development endeavors to alleviate salinity problems have been minimal in Ethiopia. The extent and causes of salt-affected soils in Ethiopia are not precisely known. The economic implications of the salinity problem are not well-documented, and there are no autonomous institutions to take responsibility for solving salinity problems in the country. Therefore, there is a strong need to develop short-term and long-term strategies and plans to mitigate salinity and sodicity in Ethiopia. This indicates the urgent need to embark on a sustained research endeavor to characterize saline soils, quantify the extent of damage, and develop technologies to reclaim and halt further expansion of soil salinity in the country. The most common short-term and long-term strategies for the reclamation of salt-affected soils are discussed below.

4.1 Short-Term Strategies for Soil Reclamation

For the reclamation of salt-affected soils and to curtail the future expansion of salinity in irrigated areas, recommendations should be made based on detailed studies, investigation, and thorough analysis of factors affecting salt built-up and their practical management, including reclamation and intended utilization. Under the prevailing conditions of Ethiopia, the combination of two or more of the following methods may be practiced for controlling and/or minimizing salinity and sodicity problems. Nonetheless, it should be noted that the practice may not always be successful because the suggested methods are based on the results of studies and investigations made elsewhere and experience in other countries. The following measures could help address salinity and sodicity problems.

- Install proper drainage systems to prevent groundwater tables from rising to the surface—control over-irrigation to avoid excessive percolation of water to groundwater.
- Practice surface mulching to reduce soil evaporation and increase deep percolation to facilitate deep leaching and reduce salt accumulation.
- Perform pre and post-plant leaching to remove stored salts from the root zone.
- Maintain water available in the root zone during critical crop growth stages.
- Select appropriate planting methods to optimize plant density to ensure good crop growth. Eradicate weeds to avoid nutrient and water competition with other crops.
- Select suitable lands for crop cultivation. The areas with high groundwater tables and poor soil structure may create perch groundwater by impeding drainage.
- Avoid bringing sub-soil with high sodium and salt accumulation to the surface during land leveling. If needed, spread a uniform layer of salt-free soil on the surface after land leveling.
- Use lined canals or salt-free conveyance or waterways for primary and secondary irrigation canals crossing soil layers with high salt accumulation.
- Avoid mixing drainage water with irrigation water and avoid direct drainage water use for irrigation because it may contain higher salt content.

The adverse effects of soil salinity and sodicity can also be reduced by adopting suitable agronomic practices as given below:

- Grow crops or crop species, which are salt-tolerant.
- Grow ameliorating crop species and perennial forage grasses where the latter in turn may initiate livestock farming, such as cattle fattening.
- Grow salt-tolerant crops, forages, legumes, etc. This practice is more feasible for soils having high salt concentrations.
- Adverse effects of excessive salts and exchangeable sodium on plant growth can be minimized by increasing the availability of plant nutrients through the application of less available elements such as P, K, Fe, Mn, Zn, Cu, and in some cases, Ca and Mg, due to the high $CaCO_3$ content, high exchangeable sodium, and alkaline soil reactions.
- Initiate reclamation of saline and sodic soils through chemical amendments where calcium sources such as gypsum ($Ca\ SO_4{\cdot}2H_2O$) are available.
- Promote and uphold proper soil, water, and crop management practices and enforce rules and regulations regarding the use of salt-affected soils.
- Monitor, evaluate, and regulate the expansion of irrigated farms in all parts of the country, especially in dry areas.

4.2 Long-Term Strategies for Soil Reclamation

The reclamation of salt-affected soils, halting future expansion, and proper management of soil and water resources require a profound knowledge of resources and their optimum utilization. One of the most cardinal problems of soil reclamation and management in arid and semi-arid regions is the lack of locally amendable technologies. For technology development, an in-depth investigation is required to get quantitative and qualitative information on the dynamic nature of soil and water resources. This scientific knowledge will help us understand the complex physical environment. Thus, a continuous search into the truth and accumulation and dissemination of knowledge and technology is needed. Hence, focused research is vital for generating science and technologies that will change the lives and livelihoods of millions living in marginal environments.

The research priorities for the management of saline and sodic soils are given below.

- Observational and diagnostic studies must be made in salt-affected areas.
- The physical, chemical, biological, environmental, and socio-economic factors influencing soil salinity need to be investigated.
- Field and laboratory studies should be conducted to characterize salt-affected soils.
- Research findings related to environmental, hydro, and agrotechnical, socio-economic factors responsible for the development of salt-affected soils must be implemented.
- Create awareness among farmers and develop preparedness plans to combat salinity and sodicity problems.

- Map salt-affected soils at zonal, regional, and national levels through reconnaissance and a large-scale survey of irrigated and dryland areas.
- Study the effects of saline soils and irrigation water on soil fertility, and productivity, and monitor the impact on plant growth and land value.
- Introduce suitable management practices for irrigation, drainage, leaching, and soil and crop management to control salinity and sodicity.
- Introduce agronomic methods that can be used to reclaim and manage salt-affected soils. These may include appropriate salt-tolerant crops, forages, grasses, and tree species.
- Evaluate different reclamation techniques for saline and sodic soils. These may include the rate of gypsum to be applied, soil amendments, leaching requirements, and irrigation management strategies.
- Prepare soil and water quality maps indicating the areas where immediate action is required.
- Identify and characterize representative watersheds to develop proper water management and drainage plans.
- Propagate available soil reclamation technologies to the end-users.
- Develop agricultural water management manuals, bulletins, and flyers to improve soil and water management.
- Impact on the environment and socio-economic aspects must be assessed to establish a system to sustain agricultural production and protect the environment.

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Chapter 6
Irrigation Water Management Under Salinity Conditions in Arid Regions

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Abstract In most of the arid regions such as Saudi Arabia, water used for cultivated land is counted as one of the most important factors that affect the consumption of water, as sources of irrigation include underground water, precipitation, and treated sewage water. This chapter focusses on the impact of different soil amendments at different rates (4% biochar, 0.4% polymer, and a mixture of both) on selected soil parameters: soil moisture content and salinity distribution, in addition to tomato yield, and water productivity (WP). Greenhouse experiments were conducted during two successive growing seasons in 2017 and 2018 under different levels of irrigation. The experiments consisted of deficit irrigation treatments of 100%, 80%, and 60% of ETc, additional full irrigation 100%; and using two different water qualities: fresh water (EC 0.9 dS m^{-1}), and saline water (EC 3.6 dS m^{-1}). The results showed that under biochar, polymer, and mixture treatments, soil water distribution (SWD) increased by 12.94%, 37.87%, and 42.21%, respectively, at 100% of ET_c; by 6.35%, 16.56%, and 16.37%, respectively, at 80% of ET_c; and by 15.70%, 24.80%, and 41.26%, respectively, at 60% of ET_c, salinity was increased by 59.10% with biochar, while as was reduced by 7.19% and 57.63% with polymer and mixture respectively. The results confirm that the biochar and mixture treatments enhanced yield compared to the polymer and control. However, the saline water reduced the yield compared to freshwater. We recommend that the use of biochar at the rate of 4% led to improve yield in sandy soils.

Keywords Water quality · Biochar · Polymer · Deficit irrigation · Tomato · Salt distribution · Saudi Arabia

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1 Introduction

In arid and semi-arid regions, the sustainable development of agriculture faces many problems such as limited water supply, low precipitation, and high temperatures especially in the summer. In addition, most of the cultivated soils are sandy, which characterized by high permeability rate, high evaporation, low fertility levels, low maximum water holding capacity, and deep percolation. These restrictions caused the lower water productivity (WP), thus decreasing crop productivity. Other problem facing the agricultural development in the area is water quality. The scarcity of good quality water forces growers to use water with moderate or high salinity levels. The brackish water salinity can vary considerably over space and/or time. The brackish water with low salinity level (0.5–8 gm l^{-1}) as in Saudi Arabia groundwater can be used for irrigation purposes under good irrigation practice. The Saudi Arabia mainly depends on brackish groundwater for different Agriculture purposes, considerably the status and development on the use of this type of water is considered an important topic. Many researchers have been reported on the evaluation of irrigation water quality in different region of Saudi Arabia, for Riyadh region, Al-Hasa oasis, Al-Qassium, Al-Kharj (Al-Omran et al. 2016, 2017, 2018). The water composition of 16 different aquifers is reported in Water Atlas of Saudi Arabia (MAW 1985). The groundwater from the aquifers was analyzed and sodium adsorption ratio (SAR), adjusted sodium adsorption ratio (adjRNa), adjusted sodium adsorption ratio (adj SAR) exchangeable sodium percentage (ESP), calcium/magnesium ratio (Ca^{++}/Mg^{++}), and chloride/sulfate ratio (Cl^{-}/SO_4^{--}) were calculated from analytical data. Plant in Saudi Arabia growth is influenced by soil salinity due to the use of brackish water in irrigation which results in a loss of productivity. The soluble salts present in soil mainly: Na, Ca, Mg, Cl, and SO_4. Saline soils are defined as soils have an electrical conductivity (ECe) higher than 4 dS/m at 25 °C, with a sodium absorption rate (SAR) less than 15 and pH generally less than 8.5. The available brackish groundwater resources are usually not being exploited as yet. The salinity levels of brackish waters are too high for the irrigation of conventional crops. However, many of the barren lands could be made productive if suitable salt-tolerant crops or special cultivable techniques could be adopted to use the brackish water. Appropriate large-scale production systems using this water have not been developed so far. Small-scale experiments, however, as well as developments elsewhere in the Middle East, do indicate that suitable opportunities exist to use the brackish water. Generally, the most tolerant crops to salt are sugar beet, barley, and cotton; among vegetables, the most tolerant are spinach, garden beet, asparagus, and kale; among fruit, the most tolerant is date palm. Even poor quality waters with salinity over 2000 ppm, soluble-sodium percentage (SSP) as high as 75% and over 2.0 ppm boron can be used for the above crops with careful management practices on permeable soils (Al-Omran 2002).

In the Saudi Arabia most of the soils are suitable for cultivation since these soils have lower values of ECe than 4 and with very good aeration condition (Hekeal and AlAwajy 1989). However, in some area of Saudi Arabia crops can grow in saline soil where ECe reaches up to 16–20 dS/m (Bashour et al. 1983), mainly in central region, and between 2 and 8 dS/m in Al-Hasa oasis (Al-Barrak 1990), and more than 20 dS/m in coastal soils of Al-Hasa (Al-Barrak 1997).

Al-Harbi et al. (2008) investigated the effects of four irrigation water salinity levels (0.5, 2.5, 5, and 10 dS m^{-1}) and four nitrogen fertilizer rates (0, 5, 10, and 15 mM) on germination, emergence, and seedling growth of tomato cvs. Pascal, Red Stone, Shohba, Super Marmand, and Tanshet Star in a greenhouse of agricultural research and experiment station of the faculty of food and agricultural sciences, King Saud University, Riyadh, Saudi Arabia, and found that the germination percentage, germination rate, emergence percentage, and emergence rate were decreased and delayed with increasing salinity, from 2.5 dS m^{-1} to 10 dS m^{-1}, in all cultivars. All seedling growth characters, except seedling height, were decreased with increasing salinity levels and enhanced with increased N levels. At the germination and emergence stages, cvs. Pascal and Tanshet Star were more tolerant to salinity level than cvs. Shohba, Super Marmand, and Red Stone. The interaction between salinity and N levels was significant for seedling leaf numbers and fresh and dry weight, indicating that N fertilization may reduce negative effects of salinity. However, the results of other characters did not describe any clear trend to indicate that N levels had a direct effect on salinity-induced decreased growth. Al-Harbi et al. (2008) investigated the effects of four irrigation water salinity levels (0.5, 2.5, 5, and 10 dS m^{-1}) and four nitrogen fertilizer rates (0, 5, 10, and 15 mM) on interactions of the leaves nutrients concentrations of tomato seedlings. The experiments were carried out at a greenhouse of agricultural research and experiment station of the faculty of food and agricultural sciences, King Saud University, Riyadh, Saudi Arabia, and found that the leaf nutrients contents of Ca, Mn, K, N, and P were increased. Interaction effects between salinity x nitrogen levels for the different determined nutrients indicated that increasing nitrogen levels mitigated the negative effects of salinity levels.

The trend toward sustainable greenhouse production includes all agricultural practices that utilize available resources such as irrigation management of saline water. In addition to affecting crop yield and soil physical conditions, irrigation water quality can affect soil fertility and irrigation system performance. Therefore, knowledge of irrigation water quality is critical in understanding the necessary management changes for long-term productivity (Bauder et al. 2011). Al-Omran et al. (2010) revealed in their field study on tomato that the water quality significantly affected both the yield and WP. The use of low-quality water resulted in 39.2% lower yields. The introduction of drip irrigation system will provide an advantage using saline water with more frequent irrigation to keep a high soil matric and low salt concentration in the root zone (Malash et al. 2008). Gawad et al. (2005) reported that WP was higher with surface drip irrigation over traditional methods (furrow) in different tomato varieties. The objective of this chapter was to report on the effects of irrigation water qualities and different soil amendments, irrigation methods, and rates on tomato yield and WP under greenhouse conditions of calcareous sandy soils.

2 Materials and Methods

2.1 Preparation of Biochar and Compost

The pyrolysis of date palm to produce biochar was performed in a greenhouse complex of Almohous Farm, 120 km northwest of Riyadh, Kingdom of Saudi Arabia (altitude: 722 m above mean sea level, latitude: 25° 17′ 40″ N longitude: 45° 52′ 55″ E). Leaves of the date palm were used, without leaflets, as the source material for biochar production. The leaves were collected from different locations, exposed to direct sunlight to dry out, and then the petiole bases (fronds) were cut down to small pieces (20–30 cm). The pieces were packed in the biochar kiln. The kiln was designed as a stainless-steel cylinder container covered tightly to minimize the air volume and provide almost oxygen-free conditions. The kiln was subjected to pyrolysis at a temperature of 400–450 ± 10 °C. Then after the pyrolysis, biochar pieces were crushed manually by a 12 kg hammer, and the biochar was grounded using an electrical grinder, and screened through a 2 mm sieve.

2.2 Experimental Site

Experiments were conducted at Thadaq district, Riyadh, 120 km northwest of Riyadh Saudi Arabia (altitude 722 m above mean sea level, latitude 25° 17′ 40″ N and longitude 45° 52′ 55″) under greenhouse conditions throughout two successive growing seasons in 2017 and 2018. Composite soil samples were taken from the surface and subsurface layers from the study area before starting the experiment, and analyzed using the recommended methods as outlined by (Klute and Dirksen 1986). The soil was non-saline (ECe ranged from 1.8 to 2.75 dS m^{-1}), calcareous ($CaCO_3$ ranged from 24 to 32%), the texture of the soils is sandy and had a pH ranging from 7.5 to 8.0. The irrigation system used in the experiments are surface drip irrigation in includes a main line with a diameter of 90 mm, a water source tank with a capacity of two m^3 and a pump connected to the main line. The pump was operated daily within a system that was connected to a fertilizer injection pump (injector used to inject fertilizer into irrigation water), a filter and a flow meter to estimate water use for irrigation. The main line pipe was connected to a sub-main line and a dripper line. The deficit irrigation treatments consisted of three levels of evapotranspiration (ET_c) (100%, 80% and, 60%); and soil amendments treatments consisted of biochar, synthetic polymer, and a mixture of both, as shown in Table 1. Two different qualities of irrigation water were used: (i) freshwater with an EC_w of 0.9 dS m^{-1} was collected from a well and placed into a tank with a capacity 2 m^3; (ii) saline water with an average electrical conductivity EC_w of 3.6 dS m^{-1}, was prepared by adding sodium chloride to obtain the required electrical conductivity (EC) value and sodium adsorption ratio (SAR). The experiments were conducted using a randomized block design with each treatment replicated three times.

Table 1 Chemical properties of the soil and water at the experimental location

Soil depth cm	pH	EC dS m^{-1}	Cations $meql^{-1}$				Anions $meql^{-1}$			SAR
			Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	$CO_3{}^{-2}$	$HCO_3{}^{-}$	Cl^{-}	
0 - 15	7.34	3.21	16	10	3.8	2.41	0.11	21	9.6	1.05
15 - 30	7.58	2.41	13	8.3	1.76	1.36	0.12	16.6	6.3	0.54
30 - 45	7.34	2.49	10.2	8.2	4.94	1.18	0.013	16.6	7.2	1.63
Fresh water	7.1	0.9	4.2	2.4	7.3	0.13	0	2	7.2	4.02
Saline water	7.52	3.6	2.8	2.2	32.04	0.29	0	2.86	31.29	20.26

Soil physical properties

Soil depth cm	Bulk density g cm^{-3}	Field capacity %	Wilting point %	Hydraulic Conductivity cm day^{-1}	Texture
0–15	1.61	14.49	3.51	105.12	Loamy sand
15–30	1.61	14.49	3.51	105.12	Loamy sand
30–45	1.64	13.19	1.99	501.2	Sand

Physical and chemical properties of biochar

Parameters	Value	Units	Parameters	Value	Units
pH	8.92	–	K	0.87	%
Electrical Conductivity (1:25)	3.98	dS m^{-1}	Ca	5.63	%
Organic matter (O.M)	30.32	%	C / N ratio	250:1	–
C	60	%	Moisture	3.53	%
H	3.44	%	Mobile material	22.82	%
N	0.24	%	Ash	25.70	%
P	0.22	%	Resident material	47.95	%
Surface area	237.8	m2 g^{-1}	Bulk density	0.33	g cm^{-3}

Seeds of tomato (*Solanum lycopersicon L.*; commercial name, Red Carpet, a hybrid tomato) were sown on 5 March in 2017 and 1 September 2018. After germination seedlings were transplanted in a fiberglass greenhouse under controlled conditions at day-time and night-time temperatures of 25 ± 1 °C and 20 ± 1 °C, respectively (to protect seedlings from cold weather). Four weeks after sowing, seedlings were transferred to the greenhouse in rows of 5 m in length and 1 m in width. Cultivation practices commonly recommended in commercial tomato production were applied under greenhouse conditions, such as soil sterilization, pest control, and fertilization. The rates of fertilizer application per hectare were 285 kg N, 142 kg P_2O_5, and 238 kg K_2O. At the beginning of each season, surface drip irrigation with only fresh water was applied to all treatments for 10 days to establish the plants and to avoid any accumulation of salts affecting growth.

2.3 Salinity, Water Content, and Root Measurements

The soil samples were collected representing the plant rhizosphere by auger in the soil 15 cm far from each plant sides with the depth of 30 cm. Soil samples were taken at a distance of 10 cm in all directions. The saturation extract (EC_e) was determined for each sample, and then the contour maps for water and soil salinity distributions in the root zone were drawn using Surfer Software (Golden 2002). The root distribution patterns were determined by taking photos using a digital camera from the soil profile at the root zone with 50 cm from the plant at the three directions down, left, and right. Then, photographs were transferred as a background for the Surfer Software program and took the X and Y dimensions of the root as described by (Land et al. 1977). Then, the X and Y dimensions were drawn using Microsoft Excel program. The Soil water content pattern was determined by the simple gravimetric method. The distribution of root system was measured for each treatment by digging a soil block of 50 × 50 × 70 cm and excavating the soil around the plant. Then the plant was picked and the soil around the roots was removed to have clear picture of the roots.

2.4 Gross Water Requirement

At the end of each growth seasons, the total yield and irrigation water applied were determined. The WP was calculated for the irrigated tomato crop using the PRD irrigation technique under greenhouse conditions in detailed steps, as follows:

2.4.1 Leaching Requirements

$$LR = \frac{\mathrm{EC_{iw}}}{2\left(\mathrm{Max_{Ece}} * \frac{1}{\mathrm{LE}}\right)} \tag{1}$$

where *LR* is the leaching requirement, EC_{iw} is the salinity of irrigation water (dS m^1), max EC_e is the maximum tolerable salinity of soil for tomato crop (dS m^{-1}) (max $EC_e = 8.6$), and *LE* is the leaching efficiency ($LE = 90\%$) (Maas and Hoffman 1977).

2.4.2 Uniformity Distribution

$$UD = \frac{Q_{\frac{1}{4}}}{Q_{\text{mean}}} * 100 \tag{2}$$

where *UD* is the uniformity distribution, $Q_{¼}$ is the mean of the lowest quarter of the observed emitter discharge values, and Q_{mean} is the average discharge of all of the emitters (Keller and Karmeli 1975).

2.4.3 Storage Efficiency (Ks)

The storage efficiency was estimated as $Ks = 0.91$ according to (Keller and Karmeli 1975). Then, the irrigation efficiency was calculated by the following equation:

$$Eff_{irr} = EU * K_s \tag{3}$$

where: *EU* is efficiency of uniform, *Ks* is water stress coefficient.

2.4.4 Crop Evapotranspiration (ETc)

The calculation of evapotranspiration was based on the pan evaporation (class A pan) method, according to (Allen et al. 1998), as follows:

$$ET_c = E_O * K_p * K_c \tag{4}$$

where ET_c is the maximum daily *ET* in (mm), E_o is the evaporation from the class A pan (mm), K_p is the pan coefficient, and K_c is the crop coefficient of Tomato.

The *Kc* of Tomato crop was recorded as *Kc*-ini = 0.6, *Kc*-mid = 1.15, and *Kc*-end = 0.9 from FAO standard tables (Allen et al. 1998).

The daily crop water requirements (mm day^{-1}) were estimated by the following equation:

$$GWR = \frac{ET_c}{[(1 - LR) * (Eff_{irr})]} \tag{5}$$

2.4.5 Water Productivity (WP)

The water productivity was calculated by two ways by the following equations:

$$WP = \frac{Yield_{kg}}{WaterConsumption} \tag{6}$$

$$IWP = \frac{Yield_{kg}}{AppliedWater} \tag{7}$$

where yield is the crop production (kg) and applied water is in m^3 (Wang et al. 2016; Yang et al. 2017).

3 Statistical Procedure Approach

The experimental design was laid out as a split-plot design in a randomized complete block design (RCBD) with triplicate experimental plots. Statistical analysis was applied for processing the statistical evaluation for all findings and measured data to test for variance and differences in the soil physical properties among investigated treatments. The significant differences between means and the interactions among measured parameters were analyzed by least significant difference (LSD), analysis of variance (ANOVA), correlation, and regression in the RCBD. All statistical analysis was carried out using SPSS v.23 software (Spss 2012).

4 Results

4.1 Gross Water Requirements (GWR)

The total irrigation water requirements shown in Tables 2 and 3, the total amounts of irrigation water required differed between the two seasons. The gross water requirement (GWR) values in the first season were 1034, 827 and 620 mm $season^{-1}$, while during the second season GWR values were 743, 588 and 411 mm $season^{-1}$ under 100%, 80%, and 60% of ET_c, respectively. The GWR during the first season was 71% higher compared to the second season, due to the higher value of the daily reference evapotranspiration (ET_o) calculated bb Penman-Montieth equation.

Table 2 Total fruit yield of tomato as affected by the interaction between water quality and deficit irrigation and soil amendments during 2017

	Irrigation level	Treatments	kg m^{-2}	ton ha^{-1}	ETc, mm	WA mm *	WA mm^{**}	WP kg m^{-3}	IWP kg m^{-3}
Fresh Water	100	C	18.6	186.0	820.49	1034	7.83	22.67	17.99
		B	18.83	188.33	820.49	1034	7.83	22.95	18.22
		P	12.43	124.33	820.49	1034	7.83	15.15	12.03
		B:P	15.9	159.0	820.49	1034	7.83	19.38	15.38
	80	C	15.73	157.33	656.39	827	6.27	23.97	19.02
		B	13.57	135.67	656.39	827	6.27	20.67	16.4
		P	16.17	161.67	656.39	827	6.27	24.63	19.55
		B:P	14.87	148.67	656.39	827	6.27	22.65	17.98
	60	C	14.8	148.0	492.29	620	4.7	30.06	23.86
		B	12.93	129.33	492.29	620	4.7	26.27	20.85
		P	18.97	189.67	492.29	620	4.7	38.53	30.58
		B:P	22.03	220.33	492.29	620	4.7	44.76	35.52
	LSD $_{0.05}$		0.379	3.79	–	–	–	0.215	0.215
Saline Water	100	C	12	120	820.49	1034	7.83	14.63	11.61
		B	16.17	161.67	820.49	1034	7.83	19.7	15.64
		P	10.27	102.67	820.49	1034	7.83	12.51	9.93
		B:P	13.13	131.33	820.49	1034	7.83	16.01	12.7
	80	C	11.33	113.33	656.39	827	6.27	17.27	13.7
		B	10.1	101.0	656.39	827	6.27	15.39	12.21
		P	10.03	100.33	656.39	827	6.27	15.29	12.13

(continued)

Table 2 (continued)

	Irrigation level	Treatments	kg m^{-2}	ton ha^{-1}	ETc, mm	WA mm *	WA mm**	WP kg m^{-3}	IWP kg m^{-3}
		B:P	9.93	99.33	656.39	827	6.27	15.13	12.01
	60	C	8.63	86.33	492.29	620	4.7	17.54	13.92
		B	5.6	56.00	492.29	620	4.7	11.38	9.03
		P	10.87	108.67	492.29	620	4.7	22.07	17.52
		B:P	10.83	108.33	492.29	620	4.7	22.01	17.46
	LSD $_{0.05}$		0.234	2.34	–	–	–	0.474	0.474

(C) Control, (B) biochar 4%, (P) polymer 0.4%, (B: P) mixture 4%: 0.4% biochar: polymer, ET_c (mm) crop evapotranspiration per season, WA mm* water added per season, WA mm** added per day, WP water productivity and IWP irrigation water productivity

Table 3 Total fruit yield of tomato as affected by the interaction between water quality and deficit irrigation 2018 for soil amendments during 2018

Irrigation level		Treatments	kg m^{-2}	ton ha^{-1}	ETc mm	WA mm*	WA mm**	WP kg m^{-3}	IWP kg m^{-3}
Fresh Water	100	C	27.55	275.49	583	743	4.50	47.25	37.08
		B	33.91	339.10	583	743	4.50	58.16	45.64
		P	31.20	312.00	583	743	4.50	53.52	41.99
		B:P	28.62	286.19	583	743	4.50	49.09	38.52
	80	C	23.30	232.99	466	588	3.56	49.96	39.65
		B	32.67	326.69	466	588	3.56	70.06	55.60
		P	26.51	265.09	466	588	3.56	56.85	45.12
		B:P	26.51	265.10	466	588	3.56	56.85	45.12
	60	C	23.41	234.14	350	441	2.67	66.95	53.13
		B	23.73	237.31	350	441	2.67	67.85	53.85
		P	25.43	254.30	350	441	2.67	72.71	57.71
		B:P	28.51	285.10	350	441	2.67	81.52	64.70
	LSD $_{0.05}$		0.065	0.65	–	–	–	0.087	0.0588
Saline Water	100	C	22.06	220.64	583	743	4.50	37.85	29.70
		B	22.50	225.00	583	743	4.50	38.59	30.28
		P	28.38	283.81	583	743	4.50	48.68	38.20
		B:P	20.67	206.74	583	743	4.50	35.46	27.83
	80	C	19.53	195.29	466	588	3.56	41.88	33.24
		B	19.70	197.00	466	588	3.56	42.24	33.53
		P	18.54	185.44	466	588	3.56	39.77	31.56
		B:P	22.23	222.30	466	588	3.56	47.67	37.83

(continued)

Table 3 (continued)

Irrigation level		Treatments	kg m^{-2}	ton ha^{-1}	ETc mm	WA mm^{*}	WA mm^{**}	WP kg m^{-3}	IWP kg m^{-3}
	60	C	16.00	159.99	350	441	2.67	45.75	36.31
		B	18.73	187.32	350	441	2.67	53.56	42.51
		P	16.81	168.13	350	441	2.67	48.07	38.15
		B:P	17.42	174.20	350	441	2.67	49.81	39.53
	$LSD_{0.05}$		0.244	2.44	–	–	–	0.17	0.167

(C) Control, (B) biochar 4%, (P) polymer 0.4%, (B: P) mixture 4%: 0.4% Biochar:polyemer, ETc (mm) crop evapotranspiration per season, WA mm * water added per season, WA mm ** added per day, WP water use efficiency and IWP irrigation water productivity

4.2 Soil Moisture Distributions (SMD)

The soil moisture distribution (SMD) in the root zone for all soil amendment treatments was graphically represented on a surface contour plot program. Data were selected from the 100% ET_c treatment that was irrigated by fresh water, the depths were as follows 0–15, 15–30, and 30–45 cm (Fig. 1 freshwater). The results show water distribution patterns by the different amendments used in the experiments and the control by the two-water quality (fresh and saline water) under surface drip irrigation systems. the distribution patterns depended on the type of amendment used in the experiment (Biochar, polymer or the mixture between both of them) and the depth of soil. The highest (SMD) were observed under the dripper compared with the sides of plant. On the other hand, the soil amendments types shown that (SMD) was increased by 12.94%, 37.87%, and 42.21% with biochar treatments compared to untreated soil. Nevertheless, the polymer, (SMD) increased by 6.35%, 16.56%, and 16.37% compared to the control; and in the mixture treatment, (SMD) increased by 15.70%, 24.80%, and 41.26% at the depths 0–15, 15–30 and 30-45 cm, respectively.

Figure 2 illustrate the soil moisture distribution (SMD) under soil amendments soil in greenhouse condition with saline water. The results indicate that soil water moisture was higher under the control (without addition of any amendments) compared to all treatments, especially under the dripper. However, at 30 cm away from dripper in both side of the plant right and left, the results obtained represent a high (SMD) and were increased by 33.58%, 16.89%, and 12.93% on average in both sides, with biochar, polymer, and mixture, respectively, compared to the control. These results agree with (de Melo Carvalho et al. 2014), was observed an increase in available soil water moisture for plants with an application rate of 0.8% of biochar in the upper soil layer. Vijayalakshmi et al. (2013) and Hou et al. (2018) concluded that the application of superabsorbent polymer (SAP) to the soil caused an increase soil moisture in the soil, due to the increased water holding capacity of the polymer and the decreased permeability rate of the soil. Vitkova et al. (2017) reported that biochar applied at the rate of 20 t ha^{-1} enhances the soil water moisture distribution, which was strongly related to the type of biochar used in the experiment. (Novak et al. 2012) reported that the addition of biochar improved the moisture storage capacity by 0.5–0.8 cm of water per 15 cm of soil depth in Ultisols and Arid soils. Also, the results agree with the findings of (Yuan et al. 2019), reported that (SMD) was increased with saline water irrigation more than freshwater; this mainly due to lower soil water potential brought by the salt into the soil, which then caused salt stress on crops that affected water uptake by the roots (Fig. 2).

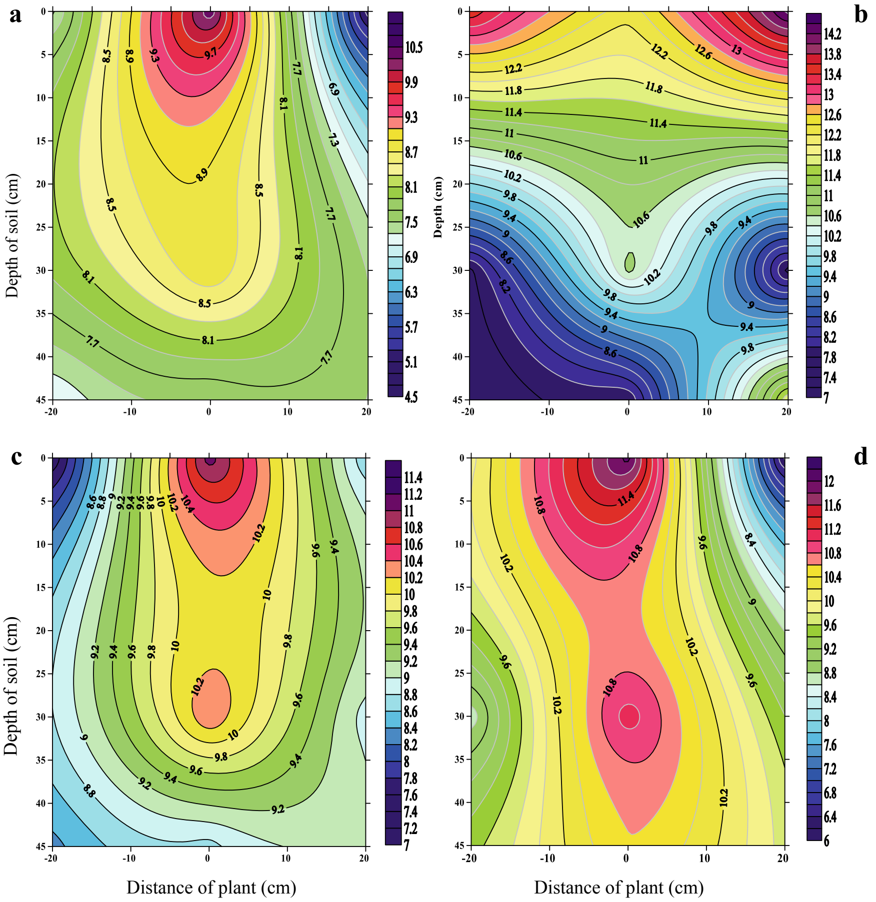

Fig. 1 Soil moisture distribution as percentage (%) in soil treated with an amendment (control, **a**), 4% of biochar (**b**), 0.4% of polymer (**c**) and 4%:0.4% mixture of Biochar: polymer (**d**) with freshwater irrigation 100% of ET_c

4.3 Soil Salinity Distribution (SSD)

Figures 3 and 4 showed the soil salinity distribution for both fresh and saline water, respectively. The results indicate that soil salinity distribution was mainly affected by the amount of irrigation water and the soil amendments. Salinity distribution pattern in the root zone for all soil amendments. Salt was increased relatively high on the surface with soil amended as biochar especially with saline water. The results explained salt concentration was higher by 59.10% with biochar, the polymer and mixture treatments were lower by 7.19% and 57.63%, respectively, compared to control under the irrigation with freshwater. The results also revealed that soil salt

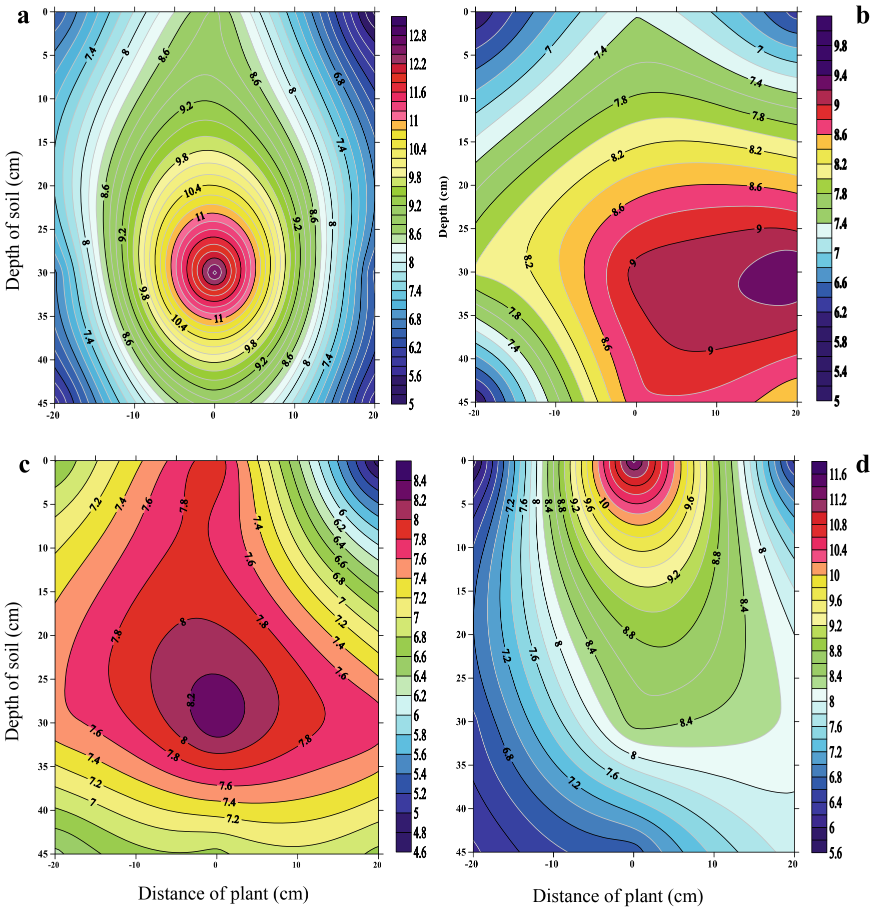

Fig. 2 Soil moisture distribution as percentage (%) in soil treated with an amendment (control, **a**), 4% of biochar (**b**), 0.4% of polymer (**c**) and 4%:0.4% mixture (**d**) Biochar: polymer with saline water irrigation 100 % of ET_c

concentration increased with increasing irrigation water salinity under the same irrigation amount at 100% of ET_c, especially in the untreated soil (control). However, in the case of biochar which is prepared at 450 ^{0}C, the salt concentration decreased compared to the control and polymer treatments, thus, the biochar alleviated the effect of salt, i.e., salts content decreased by 23.90% and 33.73% in the biochar and mixture treatments, respectively. Yuan et al. (2019) concluded that soil water moisture of deficit irrigation was lower than Full irrigation and soil salt content increased with the decrease of irrigation water amount under the same irrigation water salinity. They added that soil salt accumulation increased gradually with the increase of irrigation water salinity and decrease of irrigation water amount under the combined effect of irrigation water amount and irrigation water salinity. This could be due to water evaporation from the surface, resulting in the accumulation of salts on the surface. Our results agree with those studies reported by (Abd El-Mageed and Semida 2015; Abd El-Mageed et al. 2016; Al-Omran et al. 2005; Alomran et al. 2012; Ballester et al. 2014; Li et al. 2018; Liu et al. 2011).

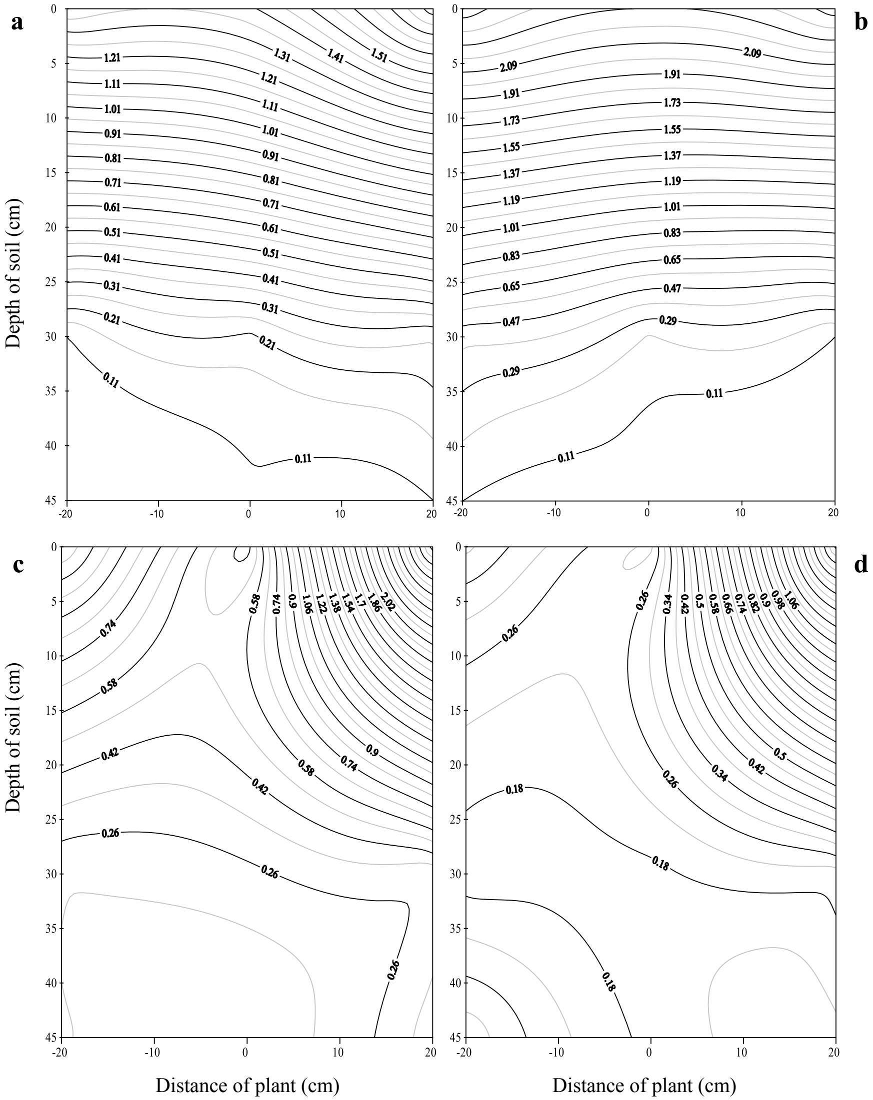

Fig. 3 Salt distribution (dS m^{-1}) in soil treated with an amendment (control, **a**), 4% of biochar (**b**), 0.4% polymer (**c**) and 4%:0.4% mixture (**d**) with freshwater irrigation (ET_C 100%)

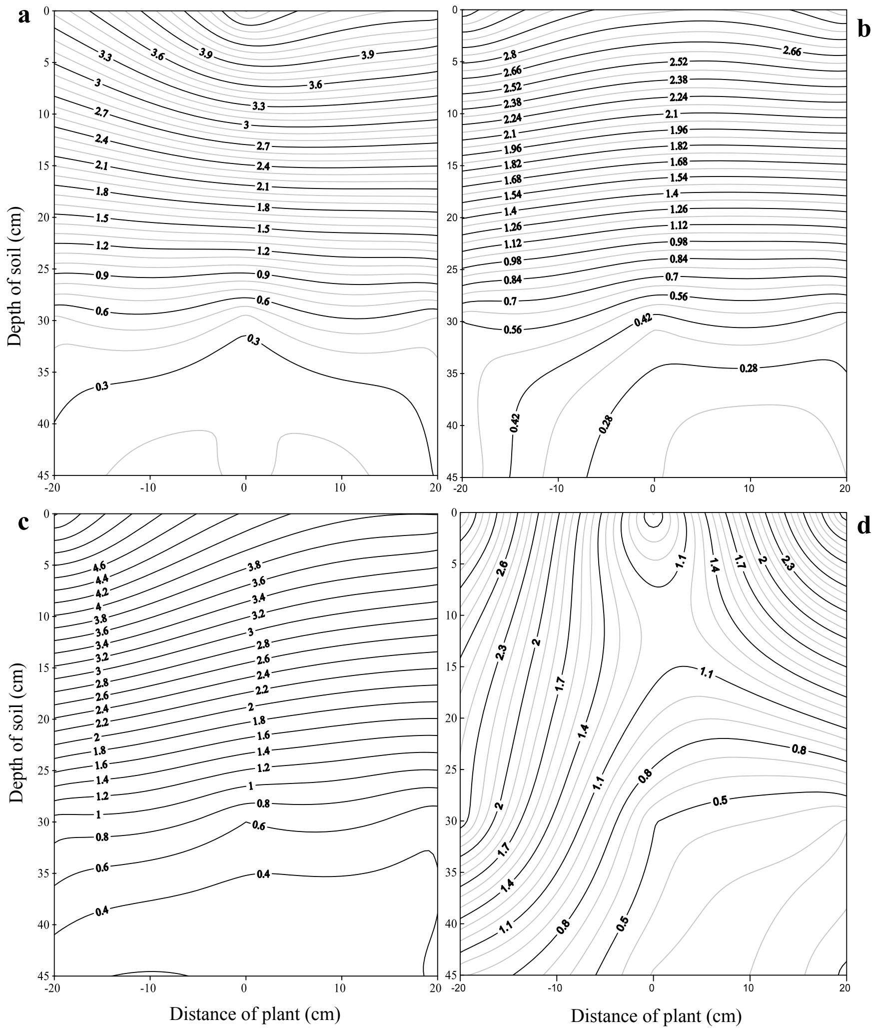

Fig. 4 Salt distribution (dS m^{-1}) in soil treated with no amendment (control, **a**), 4% of biochar (**b**), 0.4% polymer (**c**) and 4%:0.4% (**d**) under saline water irrigation (ET_C 100%)

4.4 Effect of Soil Amendments and Deficit Irrigation on Tomato Yield

The results in Table 2 display the yields of tomato crop at different irrigation level of both water qualities: fresh and saline waters during the first season. The total yield under freshwater at 100% of ET_c was significantly higher with biochar soil amendment compared to the polymer treatment, i.e., biochar and polymer yields were 188.33 and 124.33-ton ha^{-1}, respectively. However, the highest yield under 80% of

ET_c was for the polymer and control treatments, measured at 161.67 and 157.33-ton ha^{-1}, respectively. The highest yield of 220.33-ton ha^{-1} was observed under 60% of ET_c in the mixture treatment. The yield under 100% of ET_c was significantly lower by 33.15% and 14.51% for both polymer and mixture treatments, respectively, while the yield was higher by 1.25% for the biochar treatment, compared to the control. However, at the irrigation level of 80% of ET_c, the percentage of yield decrease in the mixture and biochar treatments were 5.5% and 13.76%, respectively, compared with control. In contrast, at the irrigation level of 60% of ET_c, yield increased by 28.15% and 48.87% for polymer and mixture treatments, respectively, compared to the control. However, using saline water for irrigation, the results showed that yield of tomato was significantly lower by 14.44% with the polymer treatment, in contrast to the biochar and mixture treatments have higher yield by 34.72% and 9.44%, respectively, compared to the control under 100% of ET_c. However, under 80% of ET_c, the yields were lower by 10.87%, 11.47%, and 12.35% in the biochar, polymer, and mixture treatments, respectively, compared to the control. At the irrigation level of 60% of ET_c, the polymer and mixture treatments were higher by 25.87% and 25.48%, respectively, compared to the control. These results may be due to the interaction between water and different soil amendments. Moreover, irrigation with relative saline water led to increasing salt accumulation in the soil, which affected soil productivity adversely, as indicated by the lower yield of tomato plants with saline water, compared to irrigation with freshwater. The use of saline water adversely influenced the yield of tomatoes compared to freshwater during the first season, under 100% of ET_c, yields were increased of freshwater by 55.00%, 16.49%, 21.10% and 21.07% for the control, biochar, polymer and mixture treatments, respectively, compare to saline water. On the other hand, under 80% of ET_c, the yields were increased by 38.82%, 34.33%, 61.14%, and 49.67%. for control, biochar, polymer and mixture treatment, respectively. Notably, at the highest level of deficit irrigation of 60% of ET_c, produced yields were higher by 71.44%, 103.94%, 74.54%, and 103.39% for control, biochar, polymer, and mixture treatment, respectively, with freshwater compare to saline water. The yield in the second season of 2018 is shown in Table 3, which lists yields for each soil amendment at each 100%, and deficit irrigation of 80% and 60% of ET_c using fresh and saline water. The addition of biochar to the soil tended to increase the yield. The highest yields were 339.10 and 326.69-ton ha^{-1}, obtained with biochar under 100% and 80% of ET_c, respectively. The yields of tomato were higher by 23.08%, 13.25%, and 3.88%, for biochar, polymer, and mixture treatments, respectively, compared to the control under full irrigation of 100% of ET_c. On the other hand, at 80% of ET_c, yield with biochar was higher by 40.21% compared to the control, while polymer and mixture treatments were higher by 13.77% and 13.78%, respectively, compared to the control. However, at the highest level of deficit irrigation of 60% of ET_c, the yields were higher by 1.35%, 8.61%, and 21.76% for biochar, polymer, and mixture treatments, respectively, compared to the control. Therefore, in the second season, the yield data showed the same trend as in the first season, i.e., yields were higher when using freshwater compared to saline water. Using saline irrigation at 100% of ET_c the yields were higher by the following percentages: 24.86%, 50.71%, 9.93%, and 38.48%, for control, biochar, polymer, and the combination, respectively. At irrigation level of 80% of ET_c, the increase in yield was 19.30%, 65.83%, 42.95%, and 19.25%, while at 60% of ET_c the increase was 46.35%, 26.69%, 51.25%, and 63.66%, for control, biochar, and polymer and combination treatments, respectively. These results are due to the high salts concentration that increased the osmotic potential in soil solution to the point that the plant has to use more energy to absorb water. In addition, increasing salinity in irrigation water could lead to changes in the morphological and physiological properties of plants, such as the reductions in plant leaf area, stomatal density, stomatal conductance, transpiration, and net CO_2 assimilation as reported by many researchers (Al-Harbi et al. 2017; Hajer et al. 2006; Romero-Aranda et al. 2001). The saline conditions reduced the growth indices such as fresh and dry vegetative and root weights and weight at pre-harvest growth stages. Similar results were reported by (Chen et al. 2009) and (Wan et al. 2007), who found that the yield of oleic oil from sunflower decreases by 1.8% for every 1 dS m^{-1} increase in salinity level of the irrigation water; similarly, the yield of cucumber decreased by 5.7% per unit increase in EC_{iw}. Our results agree with previous findings as reported by (Al-Harbi et al. 2017).

4.5 Effect of Water Quality

The interaction between water quality (fresh and saline) and deficit irrigation (DI) has significant effects on total yield, water productivity (WP), and irrigation water productivity (IWP) during both growing seasons presented in Tables 2 and 3. The results revealed that the highest average yield was 171.83-ton ha^{-1} with freshwater irrigation water at 60% of ET_c during the first season. Whereas the highest average yield with saline irrigation water was 128.91-ton ha^{-1} at 100% of ET_c. The lowest yields under freshwater irrigation were 164.41 and 150.83-ton ha^{-1}, produced during the first season at 100% and 80% of ET_c, respectively. The lowest yields under saline water irrigation were 10.35 and 8.98 ton ha^{-1} under 80% and 60% of ET_c, respectively. Meanwhile, the values of water productivity (WP) and irrigation water productivity (IWP) at 60% of ET_c tended to increase (compared to 100% ET_c) when the amount of irrigation water decreased, with the highest values of 34.90 and 27.70 kg m^{-3}, respectively, under freshwater irrigation and 18.25 and 14.48 kg m^{-3}, respectively, under saline water. The lowest values of WP and IWP were 20.04 and 15.90 kg m^{-3}, respectively, under freshwater irrigation and 15.71 and 12.47 kg m^{-3}, respectively, under saline irrigation water. On the other hand, WUP and IWP values under 80% of ET_c were 22.98 and 18.23 kg m^{-3} under freshwater irrigation and 15.77 and 12.51 kg m^{-3} under saline water irrigation. The final average yields of tomato irrigation during the second season were affected by different levels of irrigation water, i.e., the amount of water applied was positively related to and final yield. The highest yield was 303.20-ton ha^{-1}, as a result of applying water at 100% of ET_c, while the lowest yield was 252.71-ton ha^{-1}, under freshwater irrigation at irrigation level of 60% of ET_c. The same trend was observed with yields under saline irrigation water, and the results were 234.05, 200.01, and 172.41ton ha^{-1} at 100%, 80%, and 60% of ET_c, respectively. Higher values of water productivity and irrigation water productivity were obtained when the amount of irrigation water decreased at 80% and 60% of ET_c levels. These results agree with previously published work by (Al-Harbi et al. 2015; Alomran et al. 2013; Patanè and Cosentino 2010).

4.6 Water Productivity (WP)

The water productivity (WP) can be improved by either increasing yield or decreasing the amount of irrigation water applied, and growers usually aim to decrease the water applied of crops while saving yield and quality (Kirnak et al. 2002). The tomato crop grown under deficit irrigation levels of 80% and 60% of ET_c showed higher WP and IWP than those grown under 100% of ET_c. Figure 5 shows the values of WP and IWP under deficit irrigation levels of 100%, 80%, and 60% of ET_c and different soil amendments and the quality of irrigation water during first season 2017. The WP values increased significantly by average values of 14.67% and 74.18% at 80% and 60% of ET_c, respectively, as compared to 100% of ET_c. The application of soil amendments (biochar, polymer and mixture) improved WP. The highest WP value of 22.95 kg m^{-3} was observed under biochar treatment at 100% of ET_c, while the polymer treatment at an irrigation level of 80% of ET_c resulted in a WP value of 24.63 kg m^{-3}, but the mixture treatment at 60% of ET_c resulted in a WP value of 44.70 kg m^{-3}, compared with other soil amendments. This result may be related to the effect of the soil amendment to increase the specific surface area of soil and to keep water moving while increasing the water holding capacity. Water productivity tended to increase more under freshwater irrigation compared to saline water. The percentage of increase in WP values at 100% of ET_c were 55.00%, 16.49%, 21.10% and 21.07%, for control, biochar, polymer and mixture treatments, respectively. However, these values at 80% of ET_c, were 38.82%,34.32%,61.13%, and 49.66%, for control, biochar, polymer, and mixture treatments, respectively; and at 60% of ET_c, the corresponding values were 71.43%, 130.95%, 74.54%, and 103.39%, for control, biochar, polymer and mixture treatments, respectively. Figure 6 illustrates the effect of deficit irrigation and soil amendments on WP and IWP during the second season in 2018. Average WP values increased by 12.99% and 39.73%, at 80% and 60% of ET_c, respectively, as compared with 100% of ET_c. On the other hand, WP increased when the amount of water irrigation decreased. The highest WP values of 72.71 and 81.52 kg m^{-3} were for polymer and mixture treatments, respectively, under 60% of ET_c. The lowest WP values of 47.25 and 49.09 kg m^{-3} were for the control and mixture treatments, respectively, under 100% of ET_c. The results clearly showed the decrease in production mainly due to the accumulation of salt in the root zone, thereby increasing the osmotic pressure, which leads to reduced absorption of available water by plants. Improved WP is attributed to the application of soil amendments that improve the soil microenvironment for crop growth, thereby significantly enhancing the crop yield and WP. Generally, the application of biochar

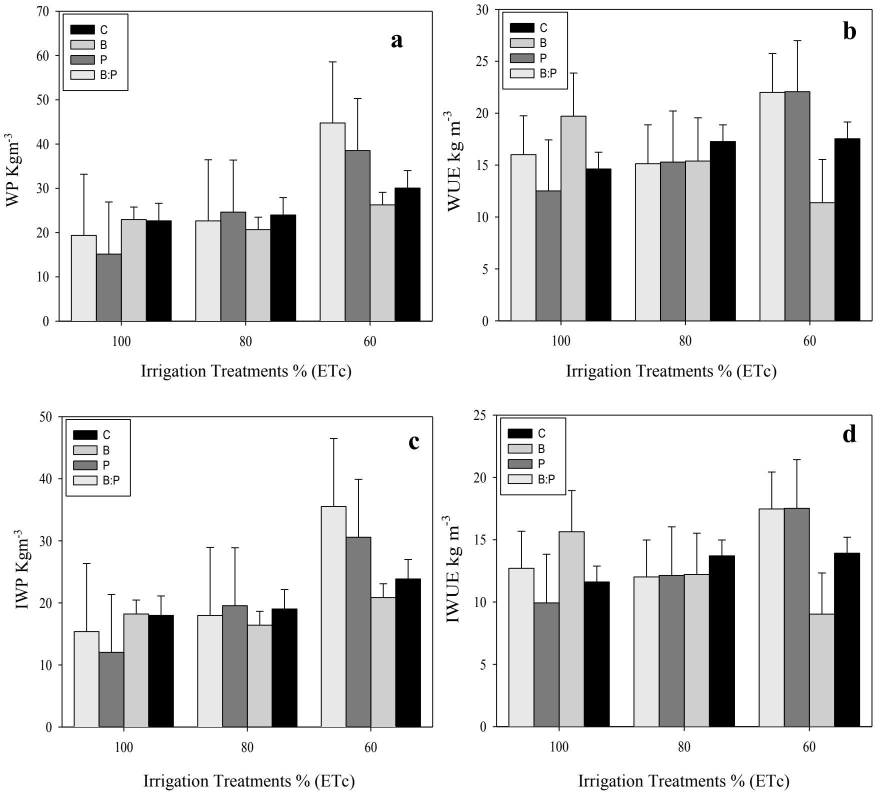

Fig. 5 Effect of deficit irrigation and soil amendments on water productivity (WP) and irrigation water productivity (IWP) for first season 2017 (**a**, **c**, for freshwater, and **b**, **d**, for saline water). The application rate 4% of biochar (B), 0.4% polymer (P), and 4%:0.4% Biochar: polymer (B-P). C is the control

and polymer improved yield and WP; these results are similar to previously reported findings (Agbna et al. 2017; Al-Harbi et al. 2015; Alomran et al. 2012; Islam et al. 2011; Qin et al. 2013; Usman et al. 2016; Uzoma et al. 2011; Wang et al. 2007; Yang et al. 2010).

5 Conclusion

Saudi Arabia is a limited water supplies country. More than 90% of water supplies come from groundwater which is essentially classified as brackish nonrenewable water resources. Excessive use of groundwater lead to major problems such as groundwater aquifers depletion and quality deterioration. The successful production of a tomato crop requires water, which is a limited resource in arid and semi-arid

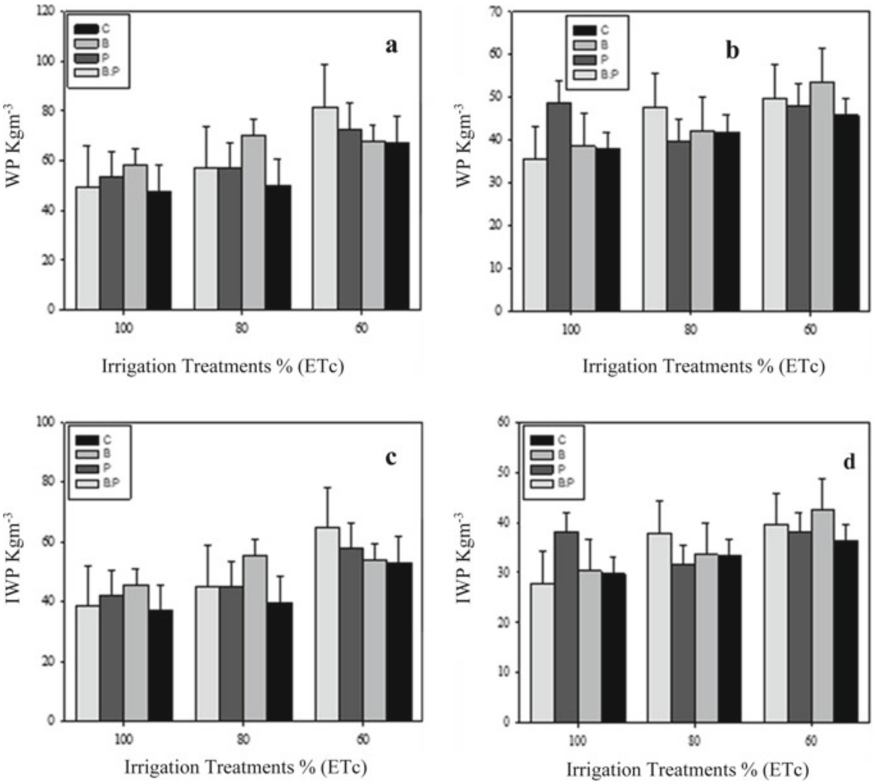

Fig. 6 Effect of deficit irrigation and soil amendments on water productivity (WP) and irrigation water productivity (IWP) for the second season 2018 (**a**, **c**, for freshwater, and **b**, **d**, for saline water). The application rate 4% of biochar (B), 0.4% polymer (P) and 4%:0.4% Biochar: polymer (B-P). C is the control

regions that are also characterized by sandy soil. In this study, soil amendments, either natural (date palm biochar waste at rate of 4%) or synthetic (polymer at rate of 0.4%) were used to improve soil properties and increase crop production, partly by increasing water use efficiency. Moreover, the use of a deficit irrigation strategy under freshwater at 100% of ET_c resulted in significantly higher yield with biochar compared to the polymer treatment, i.e., biochar and polymer yields were 188.33 and 124.33-ton ha^{-1}, respectively. The saline water led to increasing salt accumulation in the soil, which affected soil productivity adversely, as indicated by the lower yield of tomato compared to freshwater irrigation. The application of soil amendments (biochar and polymer) improved yield and WP in both seasons, and freshwater led to an increase in yield and WP compared with saline water. Therefore, under arid field conditions, the use of a deficit irrigation strategy along with soil amendments can increase the yield of tomato crops and save water. Research findings should be translated into field situation. Government agencies, together with universities, extension agents, and private consultants, should provide all type of water conservation measures to improve water use and management.

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Chapter 7
Seed Priming and Nano Priming Techniques as Tools to Alleviate Osmotic Stress in Legumes

Mohammed Mouradi, Mohamed Farissi, Ahmed Khadraji, Abdelaziz Bouizgaren, Ahmed Qaddoury, and Cherki Ghoulam

Abstract Salinity and drought are among the most influencing factors facing agricultural production. In many regions they cause up to 50 yield loss due to the secondary oxidative stress they create. The physiological reactions caused by oxidative stress adversely affect germination rate, plant growth, and development. Legumes, with their N2 fixing symbioses, developed various tolerance strategies to cope with these constrains, but the complexity of oxidative stress and climate change make it more difficult to maintain crop productivity. Seed priming may constitute an alternative as an easy, inexpensive, safe, and reliable technique for ameliorating germination under stress. It consists of inducing a particular physiological state in the plant via the treatment of the seeds with natural or synthetic agents before germination. Under unfavorable environmental conditions, seed priming allowed to restart the germination metabolism, thus improving the germination percentage and germination rate and reducing the germination time. Seed priming with nanoparticles (NPs) is a promising field of plant nanotechnology that can enhance osmotic stress tolerance by alleviating oxidative stress injuries in plants and install stress resistance in treated seedlings. Thus, this review will highlight the various potential benefits of NPs application as priming agents in the seeds of legumes and non-legumes, in some cases, through the comparison to the standard priming agents like polyethylene glycol (PEG), NaCl, and bioactive agents. Primed seeds 0showed low

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oxidative injuries due to the accumulation of osmoprotectants and osmotic adjustment stimulated by the variant priming agents including PEG, NaCl, etc. Bioactive priming agents like plant growth-promoting rhizobacteria (PGPRs), *Pseudomonas,* and *Trichoderma* are among many beneficial microorganisms used against biotic and abiotic stressors. Active NPs act in priming like biostimulants of salinity and drought resistance and enhanced water uptake. Seed germination and vigor, stimulate aquaporin (AQP) synthesis, photosynthesis, RuBisCo activity, antioxidant defense, nodulation in legumes, and nutrient uptake.

Keywords Salinity · Drought · Seeds · Priming · Nanoparticles · PGPRs

1 Introduction

Agriculture is facing many challenges due to climate change. Salinity and drought are the main abiotic factors to which plants are exposed during their life cycle. These two environmental constraints cause severe production loss by affecting growth, development and productivity of crops, especially in arid and semi-arid regions (Singh et al. 2015). Almost 20% of the world's arable land is affected by salinity, with an annual increase of 1 to 2% of land becoming affected. The presence of more salt in the soil than the plant needs disrupts its physiological, biochemical and metabolic processes (Xiong and Zhu 2002). Due to osmotic stress and ionic toxicity, salinity and water deficit induce the generation of reactive oxygen species (ROS), inhibit seed germination, reduce photosynthetic activity, disrupt membrane stability, and ionic balance and lipid metabolism (Farissi et al. 2018; Muchate et al. 2016; Aqtbouz et al. 2016; Zargar et al. 2017; Mouradi et al. 2018).

Various methods are used to improve plants' tolerance to abiotic stress. Selection of resistant varieties, natural crossings and genetic engineering are the main techniques to improve plants' tolerance to salt and water stresses (Jisha et al. 2013). Recently, 'seed priming' a pre-sowing treatment has been developed as a simple, effective, ecological, and natural method for improving plants' resistance to abiotic and biotic stresses (Bhanuprakash and Yogeesha 2016; Conrath et al. 2015). It consists of partially hydrating the seeds with natural or synthetic agents to proceed the pre-germinative events and prevent the radicle emergence in the imbibition phase. This creates a particular physiological state (plant tolerance memory) in the seed that can impact the plant tolerance in later growth stages (Abid et al. 2018; Chen and Arora 2013). When primed with the suitable agent, dry seeds accumulate more osmoprotectants and compatible solutes like proteins, glycine betaine, and sucrose, responsible of osmotic adjustment under salinity and drought constraints. It has been reported that this technique could improve seed germination, growth, photosynthesis, mineral and water nutrition, and the antioxidant system of plants (Lahrizi et al. 2021; Tounekti et al. 2020; Sen and Puthur 2020; Llorens et al. 2020; Parveen et al. 2019; Yusefi-Tanha et al. 2019).

Many nanomaterials, especially nanoparticles (NPs), belong to nanotechnology and have the potential to contribute as a new technological solution for agriculture problems. Many of them have proven their effectiveness when applied to plants for the protection from phytopathogens, plant nutrition amelioration and inducing resistance to abiotic stressors (Nayana et al. 2020; Maswada et al. 2020; Kumar et al. 2020). It has been reported that the binding proportion between seeds and NPs agents in nanopriming was found to be high compared to other priming agents like PEG, water and vitamins (Mahakham et al. 2017; Anand et al. 2019). The use of NPs and nanofetilizers as priming agents can strongly contribute to pest control, plant nutrition amelioration, and ecofriendly production methods. The NPs in seed priming can also act as biostimulants, improving seed germinative metabolism, plant growth, and activators of many signaling pathways. These effects depend on the size and the properties of the NPs applied to the seed. Researchers are exploring avenues for reducing fertilizer requirements by tweaking the seed metabolism through growth booster molecules or seed priming agents and using different nanoparticles as fertilizers.

The aim of this review is to provide an update concerning the potential applications of seed priming and nanopriming techniques with NPs and plant growth promoting rhizobacteria (PGPR) in legumes with their N_2 fixing symbioses and other plant species for mitigating the climate change effects and particularly salinity and drought constraints.

2 Seed Priming Techniques and Utilization in Legumes

One of the important challenges seed physiologists face is the selection of the priming medium. Seed priming has been reported to be one of the most widely used techniques to improve the tolerance of plants to abiotic stresses. This technique consists of inducing a particular physiological state in the plant by treating the seeds with natural or synthetic agents before germination (Lutts et al. 2016). Under unfavorable environmental conditions, seed priming helped restart germinal metabolism, thereby improving germination parameters as germination percentage, its rate and germination time (Pradhan et al. 2017; Lemmens et al. 2019).

Various seed priming techniques, including hydropriming, halopriming, osmopriming, chemopriming, biopriming, priming with growth hormones, etc., have been reported for their positive effects in improving plants' tolerance to some abiotic stresses like salinity and drought (Mouradi et al. 2018; Khadraji et al. 2020; Lahrizi et al. 2021) (Table 1). Although the role of seed pretreatment in improving seed and plant emergence has been reported by several authors (Khadraji et al. 2017, Mouradi et al. 2016b), the most suitable type of pretreatment mainly depends on the plant species and the type of stress to which the plants are exposed (Paparella et al. 2015).

Table 1 Techniques of seed priming, priming agents, and main effects

Priming technique	Plant species	Priming agent and concentrations	Abiotic stress	Seed germination and Agro-physiological effects	Citation
Halopriming (NaCl)	*Cicer arietinum* L	1 and 1.8 g.L^{-1} NaCl	Drought	• Increases germination rate • Highest mean germination time and time to 50% germination (T_{50})	Khadraji et al. (2020)
Halopriming (NaCl)	*Medicago sativa* L	200 mM NaCl for 24 hours	Salinity	• Germination success (89.17%), • Germination velocity (index value of 14.9)	Farissi et al. (2016)
Osmopriming (PEG_{6000})	*Cicer arietinum* L	−0.5 and −0.7 MPa	Drought	• Improves germination performances • Increases seedling vigor index, growth and plant height • Enhanced the activity of peroxidase, catalase and reduced the malonyldialdehyde content	Khadraji et al. (2017)
	Medicago sativa L	−0.6 MPa	Drought	• Increases growth, leaf area, and nodulation • Enhance the photosystem II (PSII) efficiency, and relative water content • Improves Nitrogen fixation, P and K^+ uptake	Mouradi et al. (2016a)

(continued)

Table 1 (continued)

Priming technique	Plant species	Priming agent and concentrations	Abiotic stress	Seed germination and Agro-physiological effects	Citation
	Medicago sativa L	−0.6 MPa	Drought	• Higher germination rate and growth • Enhance the activity of peroxidase (PO) and catalase (CAT) • Reduce the malonyldialdehyde (MDA) content and the electrolyte leakage	Mouradi et al. (2016b)
Biopriming	*Medicago sativa* L	*Ensifer meliloti* (Rm1021) strains	Drought	• Significantly improved chlorophyll, and photosynthesis performance and stomatal conductance • Enhance cell membrane stability	Lahrizi et al. (2021)
	Vigna radiata L and *Cicer arietinum* L	*Bacillus cereus*	Salinity	Increasing seedling height, number and length of leaves, root, and shoot biomass	Chakraborty et al. (2011)
	Pisum sativum L	*Typha angustifolia*	Salinity	Adequate levels of osmotica (Proline, total soluble sugars, Potassium and Phosphorus) Increases Chlorophyll and carotenoid contents	Ghezal et al. (2016)

2.1 Osmopriming

Osmopriming consists of immersing the seeds in an osmoticum such as mannitol, sodium chloride, or polyethylene glycol (PEG) and has a positive effect on the enhancement of seeds germination and seedlings growth, especially under stress conditions (Farooq and Basra 2006; Farooq et al. 2009; Chen and Arora 2011). This pretreatment makes it possible to influence the development of the seedlings, by modulating the metabolic and biochemical activities during the reversible phase of germination, which gives the seed a significant germination potential and subsequently allows a certain tolerance level to various abiotic stresses (Khadraji et al. 2017; Mouradi et al. 2016a) (Fig. 1). Osmopriming is a simple technique for the successful germination of many species, nodulation, and N2 fixation capacity for legumes and their production under environmental stress through the acquisition of nutrients from poor soils (Mouradi et al. 2016b; Amooaghaie and Nikzad 2013). Studies on the germination of alfalfa and chickpea seeds primed with polyethylene glycol 6000 (PEG 6000) showed a higher germination rate and growth compared to untreated plants. The highest germination percentages reached 90.8% under severe stress (Mouradi et al. 2016b). Osmopriming treatment by PEG 6000 improved the activity of antioxidant enzymes (peroxidase and catalase), maintained membrane stability through limiting phospholipids peroxidation (reduced malonyldialdehyde content) and reducing electrolyte leakage under this stress. In general, germination success was positively correlated with peroxidase (PO) and catalase (CAT) activities and the degree of membrane stability in drought-tolerant populations (Khadraji et al. 2017; Mouradi et al. 2016b) (Table 1).

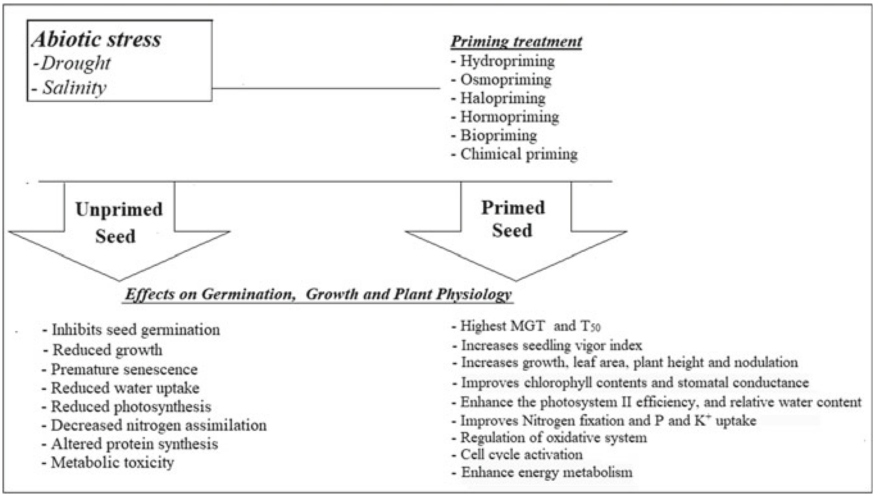

Fig. 1 Effects on germination parameters, growth, and plant physiology under different abiotic stresses

2.2 Halopriming

Halopriming is a technique of priming based on immersing seeds in different saline solutions ($CaCl_2$, $CaSO_4$, NaCl, etc.) that allows uniform germination of seeds, early emergence of seedlings, and an increase in biomass production, even under adverse environmental conditions (Khadraji et al. 2020; Jisha and Puthur 2014). This technique also induces the activation of enzymes involved in the breakdown and mobilization of reserves (Varier et al. 2010). The positive effects can continue even at the time of flowering and pod formation (Zare et al. 2011; Giri and Schillinger 2003). Several authors have explained the rapid and synchronized germination in the case of halopriming by activation of pre-germination processes, which promote quantitative and qualitative biochemical modifications at the level of the seed (Maroufi et al. 2011; Varier et al. 2010). Halopriming induces membrane repair (Jowkar et al. 2012) as well as the activation of endo-β-mannase (Varier et al. 2010) and more generally the increased activity of antioxidant enzymes (Ahmad et al. 2012). On the other hand, Varier et al. (2010) have explained the beneficial effects of halopriming on growth by an acceleration of nuclear replication in the roots and leaves.

2.3 Biopriming

Biopriming is an advanced treatment of seeds with biological means which allows both hydration and inoculation of the seeds by beneficial microorganisms before sowing, for improving the viability and vigor of the seeds as well as their germination, in particular under unfavorable conditions (Lahrizi et al. 2021; Mouradi et al. 2018). This technique also represents a kind of biocontrol through the use of microorganisms antagonistic to bacteria and phytopathogenic fungi in the soil by coating the seeds (Mahmood et al. 2016). The term biopriming was first introduced by Callan et al. (1990), where they applied a layer of biological primer on sweetcorn seeds with the fungi *Trichoderma asperellum* and *Trichoderma harzianum* and immersed them in lukewarm water (35–40% moisture content) for imbibition. In general, the goal of this treatment is to introduce beneficial microbes into the soil environment, followed by conventional inoculation (Reddy 2012). It allows uniform seed germination, viability, plant growth and finally improves crop yield. Most importantly, this ecofriendly approach protects seeds and plants from soil-borne pathogens mainly at the early stage of plant development (Lahrizi et al. 2021; Singh et al. 2016) (Fig. 1). Some biocontrol agents used with the seeds, like *Pseudomonas fluorescens* and *Clonostachys rosea,* have been shown to be able to colonize the rhizosphere, providing solubilized minerals to plants beyond the germination and seedling stages (Bennett and Whipps 2008). This depends mainly on the photosynthates exudation along with the root mucilage. This includes organic acids, amino acids, and carbohydrates, mandatory for microbial rhizosphere and root colonization (Reddy 2012). The main concern of this technique is related to the viability of the microbial agent on the surface of the seed. It has been demonstrated that PGPR strains keep on multiplying on the surface and in the spermosphere of seeds even before sowing (Mirshekari 2012; Reddy 2012). The bacterial survival depends on the species, soil proprieties, nutrients, competition with pathogens and other microbes, and water availability. Lahrizi et al. (2021) have demonstrated that plants raised from bioprimed seeds with rhizobia showed significant improvement of photosystem II performance, leaf relative water content, nodulation, and membrane integrity under water deficit (Table 1). Reddy (2012) reported that several microorganisms like *Trichoderma*, *Pseudomonas*, *Azotobactor*, *Azospirillum*, and *Agrobacterium,* when used as priming agents, can improve drought tolerance. Mirshekari (2012) demonstrated that seed biopriming with *Typha angustifolia* improved the salinity resistance in *Pissium sativum* L. Primed seeds showed better germination into seedlings under salinity by modulating membrane integrity. Photosynthesis, sugar metabolism and ionic hemostasis were also ameliorated in bioprimed *P. sativum* seedlings (Ghezal et al. 2016).

3 Nanoparticles (NPs) for Seed Priming for Legumes

Seed nano priming is a technology of seed treatment that uses nanomaterials for seed priming (Griffin et al. 2017). The particularity of this technique is that the priming solution is a suspension of nano formulations, mainly nanoparticles (NPs) of 1–100 nm. The nanoparticles are the building blocks of the nanotechnology. NPs are abundant in nature from inorganic ash, soot, sulfur, and mineral particles found in the air or in wells, to sulfur and selenium nanoparticles produced by many bacteria and yeasts (Buzea et al. 2007; Griffin et al. 2017). These are formed by many natural processes such as volcanic eruptions (silicate and iron compounds), forest fires (carbon nanotubes), erosion plants and animals shedding (selenium and tellurite) and photochemical reactions (silver NPs) (Griffin et al. 2017; Buzea et al. 2007; Bartlett et al. 2016). The NPs are recognizably different to the bulk materials for their small size and large surface area (Hong et al. 2013). Other differences are related to the physical strength, chemical reactivity, electrical conductivity, magnetism, and also optical effects (Hong et al. 2013). These proprieties allow them to be used in several industrial domains including food production and agriculture to reduce production cost. Several studies showed that nanoparticles have a great potential to be used in agriculture like nanosensors, with phytohormones, food additives, genetic improvement, for drugs, nano pesticides and nanofertilizers (Hong et al. 2013). The main factors adjusting the effect on plants depend on the plant species, the NPs intrinsic proprieties and concentration, the interaction time, and the interaction between living environment and plant (Miralles et al. 2012).

In seed nano priming, the NPs may or may not be taken up by the seed. Most of the nano priming techniques employ nano suspensions where the majority of NPs is retained in the seed surface or coat (do Espirito Santo Pereira et al. 2021). The seed nano priming can be used with seed coating with fungicides and insecticides in order to protect the crop from biotic ravagers or with biostimulants to improve tolerance

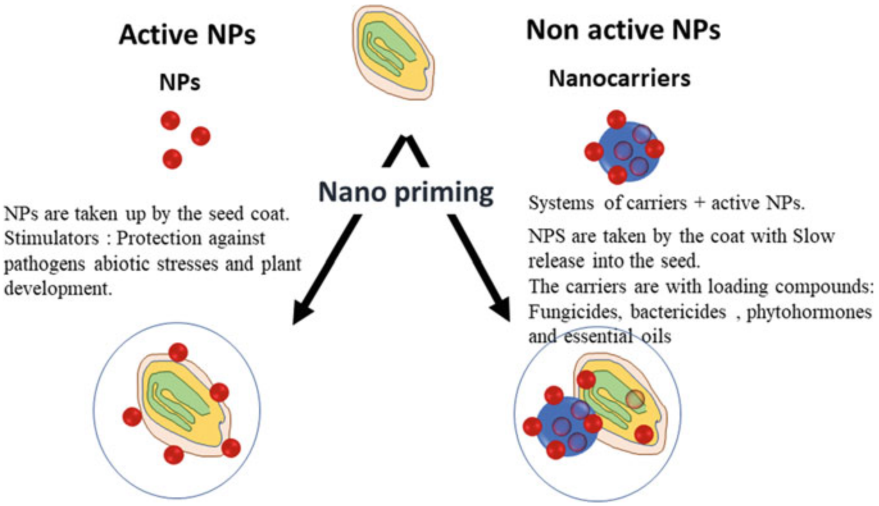

Fig. 2 Seed nanopriming. Active nanoparticles (NPs), systems that can be taken directly by the seed coat. They are generally plant growth and development stimulators and Nonactive NPs are systems of carriers providing a slow release of NPs during germination and seedlings growth and can be loaded by active compounds like fungicides, bactericides etc. (do Espirito Santo Pereira et al. 2021)

to abiotic stressors (Nayana et al. 2020; Bayat et al. 2020). In nano priming, we can distinguish two types of NPs, active or nonactive NPs (Fig. 2). The active NPs are particles that will be taken by the seed and retained in the seed coat after application. The nonactive particles will be used as nanocarriers for the active NPs when applied to the seed. The active NPs have been shown to ameliorate seed germination, and act as defense mechanisms against pathogens and environmental stresses (Chandrasekaran et al. 2020; Agathokleous et al. 2019). The system of carriers and active NPs is characterized by the slow release of the active NPs to the seed during germination. Both nano priming systems can be applied to seeds in order to provide protection during storage, improve germination, germination synchronization, and plant growth, as well as to increase the resistance to abiotic or biotic stress conditions (Chandrasekaran et al. 2020; Agathokleous et al. 2019). Active NPs can be characterized as direct stimulators of plant growth and development through activating biological effects and responses against stressors (Rizwan et al. 2019; Mishra and Singh 2015). Nanocarriers are systems of NPs that can be active itself or when loaded by other bioactive or synthetic compounds providing a slow release over time in the seed coat (do Espirito Santo Pereira et al. 2021; Kumar et al. 2020). Metallic and nonmetallic NPs can be used as active NPs priming suspension (Table 1). They have a direct effect on the seed germination and seedling growth. Many biopolymeric NPs can be used for the slow-release system. The biopolymers (more than 100 nm) are made from polysaccharides, lipids, and proteins and can be loaded by many substances of essential oils, pesticides, phytohormones, and fertilizers. For nano priming, alginate, cellulose, chitosan, and lipid NPs can be used to modify plant metabolism or against pathogens (do Espirito Santo Pereira et al.2021; Nayana et al. 2020; Kumar et al. 2020; Bayat et al. 2020).

3.1 Important Effects on Seed Germination

Nanomaterials can be applied to seeds (nanopriming) for the induction and improvement of seed germination, seed protection during storage, enhancement of plant growth, and the resistance to abiotic or biotic stressors (do Espirito Santo Pereira et al. 2021). Mahakham et al. (2017) investigated the effect of Ag NPs with *Citrus hystrix* leaf extracts to improve the germination of non-legume *Oryza sativa* seeds. The results demonstrated an enhancement of seed water uptake, α-amylase activity, and starch hydrolysis and produced more reactive oxygen species (ROS). Also, Maroufi et al. (2011) demonstrated that titanium (TiO_2, 0.02%) NPs improved germination and seedling growth of *Vigna radiata*. Carbon nanotubes also accelerated seed germination, growth rates as well as seedling vigor in tomato (Mondal et al. 2011). Bayat et al. (2020) demonstrated that the combination of iron and zinc NPs as seed priming accelerated the emergence of cotyledons in red beans and common beans cultivars. This may perhaps be due to the role of iron and zinc elements in the functional changes of different enzymes, which in turn causes positive synergistic effects on the bean plants. Furthermore, Hussain et al. (2019) reported that silicon (Si NPs) application as seed priming increased biomass and yield while reducing oxidative stress in wheat plants subjected to cadmium stress. Abdel-Aziz and Rizwan (2019) reported that silver (Ag NPs) increased growth of *Vicia faba* seedlings, photosynthesis, chlorophyll content, and starch accumulation. In the same sense, Zmeeva et al. (2017) showed that Si NPs improved plant height and tillers number, yield, fresh and dry root mass, plant transpiration, chlorophyll and carotenoids and photosynthetic pigments in *Medicago sativa*. It has been demonstrated also that silver NPs, used as priming suspension, may protect the seed from bacteria and fungi while silica NPs had the potential to improve the leaves mechanical strength, light absorption, enhance photosynthesis capacity, plant growth and endurance of plant organs and also reduce transpiration (Abbasi Khalaki et al. 2021). Iron NPs application control antioxidant activities and the functioning of phytohormones to enhance plant biomass while that of Titanium NPs helps to increase seed water absorption and boost vigor of old seeds (Abbasi Khalaki et al. 2021).

The majority of nanoparticles used with the seed nano priming for legumes are.

3.2 Seed Nanopriming and Oxidative Stress Tolerance

With their smaller size and higher effectivity, the NPs can help reduce the required quantities of chemical pesticides and fertilizers. Inside the plants and via the active transport system through xylem, NPs can change their structure and form ion complexes with other molecules or nutrients. The NPs can modulate the enzymatic activities related to the secondary oxidative stress, induced under osmotic stress, and activate the stress defense mechanisms. NPs can, at moderate levels, induce the generation of ROS, which constitute signaling pathways for transcription of different genes during the germination, and regulate secondary metabolites in germinated seedlings related to stress tolerance. These beneficial effects depend on the size and concentrations of the NPs and their physicochemical proprieties, mode of application, and the plant species (Fig. 3).

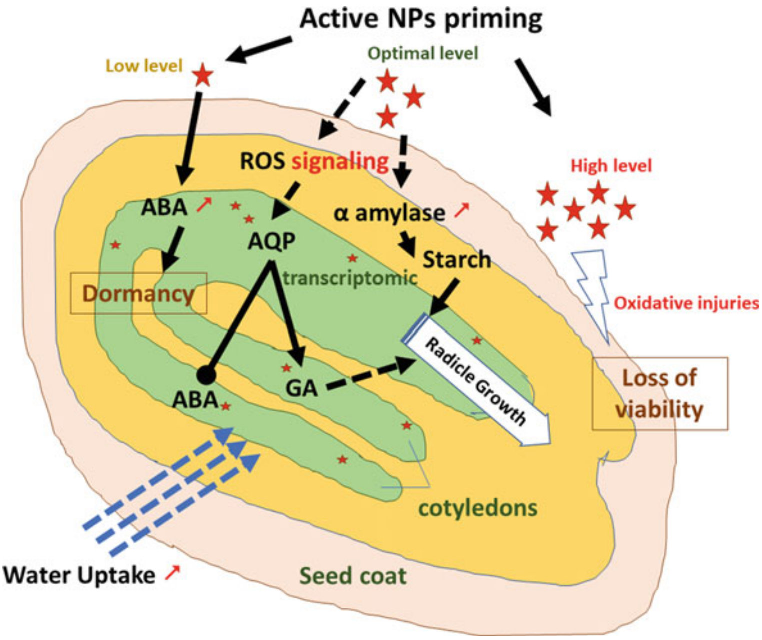

Fig. 3 Supposed model by Chandrasekaran et al. (2020) and do Espirito Santo Pereira et al. (2021) for the events occurring in nanoprimed seeds compartments by the action of active NPs. At low levels active NPs taken by the seed coat increased abscisic acid (ABA) synthesis and seed dormancy installation. At optimal level NPs induced ROS activation and signaling regulation of the gibberellic acid (GA) and ROS scavenging enzymes. Undetermined involvement of GA in internalization as well as NPs transport from seed coat to endosperm. Factors involved in sugar signaling responses, α amylase activity after NPs adhesion to radicle growth is indicated. ROS signaling of aquaporins (AQP) and increasing water uptake after NPs adhesion. At high level, NPs cause oxidative injuries through high levels of ROS and loss of the seed viability

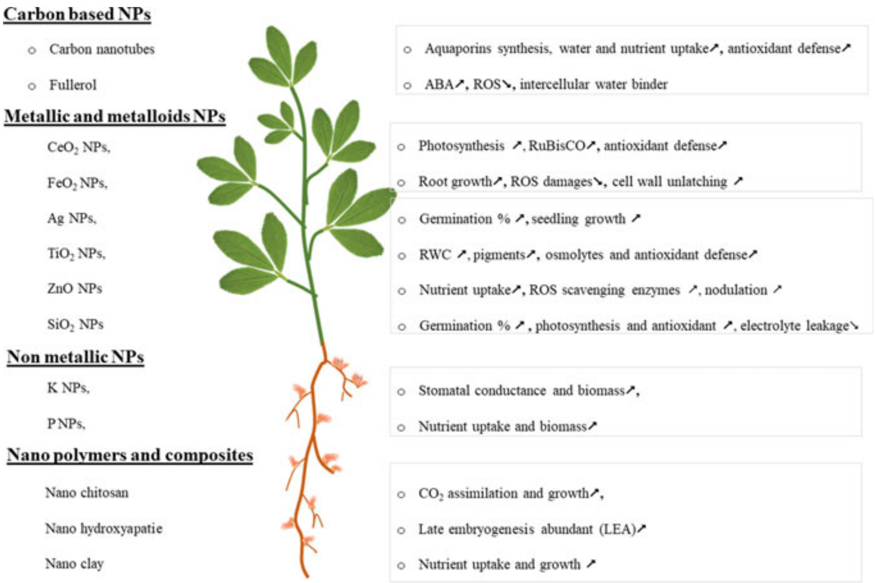

Fig. 4 NPs priming variant roles in overcoming drought stress in legumes and other plants (do Espirito Santo Pereira et al. 2021; Maswada et al. 2020; Agathokleous et al. 2019)

Generally, the beneficial effect of NPs under stress is clear at low doses and causes a low response stimulation "hormesis" under stress (Agathokleous et al. 2019). For example, in some non-legume species, carbon nanotubes application at 50 mg/l can stimulate drought tolerance by enhancing water uptake and the reduction of oxidative injury of *Hyoscyamus niger* L. while at high dose it causes cell injury (Hatami et al. 2017). Xiong et al. (2018) demonstrated that seed nanopriming with Fullerol represses ROS generation in *Brassica napus* L. by regulating the activation of non-enzymatic and enzymatic antioxidant compounds and also the ABA accumulation. The metallic NPs have also been demonstrated to be effective against drought in many species. Seed priming with iron NPs improved growth, photosynthesis, and photosystem II in sorghum plants (Maswada et al. 2018). Bayat et al. (2020) reported that soaking legumes seed with iron oxide NPs 4% for 3 hours enhanced growth and development of red beans (Table 2). Cao et al. (2018) demonstrated that Cerium oxide NPs improved biomass, water productivity, photosynthesis, and Rubisco activity in soybean plants subjected to different drought conditions (Fig. 4). Seyed Sharifi (2016) reported that ZnO NPs application next to biofertilizers improved nodulation in *Glycine max* L.. Mohaddam et al. (2017) reported that the combination of ZnO and Ag NPs enhanced nodulation in legume-rhizobium symbioses. This demonstrated that the beneficial effects of seed priming are conserved even at post germinative plant stages with markable changes in several physiological and biochemical responses in legumes and non-legumes (Mouradi et al. 2016a; Maswada et al. 2020). Seed priming with colloidal Molybdenum (Mo) NPs in the presence of microbial preparation stimulates root nodulation, symbiotic system, and antioxidant defense in chickpea under stress conditions (Taran et al. 2014). TiO_2 NPs can also stimulate plant growth in mung bean shoots and root length, nodulation, and promotes microbes in the rhizosphere (Raliya et al. 2015). These NPs have been reported enhancing the many crop performances and stress tolerance including soybean (*Glycine max* L.). this through enhancing chlorophyll content, photosynthesis and nutrient uptake (Andersen et al. 2016).

The effect of seed nanopriming on non-legumes like *Zea mays* L. and *Capsicum annum* L. under salinity stress has been investigated by Shah et al. (2021) and Ye et al. (2020). TiO_2 NPs (60 ppm) application mitigates salinity injuries in maize by maintaining leaf water content and inducing antioxidant enzymatic defense under salinity, 200 mM NaCl. Mn NPs at low concentrations (0.1, 0.5, 1 mg/L) improved the root growth (elongation) in salt-stressed seedlings of *C. annuum* L. (Ye et al. 2020). Mn NPs penetrates the seed coat, reduces the injuries of oxidative stress, and forms nanoparticle-corona complexes. This may play an important role in installing late salt tolerance in *C. annuum* L. (Fig. 5) (Ye et al. 2020). Shafiq et al. (2021) reported that Fullerenol at 80 nM improved ion uptake to reduce sodium toxicity and ameliorated biomass and grain yield in wheat plants under 150 mM NaCl. In legumes, nano silica (8 g/L) and gibberellic acid enhanced seed germination of pea, water uptake, ROS, and antioxidant in the seed under salinity (Chourasiya et al. 2021). Maroufi et al. (2011) reported that under salinity TiO_2 NPs (0.02%) significantly ameliorated germination percentage, seedling dry weight, and seedling vigor in *Vigna radiata* L. This nanopriming techniques can ameliorate seed germination performance and quality under stress in many ways including the activation of α-amylase activity, soluble sugars content, and stimulation of the activity of aquaporin channels increasing antioxidants to scavenge ROS, and the formation of nanopores to increase water uptake (do Espirito Santo Pereira et al. 2021).

3.3 Seed Nano Priming with PGPRs

PGPRs are root associated beneficial bacteria known for their ability to promote plant growth with direct or indirect mechanisms. Bacteria with direct mechanisms involve those related to nutrients mobilization like phosphate, zinc, iron, and sulfur, nitrogen-fixing symbioses and phytohormones production (Grobelak et al. 2015; Nayana et al. 2020). Indirect mechanisms involve protection against phytopathogens and enhancement of plant tolerance to abiotic stresses. The great variability of the PGPRs behavior is due to many factors like soil, plant species, and competitiveness with other microorganisms which is challenging their exploration as biofertilizers (Nayana et al. 2020).

In biopriming, PGPRs are applied as bacterial suspensions to the seeds, root surfaces, or directly in the rhizosphere. A consortium of bacteria has been proven to be more effective against indigenous microorganisms' competition in the soil then the

Table 2 Nanoparticles (NPs) utilized in seed nanopriming for legumes, their characteristics, the main effects on each studied species and stress conditions

Nano particle priming	Concentration and characteristics	Main effects	Legume species	Citation
Iron oxide	Soaked in 4% concentration and dried for 30 minutes in shade	Growth and development	Red beans	Bayat et al. (2020)
FeS_2 Nano-iron pyrite	100 µg/mL aqueous suspension of FeS_2 for 12 hours (overnight)	Biomass, number of leaves, root, and shoot length	*Medicago sativa* L	Das et al. (2016)
Zinc nanoparticles	–0.15%, size 20 nm spherical shape 40 and 60 nm elongated shape (3 hours) –0.006%, size 21.3 nm for 12 hours	Salinity resistance, increase of SOD, CAT, POD, and APX enzymes activities, photosynthetic pigments, organic solutes, as well as total phenols, ascorbic acid, and Zn over stressed plants alone	• *Phaseolus vulgaris* L • *Lupinus termis* L	Mahdieh et al. (2018), Latef et al. (2017)
Titanium NPs	2% for 24 hours	Increase in root and shoot length, lateral roots antioxidant enzymes	*Phaseolus vulgaris* L	Paul et al. (2020)
Silver nanoparticles (Ag NPs)	0.005% for 6 hours –0.000125% for 1.5 hours	Growth attributes and biomasses of bean seedlings chlorophyll contents, starch, and total carbohydrate contents • Biomass, plant height, number of nodules, Net photosynthesis intensity	• Broad bean • Green bean	Abdel-Aziz and Rizwan (2019), Prażak et al. (2020)
Platinum nanoparticles stabilized with poly (vinylpyrrolidone)	1 mM, size 3.2 nm, and spherical shape for 3 hours	Seed and seedling vigor, plant morphology, higher yield	*Pisum sativum* L	Rahman et al. (2020)

(continued)

Table 2 (continued)

Nano particle priming	Concentration and characteristics	Main effects	Legume species	Citation
Copper nanoparticle	0.1%, size 25 nm for 20 min	Seed and seedling vigor and biomass. High concentration inhibited seed germination	*Phaseolus vulgaris* L	Duran et al. (2017)
Silicon SiO_2 NPs	0.006% for 48 hours	Increased germination rate 20% of deteriorated seed, reduced the mean germination time (MGT)	*Glycine max* L	Mansouri Gandomani and Omidi (2017)
Chitosan and carbon nanotubes	• Chitosan 10% nanoparticles with size of 95 nm • Carbon nanotubes 10% with size of 40 nm for 3 hours • CsNPs 0.05%, size 20 nm for 3 hours	• Plant morphology ROS elevation • Seed germination, total polyphenols, antioxidant activities	*Phaseolus vulgaris* L Broad Beans	Zayed et al. (2017), Abdel-Aziz (2019)

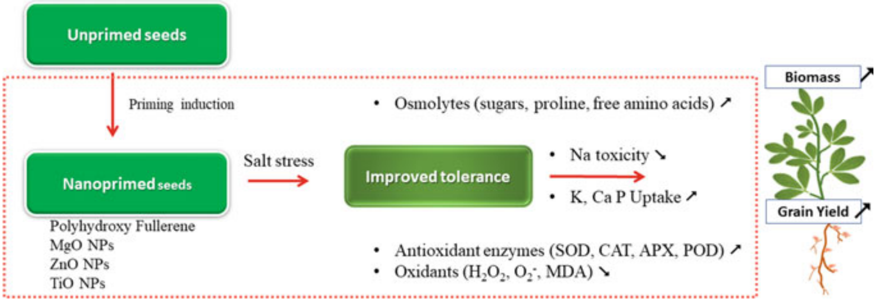

Fig. 5 Proposed Model of the effect of NPs priming on plants under salinity stress (Shafiq et al. 2021; Ye et al. 2020; Abou-Zeid et al. 2021)

single inoculation. The microbial consortium can be prepared with NPs for wider use due to their small amounts and great effects on plant growth and resistance (Fig. 6) (Nayana et al. 2020). In nature, root exudate can produce various nano size metallic formulation acting as plants bio stimulants in the rhizosphere. It is reported that Gold NPs with *Pseudomonas monteilii* enhanced indole acetic acid (IAA) production in the bacteria and improved probiotic effect in cowpea. ZnO NPs had been reported to also ameliorate nodulation, plant height, grain yield and weight in soybean (Seyed Sharifi

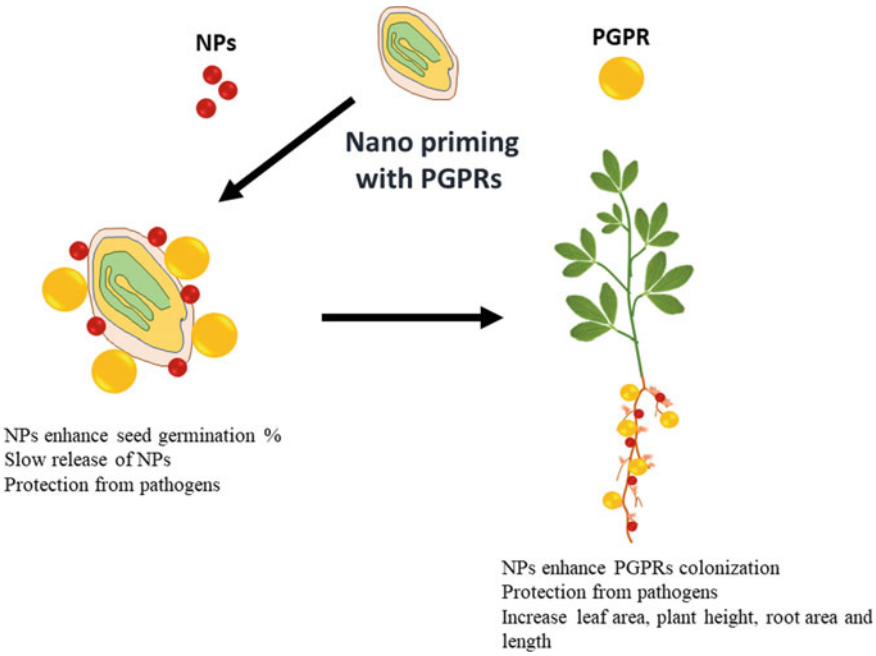

Fig. 6 Combined application effects of NPs and PGPRs (Nayana et al. 2020)

and Khoramdel 2015). In non-legumes, Karunakaran et al. (2013) reported that SiO NPs synthesized from rice ash with a consortium of *Bacillus*, *Pseudomonas,* and *Azotobacter* genera improved seed germination percentage of maize in comparison to conventional Si NPs. Hatami et al. (2021) reported that the application of SiO NPs (100 mg/L) as seed priming with *P. fluorescens* produced healthy seedlings of lemon balm with higher biomass, RWC, photosynthetic pigments and antioxidant activity, and lower membrane electrolyte leakage. The application of SiO NPs induced the appearance of micropores in the seed coat causing higher water uptake and healthier seedlings (Hatami et al. 2021).

4 Conclusion and Recommendations

Salinity and drought are the major factors facing agriculture production and food security in many regions around the world. The present chapter reveals that seed priming is a safe and easily applied technique for uniform and successful germination and establishments of legumes, especially under salinity and drought. Seed priming enhanced germination parameters under stress including germination percentage, mean germination time (MGT), germination rate, and seedlings growth by increasing antioxidants. Seed priming also ameliorated the N_2 fixing ability of legumes by enhancing nodulation, rhizobia root colonization, and nutrient uptake. According to the literature in this review, the application of NPs as nano priming agents is significantly more important in stimulating osmotic stress tolerance in legumes and other plant species than the standard priming agents like PEG, nutrients, and vitamins. NPs in seed priming can alleviate osmotic stress damages by inducing antioxidant defense, osmoprotectants, and ion balance in the seed and thus promote water uptake, seed germination, and seedling health. NPs can also stimulate aquaporins synthesis, photosynthesis, Rubisco activity, nodulation in legumes, and nutrient uptake. In addition, the application of NPs with PGPRs is a promising field of biofertilizers research. Further l studies will be needed to examine the interactions of treated plants with NPs and PGPRs consortia in order to increase osmotic stress tolerance in legumes.

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Part III
Using Saline Water for Conventional, Non-Conventional and Forage Crops

Chapter 8

Exploration and Collection of Quinoa's Wild Ancestor in Argentina

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Abstract In this paper we tested the performance of the Species Distribution Models (SDMs) to provide reliable guidelines for planning a collection mission for quinoa's wild ancestor, *Chenopodium hircinum*, across Argentina. A model was constructed by combining a prediction of the species' geographic distribution based on bioclimatic variables and herbarium specimen records. Annual temperature and precipitation seasonality, and mean temperature of the wettest quarter were the bioclimatic variables with the highest mean contribution to the model. Northwest and Central Argentina were the regions predicted with the highest habitat suitability. Then, SDMs predictions were tested by conducting a field-collection trip during February 2017 to previously unsampled localities. In each locality we determined whether or not *C. hircinum* was present. The model performed relatively poorly, as a significant number of collected populations came from localities with a low estimated probability of occurrence. On the other hand, the Humid Pampas, a region with abundant previous reports, yielded just one sample. This result is relevant for the development of new SDMs to plan subsequent field-collection trips for *C. hircinum* and points to further improvement of these models based on information gathered here. The field-collection trip produced 59 samples of *C. hircinum* populations covering a wide range of contrasting environments in terms of latitude, elevation, temperature and precipitation regimes. Moreover, a large number of collected populations came from Dry Chaco and High Monte ecoregions, which are very hot environments with maximum

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temperatures often higher than 25 °C during *C. hircinum*'s growing season (spring–summer). A comparative analysis of adaptability ranges between quinoa cultivars from the whole range of the species distribution and collected wild *C. hircinum* populations from Argentina reveals that quinoa's wild ancestor explores a hotter range and suggests it can increase quinoa's adaptation range and yield stability by providing new allelic variation to breeding programs.

Keywords Argentinean lowlands · *Chenopodium hircinum* · Germplasm collection · Maxent · Quinoa · Plant genetic resources

1 Introduction

Quinoa is a highly nutritious crop of Andean origin that evolved in harsh environments. Although characterized as a stress-tolerant species, the recent global expansion of its production exposed the crop to new challenges. One of those challenges is warm temperatures during reproductive growth (Hinojosa et al. 2019). *Chenopodium hircinum* Schrad., quinoa's wild ancestor and with which it is easily crossed to produce fully fertile offspring, is distributed throughout Argentina, including mountains and plains and along a wide latitudinal range (Wilson 1988, 1990). Argentinean populations of *C. hircinum* thrive in some of the hottest environments in South America (Jellen et al. 2011). Accordingly, some of those populations could express useful traits which if transferred to quinoa could improve the crop's adaptation to warm locations.

Recently, Curti et al. (2017) evaluated the conservation status of pseudocereal CWR species and revealed a null percentage of Argentina's *C. hircinum* wild populations are currently conserved in the country's Germplasm Bank Network (INTA GBN), or even in international gene banks. These severe gaps in ex situ collections indicate that collection efforts for quinoa CWR species must be intensified, especially as quinoa's cultivation at high altitudes is threatened by the effects of anthropogenic climate change (Castañeda-Álvarez et al. 2016).

Plant collecting missions have benefited from the application of Geographic Information Systems (GIS) and the development of fast-computational algorithms such as Species Distribution Models (SDMs) (Jarvis et al. 2005; Ramírez-Villegas et al. 2010; Fois et al. 2018). By conducting spatial analyses of species distributions, gaps in collections can be prioritized in a more objective manner and targeted for collecting missions (Cobben et al. 2015). Species Distribution Models (SDMs) have previously been used for PGR collections and positive results have been reported in terms of number of populations collected, since the models predict the potential collection sites based on the most favorable environment for the target species (Villordon et al. 2006; Parra-Quijano et al. 2012b; Fois et al. 2015). Since germplasm collectors and curators have few records for the occurrence of rare species and they urgently need reliable tools for planning future collection missions, SDMs have potential utility for optimizing collecting mission while minimizing the risk of over- or under-estimation

(Jarvis et al. 2005; Fois et al. 2018). In this context, we used SDMs to: (i) model the potential distribution of *C. hircinum* across Argentina and (ii) explore the feasibility of using these models to planning future collecting mission for this species.

2 Materials and Methods

MaxEnt (Phillips et al. 2006) was used to model the potential distribution of *C. hircinum* in Argentina. The model predicts the distribution using species presence points as well as environmental variables covering the study area (Elith et al. 2011). Occurrence records of *C. hircinum* were obtained from the Global Biodiversity Information Facility (GBIF, available at http://www.gbif.org/) and CWR Diversity (available at http://www.cwrdiversity.org/) websites, and the environmental inputs included altitude and 19 bioclimatic variables from the WorldClim (ver. 2) website (http://www.worldclim.org). It needs to be highlighted that the model does not consider soil composition variables. The ROC curves (Receiver Operating Characteristic) and AUC (Area Under the Curve) were used to evaluate the accuracy of MaxEnt in modeling the target taxon distribution, as implemented by MaxEnt (Phillips et al. 2006). Furthermore, the MaxEnt-based variables selection procedure (jackknife-based) was used to evaluate the most important bioclimatic variables that define *C. hircinum*'s geographic distribution.

The Argentina *C. hircinum* collection expedition was used to validate and determine the utility of the MaxEnt model for germplasm collecting mission planning when applied to this species. For this, the collection mission was planned by focusing on the probability threshold values ≥ 0.90 (arbitrary threshold) of the potential habitat suitability map of this species. In each previously unsampled locality having a high estimated probability of occurrence we determined whether or not *C. hircinum* was present. As one of the goals was to include samples from environments for which there are current and past cultivated quinoa reports (Andrade et al. 2015), the collection trips also included parts of the Monte ecoregion in Mendoza and Neuquén provinces toward Patagonia, environments with low predicted values according to the model. To assess the model prediction in relation to expedition data, the predicted probability of occurrence was determined for the 30-arcsec grid cell in which a population was found. All probabilities were classified from 0 to 1.0 and the number of presence and absence locations were summed per class.

We collected passport data from quinoa cultivars currently evaluated worldwide from the GRIN-global website (https://npgsweb.ars-grin.gov/gringlobal/search.aspx) and then with ArcGIS Toolbox extracted temperature and precipitation climatic information. Density plots of the average daily maximum temperature and yearly precipitation of the native ranges of C. quinoa and *C. hircinum* were calculated using the package ggplot2 (Wickham 2016).

3 Results

According to the ROC curves, modeled *C. hircinum* potential distribution showed a high level of AUC predictive performance (training 0.96 ± 0.5; test, 0.91 ± 0.7). Based on the jackknife test, environmental predictors that exhibited the highest mean contributions were temperature seasonality (Bio4) and precipitation seasonality (Bio15) both defined in terms of annual ranges, and mean temperature of the wettest quarter (Bio8) (Table 1). Bio4 was the variable with the highest gain (>2) when used in isolation, and the same variables were the ones that decreased the gain the most when omitted. Considering permutation importance, isothermality (Bio3) defined as the ratio between mean diurnal range (mean of monthly (max temp − min temp)) and temperature annual range, mean temperature of warmest quarter (Bio10) and Bio4 were the main environmental variables affecting the potential distribution of *C. hircinum* (Table 1).

C. hircinum potential distribution map in Argentina is shown in Fig. 1. Out of 2,760,555 km^2 of the total country area, 2,162,361 km^2 (~78%) was predicted as unsuitable for *C. hircinum*; the remaining 598,194 km^2 was divided into 180,687 km^2 (6.5%) with a low potential probability (0.51–0.60), 135,950 km^2 (4.9%) with a moderate potential probability (0.61–0.70) and 281,558 km^2 (10%) with the highest probability ($\geq$0.71) of suitable ecological conditions. The majority of suitable habitats ($\geq$0.71) were located in the central and northern parts of Argentina (Fig. 1).

Figure 2 shows the presence or absence of *C. hircinum* in 75 locations sampled during the collecting expedition in February 2017 (end of the Southern Hemisphere summer and of reproductive growth of the species) in relation to the MaxEnt probabilities of occurrence. The model performed relatively poorly, as at locations with

Table 1 Estimates of average contribution and permutation importance of the environmental variables used in MaxEnt modeling of *C. hircinum* according to jackknife test (Phillips et al. 2006)

Variable	Percent contribution	Permutation importance
Bio2	3.8	4.8
Bio3	5	42.4
Bio4	46.1	9.6
Bio6	2.7	0
Bio7	1.7	0
Bio8	6.5	8.4
Bio9	4.4	0
Bio10	4.7	11.2
Bio11	6	5.7
Bio12	0.2	2.3
Bio13	0.5	5.3
Bio15	15.4	8.4
Bio18	3	1.9

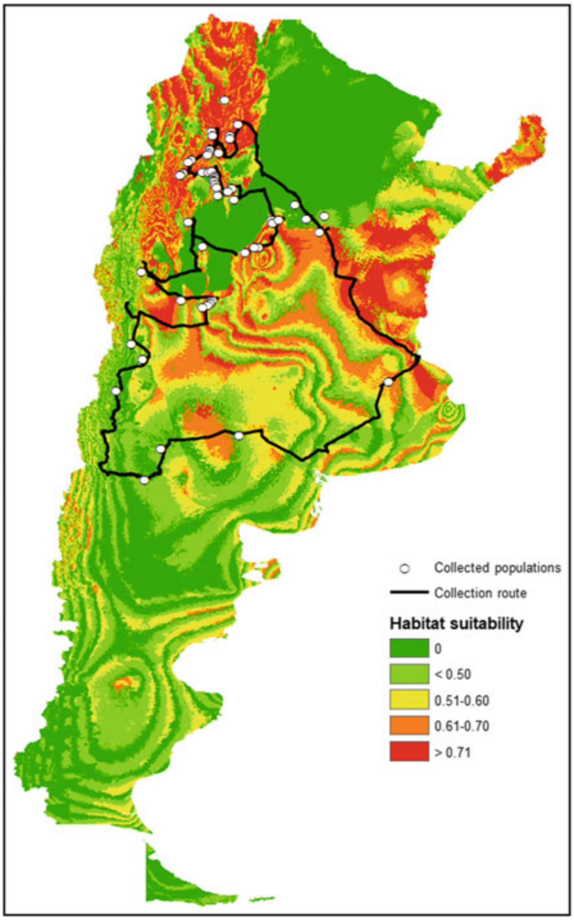

Fig. 1 Map for habitat suitability probability of *C. hircinum* according to occurrence records in Argentina. Habitat suitability classes include: unsuitable (<0.50), low potential (0.51–0.60), moderate potential (0.61–0.70) and high potential (>0.71). See color charts

low estimated probabilities of occurrence, presence of the species was comparatively higher than its absence (Fig. 2).

Fifty-nine populations of *C. hircinum* were collected from Argentina covering a large latitudinal (from –24.89 to –39.04) and altitudinal (from 32 to 2,116 m. a. s. l) range, respectively (Table 2). Most collected accessions came from Catamarca, San Luis, Salta and Santiago del Estero provinces, covering the ecoregions of Dry Chaco, High Monte and Southern Andean Yungas (Table 2).

Figure 3 shows the climatic patterns of Argentina to which the collection places are superimposed. Isohyets and isotherms maps were generated with the ArcGIS Toolbox to show the large annual precipitation (from 200 to 900 mm) and mean temperature (12 to 20 °C) ranges for the locations explored during the collection expedition. The isotherm map for mean annual maximum temperature shows that a large number of collected populations came from locations with summer maximum average temperatures higher than 25 °C (Fig. 3). In addition, density plots calculated

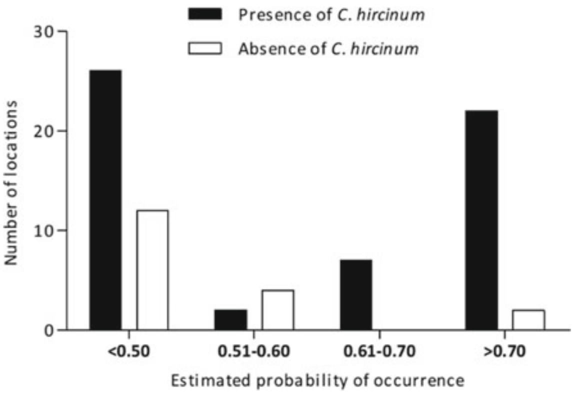

Fig. 2 Number of locations in Argentina where *C. hircinum* were present or absent plotted according to the probability classes of occurrences at these locations

for *C. hircinum* and *C. quinoa* show that wild *C. hircinum* populations grow and flower in warmer and drier (with a higher degree of overlapping for this variable however) habitats than the cultivated quinoa (Fig. 4).

4 Discussion and Conclusions

According to our results, *C. hircinum* is widely distributed across central and northern parts of Argentina covering three main ecoregions known as Dry Chaco, High Monte and Southern Andean Yungas (Olson et al. 2001), suggesting that the target taxon prefers subtropical climates (Wilson 1988; Jellen et al. 2011). This result matched with the planned collection route that allocated exploration efforts mainly to those ecoregions in which a large number of populations were collected. However, exploration of localities with a low estimated probability of occurrence for the target taxon, such as Mendoza and Neuquén provinces, and environments toward the southeastern plains of Santiago del Estero, yielded an important number of populations. These results could be explained by the data source used to construct the distribution of the species. Since herbarium data are incomplete and suffer from sampling bias, it is probable that the distribution deduced for *C. hircinum* with an associative species distribution model such as MaxEnt, wouldn't necessarily represent the complete distribution of the species. Consequently, new populations could be encountered outside the predicted distribution, for example in Northwestern Patagonia. Moreover, the species' collection points recorded in those environments should be used to redefine its predicted distribution across Argentina and direct future collection missions toward those sites.

The Pampas region, in the Center-East part of the map, deserves a special comment. Figure 1 shows a medium to high probability of occurrence for this region, which encompasses parts of Buenos Aires, Córdoba and Santa Fe provinces; however it yielded just one sample (CHIR 56 in Table 2). Additionally, this accession comes from a locality with sandy soils, perhaps the main factor explaining its survival in the

Table 2 Passport data (latitude and longitude in coordinates, elevation in m.a.s.l.) for the collected populations of *C. hircinum* in field expeditions during 2017

Accession #	Province	Longitude	Latitude	Elevation	Ecoregion
CHIR 001	Santiago del Estero	−62.44	−29.35	83	Dry Chaco
CHIR 002	Santiago del Estero	−62.85	−28.82	98	Dry Chaco
CHIR 003	Salta	−64.97	−25.8	783	Dry Chaco
CHIR 004	Salta	−64.98	−25.81	790	Dry Chaco
CHIR 005	Tucumán	−65.28	−26.24	775	Dry Chaco
CHIR 006	Tucumán	−65.3	−26.37	769	Dry Chaco
CHIR 007	Tucumán	−65.69	−26.9	1,913	Southern Andean Yungas
CHIR 009	Salta	−65.94	−26.23	1,660	High Monte
CHIR 010	Salta	−65.97	−26.07	1,615	High Monte
CHIR 011	Catamarca	−66.05	−26.73	1,912	High Monte
CHIR 012	Catamarca	−66.06	−26.78	1,956	High Monte
CHIR 013	Catamarca	−66.1	−26.88	2,063	High Monte
CHIR 014	Catamarca	−66.14	−26.96	2,116	High Monte
CHIR 015	Catamarca	−66.72	−27.16	2,064	High Monte
CHIR 016	Catamarca	−66.84	−27.22	1,869	High Monte
CHIR 017	Catamarca	−67.03	−27.63	1,355	High Monte
CHIR 018	Catamarca	−67.1	−27.71	1,179	High Monte
CHIR 019	Catamarca	−67.14	−27.71	1,237	High Monte
CHIR 020	Catamarca	−66.33	−27.58	1,074	High Monte
CHIR 021	Catamarca	−66.1	−27.62	1,767	Southern Andean Yungas
CHIR 022	Catamarca	−65.99	−27.58	1,809	Southern Andean Yungas
CHIR 023	Catamarca	−65.88	−27.77	1,393	Southern Andean Yungas
CHIR 024	Catamarca	−65.86	−27.82	1,206	Southern Andean Yungas
CHIR 025	Catamarca	−65.88	−27.91	1,221	Southern Andean Yungas
CHIR 026	Catamarca	−65.87	−27.93	1,178	Southern Andean Yungas
CHIR 027	Catamarca	−65.87	−27.95	1,165	Southern Andean Yungas
CHIR 028	Catamarca	−65.82	−28.04	1,054	Southern Andean Yungas
CHIR 029	Catamarca	−65.79	−28.16	956	Dry Chaco
CHIR 030	Catamarca	−65.76	−28.48	500	Dry Chaco

(continued)

Table 2 (continued)

Accession #	Province	Longitude	Latitude	Elevation	Ecoregion
CHIR 031	Catamarca	−65.37	−28.32	972	Dry Chaco
CHIR 032	Catamarca	−65.21	−28.2	543	Dry Chaco
CHIR 033	Santiago del Estero	−65.12	−28.62	337	Dry Chaco
CHIR 034	Santiago del Estero	−63.72	−29.4	463	Dry Chaco
CHIR 035	Santiago del Estero	−63.7	−29.5	538	Dry Chaco
CHIR 036	Santiago del Estero	−63.69	−29.5	565	Dry Chaco
CHIR 037	Santiago del Estero	−63.47	−29.39	241	Dry Chaco
CHIR 038	Córdoba	−64.22	−30.43	834	Dry Chaco
CHIR 039	Córdoba	−64.38	−30.41	661	Dry Chaco
CHIR 040	Córdoba	−64.73	−30.58	511	Dry Chaco
CHIR 041	La Rioja	−66.3	−30.36	468	Dry Chaco
CHIR 042	La Rioja	−66.84	−29.44	488	Dry Chaco
CHIR 043	San Juan	−68.61	−31.33	1,001	High Monte
CHIR 044	San Luis	−67.12	−32.38	594	Dry Chaco
CHIR 045	San Luis	−65.94	−32.37	601	Dry Chaco
CHIR 046	San Luis	−66	−32.42	652	Dry Chaco
CHIR 047	San Luis	−66.06	−32.47	637	Dry Chaco
CHIR 048	San Luis	−66.13	−32.59	768	Dry Chaco
CHIR 049	San Luis	−66.31	−32.65	715	Dry Chaco
CHIR 050	Mendoza	−68.98	−34.03	1,211	Low Monte
CHIR 051	Mendoza	−68.56	−34.58	864	Low Monte
CHIR 052	Mendoza	−69.55	−35.74	1,730	Southern Andean steppe
CHIR 053	Neuquén	−68.5	−39.04	296	Low Monte
CHIR 054	Río Negro	−67.87	−37.92	310	Low Monte
CHIR 055	La Pampa	−64.94	−37.43	291	Espinal
CHIR 056	Buenos Aires	−59.36	−35.42	32	Humid Pampas
CHIR 057	Salta	−65.47	−24.89	1,231	Dry Chaco
CHIR 058	Santa Fe	−61.95	−29.86	89	Dry Chaco
CHIR 059	Santa Fe	−61.77	−29.23	64	Dry Chaco

Ecoregions are presented according to Olson et al. (2001)

region. The Pampas region has been extensively explored by the Argentinean authors of this paper yielding no additional *hircinum* samples. The most recent herbarium specimens of the species are several decades old; meanwhile, the Pampas have been subjected to many changes in terms of tillage (mostly no tillage today), crops (soybean started to be extensively cultivated in the 80s) plus significant changes in herbicide use (Viglizzo et al. 2011). All these factors could have dramatically altered *hircinum*'s

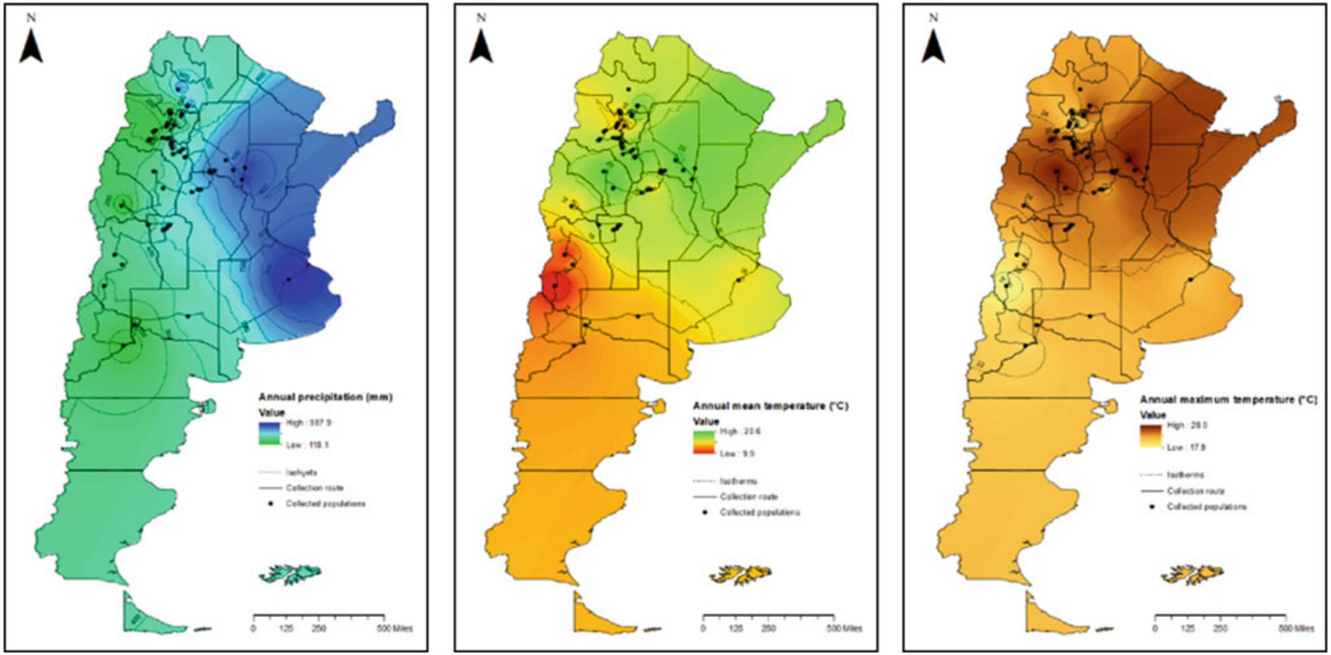

Fig. 3 Isohyets (left) and isotherms for mean (middle) and maximum (right) temperatures maps from Argentina and geographical distribution of the collected populations of *C. hircinum*. The high and low value numbers in each map legend represent the range of conditions explored by the collection

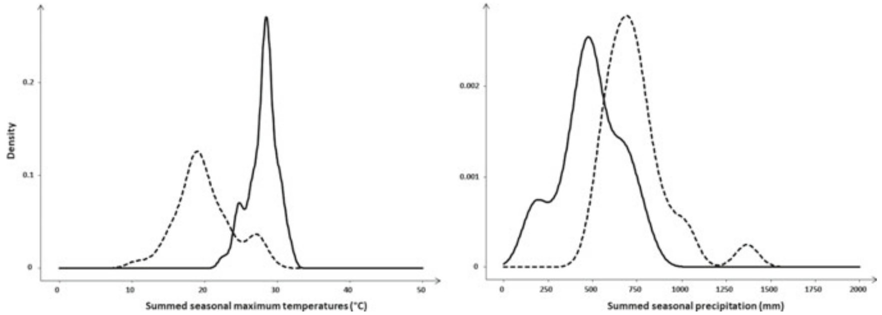

Fig. 4 Density plots representation of the average daily maximum temperature (left) during the rainy season (spring–summer) and yearly precipitation (right) of the native ranges of *C. quinoa* cultivars (dashed line) and *C. hircinum* (bold line) populations calculated from genotypes passport information and climate data retrieved from WorldClim (ver. 2) website (available at http://www.worldclim.org). Passport data from the described collection trip were used for *C. hircinum* while data from 109 locations of quinoa cultivation, spanning the whole range of distribution of the species from 2°N in Southern Colombia to 47°S in Southern Chile were used for quinoa

adaptation range in the Pampas, where the main *Chenopodium* weed today is *C. album* (Scursoni and Satorre 2010). On the other hand, *C. album* is substituted by *C. hircinum* in similar habitats (road margins and wastelands) of drier and hotter environments of the collection environments. A similar situation has occurred within the U.S. humid Corn Belt, where the North American authors of this paper have likewise struggled to find modern populations of the native, and previously abundant, North American sister-species of *C. hircinum*, *C. berlandieri*, on non-sandy coastal soils east of –96° longitude (Scursoni et al. 2006; Drewitz and Stoltenberg 2018). The ecological and management factors determining *C. hircinum* distribution are a research subject of high interest, beyond those related to species distribution maps.

For *C. hircinum*, the distribution model was to some extent useful to detect locations from where to collect germplasm, as an important number of populations were collected from localities where the model predicted the highest probability of occurrence for the target taxon. However, the performance of the model was relatively poor in those localities with low to moderate probabilities. Improvements to the model could be made by developing the ELC (Ecogeographical Land Characterization) maps that take into account information from edaphic variables (Parra-Quijano et al. 2012a, b; Marinoni et al. 2015), which to some extent seems to determine the occurrence of *C. hircinum* in the Pampa region. Furthermore, the inclusion of vegetation surveys covering a range of both habitats and landscape features (e.g. fields, hedgerows, waterways and roadsides) (Rubio Teso and Iriondo 2019; Jarvis et al. 2015) could be useful to identify the habitats and features with the highest proportion of wild *C. hircinum* populations, since these features seem to determine its occurrence in drier and hotter environments toward northern parts of Argentina.

Climatic information extracted from locations where populations of *C. hircinum* were collected revealed a large range of precipitation and temperature conditions, even for maximum temperatures. In this sense, the model guided the germplasm collectors to the preferred sites of this species, while at the same time covering a wide range of climatic conditions. Moreover, Argentinean populations of *C. hircinum* collected from hottest environments could express useful traits which transferred to quinoa and could improve adaptation to warm locations. A comparative inspection of adaptability ranges between quinoa cultivars and *C. hircinum* collected populations from Argentina reveals to what extent quinoa's wild ancestor can increase their adaptive capacity into new hottest agricultural systems by conferring new allelic variation required in breeding programs.

In conclusion, SDMs such as MaxEnt are a useful aid in planning collection missions to recover germplasm for wild populations of species with little or poor representation in gene bank collections, however improvements to the model require more consideration of expert knowledge and further refinements by including relevant information (i.e., edaphic variables, vegetation surveys and habitat features) at the species level which could be useful to determine their occurrence across different ecogeographical conditions.

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Chapter 9
Multilocation Evaluation of Alternative Forage Crops Grown Under Salinity Conditions in the South of Morocco

Ayoub El Mouttaqi, Ihssane Mnaouer, Mohamed Belcaid, Mohamed Ibourki, Lamine Diatta, Krishna Prasad Devkota, Abdelaziz Nilahyane, and Abdelaziz Hirich

Abstract Salinity is a major problem affecting agricultural activity in many regions across the world. Therefore, practices such as biosaline agriculture and crop diversification by introducing alternative crops are key solutions to overcome this problem and enhance the productivity of salt-affected lands. This study aimed to evaluate the performance of several alternative forage crops, including cereals, pseudo-cereals, grasses, legumes, and fodder beet cultivated under saline conditions in five experimental sites in the south of Morocco. The obtained results indicated that not all crops performed very well on all sites. Crops with low tolerance to salinity, such as the cereals group, showed a significant reduction in dry biomass and yield due to increased salinity. In comparison, salt-tolerant crops such as blue panicum, sesbania, and fodder beet showed higher productivity under moderate and high salinity levels in comparison with low salinity. The findings of this study clearly indicated that the good adaptation and performance of most tested alternative crops under salinity conditions, especially the perennial crops such as blue panicum and sesbania are favored by farmers due to their low requirement in terms of agricultural inputs.

Keywords Biosaline agriculture · Blue panicum · Yield · Dry biomass · Irrigation

1 Introduction

Agriculture in marginal environments such as desert areas is facing several challenges, including desertification, salinity, drought, and heat, which limit crop growth and land productivity. Salinity affects several regions of the world and increasing

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significantly due to secondary salinization caused by excess irrigation, excessive use of agrochemical fertilizers, poor drainage, groundwater salinity, sea-level rise and intrusion, drought, and irregular rainfall. Eswar et al. (2021) reported that salinity mainly affects soils in North and Central Asia, Africa, and South America. It affects about 1060 Mha worldwide, and the salt-affected area is gradually increasing due to the influence of climate change. Consequently, soil salinity tends to increase with sea-level rise, intrusion, high temperature, low precipitation, and inadequate irrigation management.

Morocco is one of the countries suffering from salinity problems, specifically in the Southern region. Recent data published by Hssaisoune et al. (2020) indicate that all groundwater in the southern area is affected by salinity with a TDS (Total Dissolved solids) exceeding 2 g/l. While in terms of groundwater quality, 31% of groundwater in Morocco has low quality due to several factors (natural and/or anthropogenic) and processes (e.g., water–rock interactions, evaporation, and seawater intrusion).

Salinity affects plants in two ways: osmotic stress and ionic toxicity. The first way is caused by a high concentration of salt in the root zone, inhibiting plant water uptake by the root system. In contrast, ionic toxicity results from the accumulation of toxic ions such as sodium and chloride in the plant tissue, which affect all major plant processes, including photosynthesis, cellular metabolism, and plant nutrition (Bernstein 2019).

Biosaline agriculture is the cultivation and growth of crops under saline conditions using salt-tolerant crops and varieties and adapted cropping practices such as soil amendment, fertilization, and irrigation management to overcome adverse salinity effects on crop growth and development (Ayyam et al. 2019). In most cases, biosaline agriculture is introduced or adopted in salt-affected environments where farmers are used to cultivating traditional crops sensitive or moderately tolerant to salinity. Unfortunately, due to increased salinity, traditional crop productivity has declined, consequently reducing farmers' income. This was the case in Foum El Oued area in the south of Morocco, where all farms with a total area of more than 400 ha are affected by salinity. Groundwater EC (Electrical conductivity) in this region exceeds 4 dS/m, which is beyond the salt tolerance threshold of traditional crops such as forage corn, for example. Alternative crops have been introduced in the southern region to replace traditional forages and rehabilitate the abandoned salt-affected farms (Hirich et al. 2021).

According to Elouafi et al. (2020), traditional crops face many challenges caused by abiotic and biotic stresses (salinity, drought, pests, diseases, etc.). Toward these constraints, alternative crops could be introduced to replace common crops in a particular geographic area to the benefit of the farming communities. Furthermore, their niche markets and the high value could improve farmers' income.

Thus, the aim of this study was to evaluate the productivity of several alternative forage crops tested under field and salinity conditions in five locations in the south of Morocco, and analyzing their responses/adaptation to different agro-climatic conditions and salinity levels.

Fig. 1 Localization of multi-location experimental sites across south of Morocco

2 Materials and Methods

2.1 Experimental Sites

In this study, for the multi-location evaluation, five experimental sites were chosen which represent the different microclimates and agricultural production areas in the south of Morocco regarding soil type, salinity level, drought condition, and climate conditions. Trials were conducted from October 2020 to August 2021. The localization of the experimental sites is presented in Fig. 1.

2.2 Climatic Data

Figure 2 presents the annual average climate of each experimental site during the 2020/2021 cropping season. In terms of maximum and minimum average temperature, precipitation, and wind speed. The hottest site is Bir Anzarane followed by Es-Smara, and the coldest is Tarfaya. In terms of rainfall, most sites receive an amount

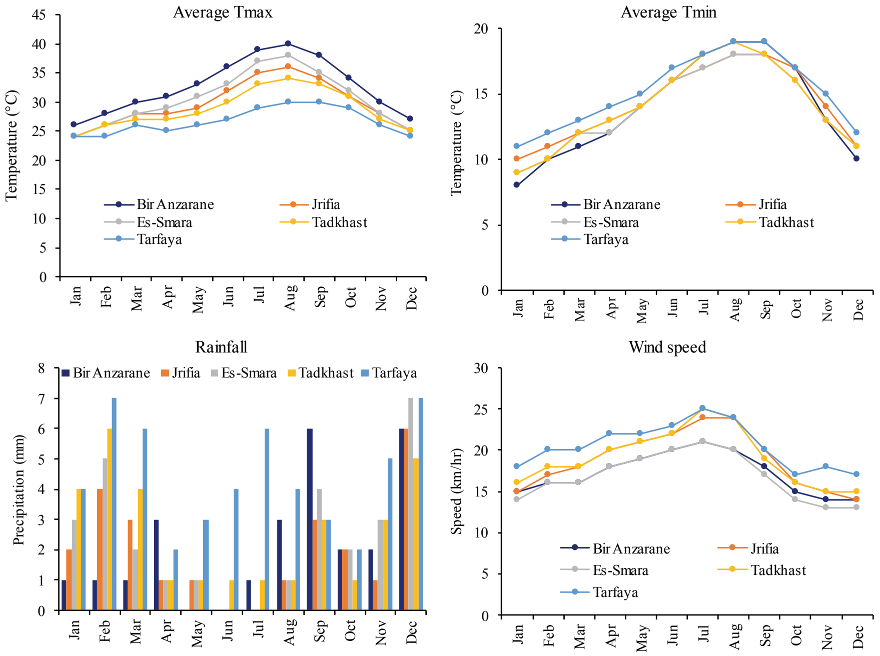

Fig. 2 Climatic data of the experimental sites in terms of maximal (Tmax) and minimal (Tmin) temperature, rainfall, and wind speed during the 2020/2021 cropping season. (*Source* https://power.larc.nasa.gov/data-access-viewer/)

of rain that does not exceed 50 mm. The driest area is Jrifia followed by Bir Anzarane and the wettest area is Tarfaya, which is closer to the Atlantic Ocean. The Tarfaya site has the highest wind speed during the year, while the Es-smara site has the lowest.

2.3 Experimental Design and Agronomic Practices

A Randomized Complete Block Design was adopted in each experimental site with four replications for each specie. The plot area was equal to 12.5 m^2 (2.5 × 5 m). Several alternative crop species were tested (Table 1).

Before sowing, the soil was plowed, and the seedbed was prepared. Irrigation was supplied using drip irrigation (25 cm between drippers and dripper discharge was equal to 2 L/hr), applying 3–4 irrigation per week with a half-hour for each irrigation. Standard agronomic practices such as weeding, pest and disease management, and harvest were conducted following farmers' practices. Crop was harvested at the grain filling stage.

Table 1 List of tested species and varieties

Category	Species	Variety
Cereals and Pseudo-cereals	Barley (*Hordeum vulgare)*	Najah, Amalou, Laanacer, Oussama and local variety
	Triticale (× *Triticosecale)*	Fouricale and local variety
	Oat (*Avena sativa)*	Rapidena and local variety
	Quinoa (*Chenopodium quinoa)*	Titicaca, Puno, ICBA Q1, ICBA Q3 and ICBA Q5
	Maize (*Zea mays)*	Torro plus and Dracma
	Pearl millet (*Pennisetum glaucum)*	IP19612, IP22269, IP12150, HHVBC Tall and MC94C2
	Sorghum (*Sorghum bicolor)*	ICSR 93034 and Tonka F1
Grasses and legumes	Alfalfa (*Medicago sativa)*	Local and Public variety
	Blue panicum (*Panicum antidotale)*	Public variety
	Sesbania (*Sesbania sesban)*	ILRI 15018, ILRI 15077, ILRI 17314 and ILRI 15037
	Atriplex (*Atriplex nummularia)*	Wild genotype
Fodder beet	*Beta vulgaris*	Monro, Jamon and Caribou

Several parameters were monitored, including agro-morphological parameters such as plant height, root length, number of tillers, root weight, plant weight, and fresh and dry biomass production.

2.4 Soil and Water Analysis

Table 2 shows the result of the soil physical and chemical analysis. The soil has a high percentage of sand and silt. According to the soil texture triangle, soils in Es-smara, Tadkhast, and Tarfaya are sandy loam, while the soil texture in Jrifia is sandy, and Bir Anzarane is loamy sand. Regarding salinity, all sites has a low salinity level except Es-Smara, which has a high level of salinity. Data indicate that both Tadkhast and Tarfaya are calcareous soils, while other sites present a low content of $CaCO_3$. Organic amendment content was moderate for Tarfaya soil and low for other sites. Regarding mineral content, all soils has high CaO, MgO, and K_2O, while P_2O_5 content was relatively low. The soil analysis indicates that soils of Tadkhast, Jrifia, and Bir Anzarane are non-saline and non-sodic, while Es-Smara soil is saline and sodic, and Tarfaya soil is saline and non-sodic.

The results of the water analysis is presented in Table 3 indicating that irrigation water in all sites is saline, with the highest EC recorded in Es-Smara. The most

Table 2 Soil physical and chemical properties in different multi-location sites of south of Morocco

Parameters	Bir Anzarane	Es-Smara	Jrifia	Tadkhast	Tarfaya
Clay (%)	4	12	2	10	6
Silt (%)	18	24	10	22	26
Sand (%)	78	64	88	68	68
pH	9.03	8.24	9.04	8.56	8.98
ECe (dS/m)	1.35	10.05	0.4	0.6	2.7
CEC (meq/100 g)	5.3	4.9	1.3	5.7	5.1
$CaCO_3$ (%)	4.2	7.6	12.3	26	38.3
Na_2O (ppm)	482	1565	73	86	717
ESP (%)	5.97	15.34	1.01	1.03	7.14
Organic matter (%)	0.13	0.5	0.08	1.01	1.49
Total Nitrogen (%)	0.01	0.03	0.01	0.06	0.09
C/N	7.54	9.66	4.64	9.76	9.6
P_2O_5 (ppm)	32	28	17	47	100
K_2O (ppm)	324	408	268	338	643
CaO (ppm	7032	7332	6694	7584	7577
MgO (ppm)	230	893	175	347	1104

CEC: Cation Exchange Capacity, ESP: Exchangeable Sodium Percentage

Table 3 Irrigation water quality

Parameters	Bir Anzarane	Es-Smara	Jrifia	Tadkhast	Tarfaya
pH	6.94	7.16	6.97	7.07	7.29
EC (dS/m)	6.64	12.40	6.20	3.85	8.67
TDS (g/l)	5.31	9.92	4.96	3.08	7.01
Na^+ (ppm)	962.88	1163.33	27.16	25.47	1306.30
K^+ (ppm)	17.47	32.64	27.16	25.47	49.19
Mg^{2+} (ppm)	89.90	242.15	51.52	64.32	173.03
Ca^{2+} (ppm)	348.00	421.70	279.19	167.04	283.46
Cl^- (ppm)	1725.43	2567.80	599.66	802.10	2655.46
$SO_4{}^{2-}$ (ppm)	512.52	855.09	2373.54	174.12	360.12
$HCO_3{}^-$ (ppm)	248.88	585.60	122.00	646.60	212.28

contributing elements to salinity increase are sodium and chloride in Bir Anzarane, Es-Smara, and Tarfaya sites, while increased salinity was due to more accumulation of sulfur in Jrifia and bicarbonates in Tadkhast site.

2.5 Statistical Analysis

Statistical analysis was carried out using R software. A one-way analysis of variance (ANOVA) was used to assess the effects of location on monitored parameters. The level of significance was set to $p < 0.05$. When the ANOVA gives a significant result for each analysis, statistically significant differences between means were identified using Tukey's pairwise comparisons test ($p \leq 0.05$).

3 Results

3.1 Agro-Morphological Parameters

Table 4 shows the obtained results regarding some agro-morphological parameters of tested alternative crops under demonstration site conditions. Plant height and root length data indicate that increased salinity has affected plant growth in all experimental sites, while average plant weight responded differently to salinity depending on crop species. For instance, there was no significant difference for oat, forage corn, quinoa, and pearl millet. However, barley and triticale plant weight declined with increased salinity. Conversely, highly salt-tolerant crops such as blue panicum, sesbania, and fodder beet showed a different trend where they accumulated more biomass under increased salinity levels.

3.2 Dry Biomass Yield

The dry biomass yield variation of cereals and quinoa is presented in Fig. 3. Statistical analysis showed a significant decrease in productivity for all tested species with an increase salinity level except for quinoa. Sorghum and pearl millet performed better under low salinity conditions, averaging 21 t/ha dry biomass. However, with medium saline irrigation water, the productivity of oat reached 19 t/ha dry biomass. This finding can be explained by the high number of tillers obtained in Bir Anzarane site compared to other sites. While triticale and barley showed the lowest decrease in productivity under high salinity conditions in Es-smara compared to Tadkhasst (low salinity), their productivity was up to 7.6 and 6.1 t/ha of dry biomass, respectively.

Figure 4 shows the dry biomass yield for the grass and legumes tested. The best performance was recorded for blue panicum under different salinity conditions. However, the crop recorded a dry biomass production of 21 t/ha/year under high irrigation water salinity levels (12.4 dS/m). Alfalfa production was decreased due to salinity. Conversely, sesbania, a very highly salt-tolerant crop, showed an increasing tendency with increased salinity to reach more than 22 t/ha of fresh biomass under Es-smara site.

Table 4 Agro-morphological parameters of different alternative crops in five different locations of south of Morocco

Species	Locality	Cereals and Pseudo-cereals							
		Plant height (cm)		Root length (cm)		Number of tillers		Plant weight (g)	
		Mean	*p* value	Mean	*p* value	Mean	*p* value	Mean	*p* value
Barley	Tadkhasst	68.67 ± 4.7 a	0.000***	12 ± 0.86	0.480	4.17 ± 0.6	0.176	13.39 ± 1.25 a	0.009**
	Bir Anzarane	63.83 ± 2.56 ab		11 ± 1.46		4.83 ± 0.95		13.98 ± 2.82 a	
	Jrifia	54.83 ± 2.65 b		11.5 ± 1.93		3.33 ± 0.33		10.1 ± 2.02 ab	
	Es-smara	34.28 ± 1.95 c		9.17 ± 0.75		6.33 ± 1.48		4.73 ± 0.7 b	
Oat	Tadkhasst	64.33 ± 5.36 ab	0.031*	13.67 ± 1.45	0.324	4 ± 0	0.059	17.72 ± 2.58	0.133
	Bir Anzarane	66 ± 1 ab		12 ± 1		5 ± 0.58		14.88 ± 2.58	
	Jrifia	76.67 ± 2.67 a		17.67 ± 5.61		2.33 ± 0.33		11.06 ± 1.17	
	Es-smara	58.67 ± 2.91 b		9 ± 2		3 ± 1		8.67 ± 3.31	
Triticale	Tadkhasst	88.5 ± 13.5 a	0.000***	17.5 ± 0.5 a	0.000***	4.5 ± 1.5	0.058	21.25 ± 4.8 a	0.000***
	Bir Anzarane	70.33 ± 3.84 ab		10.5 ± 0.67 b		3.83 ± 0.87		9.33 ± 0.81 b	
	Jrifia	65 ± 2 b		6 ± 0.63 c		1.5 ± 0.22		5.61 ± 0.91 b	
	Es-smara	49.14 ± 2.01 c		8.43 ± 0.3 b		4.5 ± 1.5		6.86 ± 0.66 b	
Forage corn	Tadkhasst	126 ± 9.87 ab	0.017*	25.33 ± 0.88	0.560	–	–	508 ± 146	0.110
	Bir Anzarane	166 ± 8 a		30 ± 1		–		434.2 ± 37.1	
	Jrifia	78.3 ± 17.2 b		26 ± 3.21		–		150.6 ± 53.4	
	Tarfaya	117 ± 14.7 ab		30.67 ± 1.76		–		344.3 ± 91	
	Es-smara	87 ± 5 b		27 ± 6		–		164.9 ± 36.7	

(continued)

Table 4 (continued)

Species	Locality	Cereals and Pseudo-cereals							
		Plant height (cm)		Root length (cm)		Number of tillers		Plant weight (g)	
		Mean	*p* value	Mean	*p* value	Mean	*p* value	Mean	*p* value
Pearl millet	Tadkhasst	111.75 ± 7.65 ab	0.037*	18.75 ± 2.14	0.252	5.75 ± 0.48	0.376	69.92 ± 9.3	0.080
	Jrifia	85.3 ± 10.9 b		26.33 ± 2.33		6 ± 0.58		252.1 ± 61.9	
	Tarfaya	134 ± 5 a		24 ± 7		7.5 ± 0.5		420.8 ± 61.6	
	Es-smara	93.75 ± 8.87 ab		22.25 ± 0.85		4.5 ± 1.5		206 ± 105	
Sorghum	Tadkhasst	105 ± 10.1 ab	0.007**	22 ± 2.08 b	0.001**	1.67 ± 0.67	0.250	236 ± 108 ab	0.032*
	Jrifia	83 ± 12 b		22.5 ± 2.5 b		2 ± 1		130.3 ± 47.1 ab	
	Tarfaya	142.3 ± 11.9 a		40.67 ± 2.4 a		2.33 ± 0.33		596 ± 167 a	
	Es-smara	85.75 ± 4.66 b		21 ± 1.96 b		1 ± 0		116.7 ± 22.2 b	
Quinoa	Tadkhasst	67.31 ± 4.48	0.002**	14.81 ± 1.13	0.479	–	–	9.46 ± 1.44	0.000***
	Es-smara	46.21 ± 4.1		15.93 ± 1.04		–		71.5 ± 12.2	
		Grasses and legumes							
		Plant height (cm)		Number of ramifications		Plant weight (g)		Fresh Biomass (t/ha/cut)	
		Mean	*p* value	Mean	*p* value	Mean	*p* value	Mean	*p* value
Alfalfa	Tadkhasst	59 ± 13.1	0.192	15.33 ± 2.33 b	0.017*	92.10 ± 40.9	0.363	5.2 ± 0.14	0.055
	Bir Anzarane	79.67 ± 5.17		37.33 ± 5.78 a		203.50 ± 59.8		4.01 ± 0.84	
	Es-smara	51.5 ± 0.5		44.5 ± 5.5 a		128.0 ± 59.1		2.11 ± 0.69	

(continued)

Table 4 (continued)

Species	Locality	Cereals and Pseudo-cereals							
		Plant height (cm)		Root length (cm)		Number of tillers		Plant weight (g)	
		Mean	p value	Mean	p value	Mean	p value	Mean	p value
Blue panicum	Tadkhasst	115.5 ± 6.71	0.253	33.5 ± 4.99	0.087	203.6 ± 33.9	0.186	7.22 ± 0.28	0.207
	Bir Anzarane	101 ± 9.02		22.67 ± 1.86		96.56 ± 9.95		4.32 ± 0.43	
	Jrifia	77 ± 4		25.5 ± 3.5		81 ± 13		5.77 ± 0.37	
	Tarfaya	111 ± 15.9		18 ± 2.08		150.3 ± 61.8		8.19 ± 1.34	
	Es-smara	101.8 ± 10.2		21.50 ± 3.4		98.3 ± 34		7.80 ± 1.71	
Sesbania	Tadkhasst	92.67 ± 9.33 b	0.014*	6.33 ± 0.33 b	0.029*	128.1 ± 34.6 b	0.023*	4.11 ± 1.89 b	0.013*
	Bir Anzarane	131 ± 8.89 a		12.67 ± 1.45 ab		257.8 ± 54.9 ab		7.83 ± 0.82 ab	
	Es-smara	81.67 ± 6.69 b		13.67 ± 2.19 a		340.6 ± 17.9 a		13.52 ± 1.63 a	
		Fodder beet							
		Root length (cm)		Plant weight (g)		Root weight (g)		Leaves weight (g)	
		Mean	p value	Mean	p value	Mean	p value	Mean	p value
Fodder beet	Tadkhasst	22.92 ± 1.26 ab	0.000***	1641 ± 292 ab	0.011*	1330 ± 251	0.066	311.3 ± 47.6 bc	0.000***
	Bir Anzarane	15.56 ± 1.06 c		1119 ± 128 b		953 ± 109		166.00 ± 26.9 c	
	Tarfaya	21.22 ± 2.42 bc		2267 ± 247 a		1683 ± 169		584.3 ± 93.7 a	
	Es-smara	30.5 ± 0.96 a		2317 ± 109 ab		1745 ± 114		572.3 ± 49.3 ab	

Values represent mean ± standard error. *, ** and *** indicate significance at $p < 0.05$, 0.01 and 0.001 respectively. a, b and c present Tuckey's test at $p = 0.05$

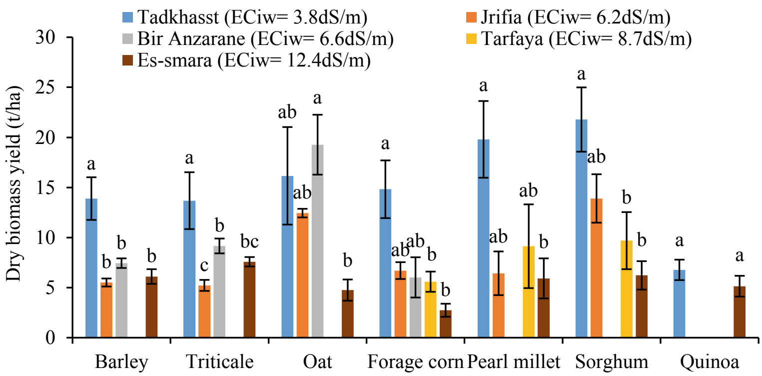

Fig. 3 Dry biomass production of evaluated alternative crops as affected by irrigation water salinity. Error bars indicate the standard error. Means sharing the same letters do not differ significantly at 5% level of significance

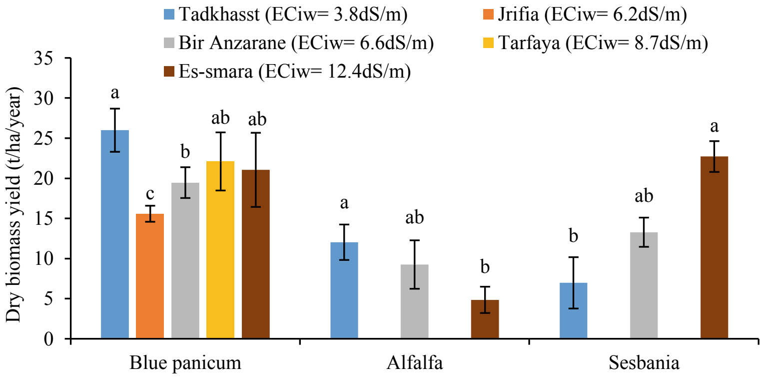

Fig. 4 Dry biomass production of blue panicum, alfalfa, and sesbania as affected by irrigation water salinity. Error bars indicate the standard error. Means sharing the same letters do not differ significantly at 5% level of significance

Fresh and dry biomass yields of fodder beet are presented in Fig. 5. Obtained results indicated that fodder beet yield increased relatively with increased salinity to reach its maximum in Tarfaya site with 140 t/ha of fresh biomass and declined slightly in Es-smara site (high salinity).

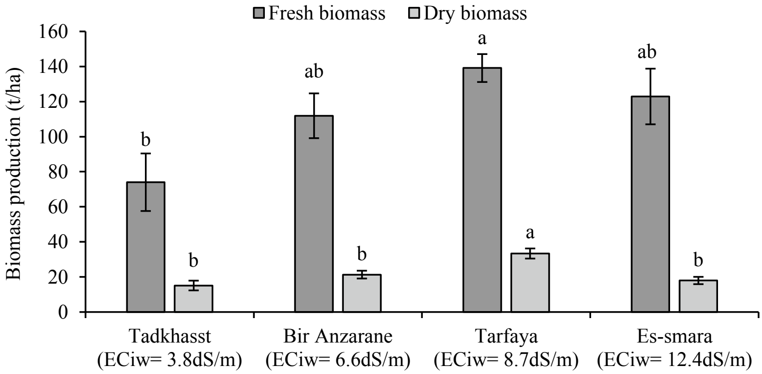

Fig. 5 Fresh and dry biomass production of fodder beet as affected by irrigation water salinity. Error bars indicate the standard error. Means sharing the same letters do not differ significantly at 5%

4 Discussion

Major cereal crops are becoming more vulnerable to climate change, and they are progressively failing to overcome salinity and water scarcity. Therefore, there is an urgent need to identify alternative solutions to sustain their productivity in marginal environments (Hirich et al. 2020). Crop diversity plays a major role in sustainable agriculture. Alternative crops are introduced to a new environment to replace traditional crops and help withstand biotic and abiotic threats to agricultural productivity (Elouafi et al. 2020).

The findings of this study indicated that tested alternative forage crops responded differently to site conditions in terms of soil, irrigation water salinity, and climate. However, we believe that several factors contributed to this difference. Still, the main influencing factor is the irrigation water salinity, as there is no significant difference in soil and climate. It was also evident that crops with low salinity tolerance, such as forage corn, sorghum, and pearl millet, were significantly affected by salinity and performed better under low salinity. On the other hand, salt-tolerant species such as barley, oat, triticale, blue panicum, sesbania, alfalfa, and fodder beet showed higher productivity under moderate and high salinity levels. The reduction in biomass production and other growth parameters for crops with low salinity tolerance can be explained by a decline in photosynthetic activity, as demonstrated by several studies conducted on maize (Omoto et al. 2012), sorghum (Netondo et al. 2004), and pearl millet (Radhouane 2009) where increased salinity has greatly reduced photosynthesis, stomatal conductance, transpiration, and chlorophyll content. Crops with low salinity tolerance generally use energy-demanding strategies such as osmotic adjustment, which requires the production and accumulation of osmolytes which are big molecules such as amino acids (proline, glycine-betaine), soluble sugars, and organic acids (Iqbal et al. 2020). On the other hand, crops resistant to salinity use other adaptation mechanisms such as salt exclusion or compartmentalization (Aslam et al. 2011). The photosynthetic activity of species with low tolerance to salinity is disturbed because of the accumulation of sodium in excessive amounts, which is highly toxic for growth due to its high interference with beneficial elements such as potassium (Iqbal et al. 2020).

To cope with salt stress, salt-tolerant crops or halophytic plants have evolved mainly two types of tolerance mechanisms based on limiting the entry of salt by the roots, or controlling its concentration and distribution (Hanin et al. 2016). Mishra and Tanna (2017) defined halophytes as salt-resistant or salt-tolerant plants that have a remarkable ability to complete their life cycle in saline conditions, and sometimes their yield increased under high salinity level by deploying mechanisms such as salt exclusion and compartmentalization. For instance, our results indicate that sesbania fresh biomass increased with the increasing salinity level which confirms the finding of (Hirich et al. 2021) who reported that sesbania biomass yield under high irrigation water salinity conditions (13–14 dS/m) is 1.3 higher compared to low salinity level (2–3 dS/m), while for blue panicum yields under both low and high salinity are more or less similar.

A previous study also showed that introduced alternative forage crops in the region of Foum El Oued, which is not far from the five sites, had a higher performance than traditional crops (Alfalfa and forage corn). For example, the fresh biomass yield of perennial species such as sesbania and blue panicum exceeded 100 t/ha, much higher than Alfalfa, where the maximum potential yield did not exceed 75 t/ha. Likewise, for an annual crop such as pearl millet which can be compared to forage corn, the fresh biomass yield was 44 and 36% higher under high and low salinity conditions, respectively (Hirich et al. 2021).

Blue panicum is highly tolerant to salinity conditions and could produce 10 t/ha of dry matter at 16 dS/m (Salehi 2020). Physiological Mechanisms for salinity tolerance in blue panicum include the accumulation of polyamines, abscisic acid, and the activities of anti-oxidative enzymes such as superoxide dismutase, peroxidase, and catalase (Ahmad et al. 2009).

Fodder beet shows good performance in a salt-affected arid land, and its productivity improved by 25% at 10 dS/m compared to 2 dS/m (Nadaf et al. 2000). Under salt stress, various physiological and biochemical mechanisms are involved in surviving fodder beet plants. According to (Yolcu et al. 2021), beet maintains leaf turgor by reducing stomatal conductance and transpiration and by accumulating compatible solutes such as proline and sucrose. Furthermore, fodder beet has a good capacity for salt-removing from soil up to 0.9 t/ha, by accumulating excessive amounts of sodium and chloride ions in leaves (Liu et al. 1997). In this context, fodder beet could be a good option for salt-affected soils.

Salt-tolerant grasses could be a judicious choice to replace traditional forages such as forage corn and alfalfa, especially in salt-affected lands where the biomass productivity of traditional forages is significantly affected (Qadir et al. 1996). Blue panicum is among other forage grasses that resist salinity stress and show great potential as feed for livestock. In a recent study conducted by (Farrag et al. 2021), it was demonstrated that blue panicum biomass yield only declined by 20% when it was subjected to saline irrigation with an EC value 9 dS/m (same salinity level as Tarfaya site), which indicates its high resistance to salinity.

5 Conclusions

In the light of the results obtained, it can be concluded that most of the evaluated alternative crops showed higher performance than traditional crops (forage corn and alfalfa) under low and high salinity conditions. Among the cereals crops, barley, triticale, and oat are the most recommended to cultivate under high salinity. In contrast, under low salinity, pearl millet and sorghum could produce a satisfactory level of biomass yield. Among other groups, a high potential has been revealed for blue panicum, sesbania, and fodder beet, especially under high salinity conditions where their fresh biomass yield can exceed 80, 50, and 100 t/ha, respectively. According to farmers, perennial crops such as blue panicum have great potential for upscaling as they are less demanding in terms of agricultural inputs (seeds, fertilizers, pesticides, etc.).

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Chapter 10
Water and Salt Regimes Under Irrigation with Brackish/Saline Water in Tunisian Semi-Arid Context

Mohamed Hachicha, Khawla Khaskoussy, and Gilani Abdelgawad

Abstract Under climate change and in the absence of appropriate irrigation management, the use of brackish/saline water as alternating water resources for irrigation leads to a considerable salt soil accumulation that causes damage to the agricultural productivity and leads to soil and groundwater properties degradation. Consequently, economic returns decrease and social stability is affected. Thus, good knowledge of salt-water dynamics associated with appropriate management practices is required to ensure sustainability of saline water irrigation. Natural rainfall associated with proper irrigation management practices and schemes may produce effective salt leaching out of root zone. Tunisia is among semi-arid regions having long experience in using saline water for irrigation. Some research activities on salt and water regimes show seasonal cyclic variation in which irrigation season induced salt buildup occurs and highlight seasonal rainfall causes its leaching, which may, in long turn, lead to groundwater salinization. Based on these outputs, it should be noted that, in the short term, sufficient rainfall amount, choice of light textured soils and low supervision costs associated with the promotion of family farmer employment is required. However, in long term and due to climate change, rainfall would be insufficient to avoid the risk of salt accumulation. Thus, salinity control will require the adoption of new tools and innovative water management practices with the integration of local natural specifications.

Keywords Brackish/saline water · Irrigation · Rainfall · Water regime · Salt regime · Sustainability · Tunisia

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1 Introduction

The scarcity of fresh-water resources allocated for agricultural irrigation is limiting the sustainable development of agriculture. To mitigate the shortage of fresh water, it is important to find a balance between the increasing water demands and available water for agriculture. Using alternating water resources for irrigation supported by sustainable irrigation water management schemes has become one of the important patterns to mitigate the fresh-water shortage (Grant et al. 2012). As one of the major alternative water resources, saline water has been extensively used for agricultural irrigation for hundreds of years (Zhang et al. 2017).

Under climate change and in the absence of sufficient natural drainage and without a proper leaching and appropriate irrigation management to remove the salts, irrigation with brackish/saline water would lead to secondary salinization of land and water resources in arid and semi-arid conditions. On one hand, with the long use of saline water irrigation, salt accumulation in soils dramatically damages the ability of roots to absorb water and nutrients, this can destroy productivity and lead to degradation of soil properties (Jingang et al. 2019). On the other hand, under strong evaporation conditions, irrigation during agricultural production increases the upward underground water level to exceed a critical depth which results in continuous water evaporation and considerable accumulation of salt on the soil surface (Guoqing et al. 2019). Soil salinity impacts include significant degradation of soil structure and hydraulic properties, low agricultural productivity and consequently low economic returns and social instability. These problems seriously affect the sustainable water management in agriculture. Thus, the challenge is to plan strategies and modern practices to alleviate the deleterious effect of salinity on crop and soil health for increasing agricultural crop production and economic returns while preserving soil ecological functionality, minimizing human health risks and ensuring sustainable use of saline water for irrigation (Assouline et al. 2015; Zhang et al. 2017).

Several previous studies have indicated that brackish water can successfully be used for irrigated crop production when suitable practices and schemes are adopted. Appropriate irrigation scheduling, irrigation systems, practices that incorporate fertigation and salinity management schemes rely on root zone salt leaching to be the most important factor for crop growth and sustainable irrigation water management (Bacci et al. 2008; De Pascale et al. 2013; Assouline et al. 2015; Çolak and Yazar 2017; Georgios et al. 2020). The majority of these studies did not consider changes in soil conditions caused by brackish water irrigation under semi-arid conditions and climate change and did not highlight the effectiveness of rainfall in sustainable use of water resources.

It is thus crucial to be focused on the local rainfall for help in developing suitable management practices for these kinds of water dependent lands. Anyway, irrigation sustainability will vary among regions characterized by their specific climate conditions and over time with changes in societal views regarding agriculture, irrigation and ecosystems (Dennis and Oster 2006). Some studies have reported the leaching effect of natural rainfall on soil salinity control (Sharma et al. 2000; Cucci et al. 2016). However, it is hard to predict the rainfall leaching due to the variability in yearly annual rainfall patterns (Shan et al. 2018). For instance, large rainfall events late in the growing season may produce leaching effect on salt accumulation in the root zone and the good salt leaching effect is produced by autumn and winter rainfall in a sandy clay loam soil (Cucci et al. 2016; Shan et al. 2018). Anyway, the effectiveness of rainfall events on salt leaching requires a proper drainage management. The effect of rainfall events on salt leaching depends also on irrigation scheduling. But rainfall events are more effective to produce salt leaching on wet soils than on dry soils, despite the large rainfall event. The salt leaching effect of rainfall is also affected by irrigation frequency (Ayars et al. 2006). Thereby, any increase in irrigation frequency will result in higher soil moisture levels, less groundwater uptake by crops and reduced soil salinity levels (Shan et al. 2018).

Proper irrigation management strategies and schemes are advised to facilitate salt leaching by natural rainfall. Over-irrigation is often applied in order to leach the salinity buildup in the root zone (Dudley et al. 2008; Assouline et al. 2015; Russo 2016). Mixing saline and fresh water to reach a relatively low level of salinity (Malash et al. 2012; Machekposhti et al. 2017), alternating fresh-saline water irrigation (Murtaza et al. 2006) and Alternate Wetting and Drying are often used (Djaman et al. 2018; Li et al. 2006; Tan et al. 2013).

In the short term, soil salinity may be decreased significantly by the natural rainfall leaching process in an average year. Over a long-term period, it has also been, suggested that an effective leaching of the crop root zone may occur by natural rainfall processes when the field water-table depth is controlled below 1.5 m and the annual irrigation is over 80 mm in the semi-arid study area (Shan et al. 2018). Although this suggestion and because the rainfall pattern changes from year to year the effect of the rainfall leaching on soil salinity control should be studied and predicted on a long-term basis by analytical models that considered soil, rain, water, groundwater, crop and climatic variables for better irrigation management and salinity control (Suarez 2012; Simunek et al. 2013; Russo 2016; Assouline et al. 2015; Shan et al. 2018).

The present paper focuses on some salinity management practices and schemes that highlight the important role of rain in sustainable use of water resources which is the case for the semi-arid region of Tunisia. The study was carried out under the regional project “Applied Research Program for the Utilization of Brackish/Saline Water in North Africa”, supported by IFAD and coordinated by ACSAD in the three North African countries, Tunisia, Algeria and Libya.

2 Materials and Methods

The methodology used concerns the transfer of adapted management to the farmers on brackish/saline water. Six farmers were selected in the semi-arid region of Mahdia and Kairouan (Centre of Tunisia). The irrigation water has between 5.4 and 7.0 dS m^{-1}. The average rain per year is about 250 mm with about 1600 mm of PET

(Potential Evapotranspiration) for Kairouan and about 350 mm with about 1400 mm of PET for Mahdia. The soil texture is loamy sand to sandy loam in Mahdia and sandy loam in Kairouan. The initial soil salinity ECe (electrical conductivity of the saturated soil extract) is around 2 dS m^{-1} in Mahdia and Kairouan. The experiments were carried out from 2002 to 2005. The main crops of the region were used in this study. Irrigation scheduling was done according to the climate parameters and water requirement of the crop and the computer program CROPWAT (Allen et al. 1998) was modified by Gaibeh et al. (2002). The salinization risks are analyzed through the water and salt balances. Soil and irrigation water for each parcel were characterized and periodically measured, soil and water samples were taken and chemical analyses were carried out. The average between the ECe (Electrical conductivity of saturated soil extract) at the soil surface and at 1 m depth was used. During the crop cycle, water quantity was controlled. The crop cost was deduced directly for any realized expense and indirectly for the family work which is estimated from the activity, number of persons, number of hours and normal job salary.

3 Results

3.1 Short-Term Water and Salt Regimes

Water regime can be defined as the total of all phenomena of water inflow to the soil. It represents a combination of the processes of absorption, assimilation and exudation of water by soil. As mentioned in the introduction, the study was carried out under the regional project supported by IFAD and coordinated by ACSAD in the three North African countries. Research activities were carried out at the farmers' parcels in Mahdia and Kairouan regions (Centre of Tunisia) experiencing salinization of irrigated water. Table 1 presents the precipitation, in which the amount varied from one region to another and saline water irrigation from 2002 until 2004 for the summer pepper, greenhouse pepper and autumn potatoes.

Results showed that quantities of water applied varied among regions and depended not only on crop and season but also to farmer's practices in the same

Table 1 Water used for some crops by farmers in Mahdia and Kairouan regions (2002–2004, both rainfall and irrigation are in mm; irrigation values give the range of application)

Crops	Mahdia		Kairouan	
	Rainfall	Irrigation	Rainfall	Irrigation
Pepper—Open field in summer	28	575–733	0	824–1589
Pepper—Greenhouse	0	396–1660[a]	0	–
Potatoes—Open field in autumn	322	24–75	110	138–271

[a] 1660 mm is for crops with long growing season

region. Taking into consideration the amount of irrigated water and rainfall water (Fig. 1), we can distinguish an exclusive irrigated water regime using saline water to irrigate summer crops and greenhouse crops (peppers) and water regime alternating saline water irrigation and rainfall water for winter and autumn crops (potatoes).

The salt regime of the soil represents the changes in salt content and its qualitative composition in soil in the inter-irrigation, annual and multi-year irrigation cycles. It depends on irrigation and natural water regime. Water and salt regime are usually studied simultaneously. Indeed, by studying the different water regimes, it is possible to deduce the salt regime under Tunisian semi-arid conditions. As shown in Fig. 2, we can distinguish three different water regimes influencing the degree of salt accumulation.

Thereby, depending on seasonal variation, three regimes can be characterized (Table 2): Summer irrigated water regime using brackish/saline water which leads to

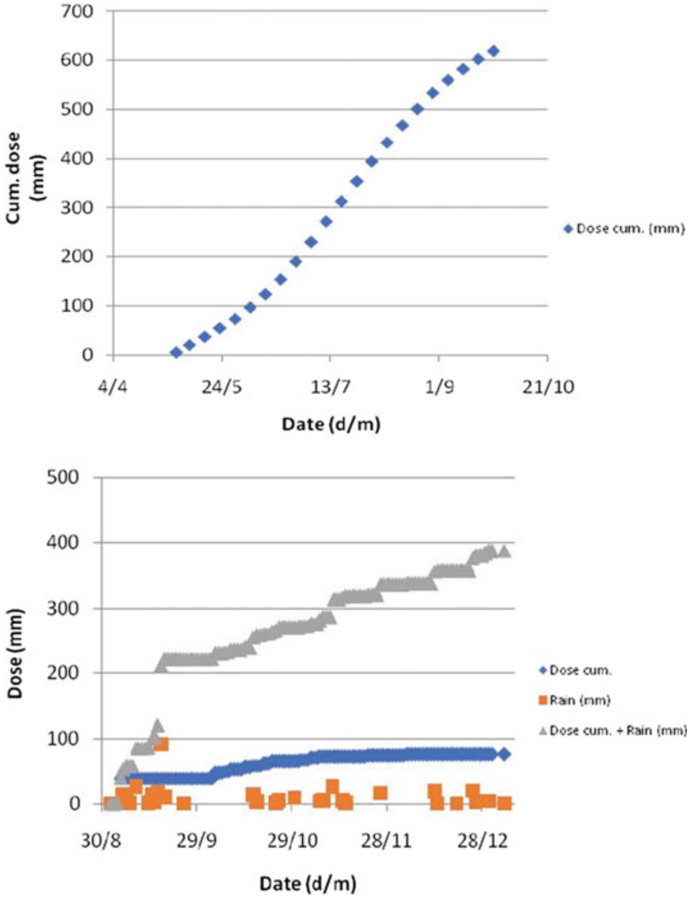


Fig. 1 Water quantities supplied for crops throughout the growing season

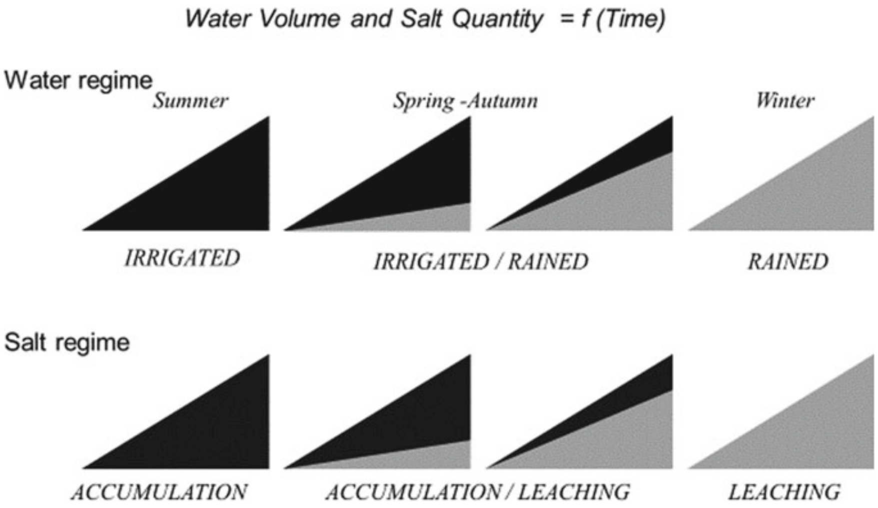


Fig. 2 Main water and salt regimes in semi-arid Tunisian context

Table 2 Water and salt regimes

Season					
Regime	Winter	Spring	Summer	Autumn	Winter
Water	Rained	Rained/irrigated	irrigated	Rained/irrigated	Rained
Salt	Leaching	Leaching/accumulation	Accumulation	Accumulation/leaching	Leaching

cumulative salt regime; winter rainfall regime induces the leaching of salts from the topsoil and spring, autumn and winter water regimes alternate between saline water irrigated regime and rainfall regime, leading in turn to alternate accumulation and leaching salt regimes.

It was found that irrigation with brackish/saline water under semi-arid climatic conditions increases the ECe of the topsoil. The decrease of ECe values, at the end of the rainy season, is attributed to the leaching of soluble salts to deeper soil. Once the dry season restarts and the water amount supplied by irrigation increases, EC increases but decreases again after rain events. These statements highlight a seasonal variation of salt regime dependent on the water regime (Fig. 3).

The dynamic of water and salt induces two main salt regimes: (a) salinization—salt accumulation, supplement regime; (b) salt removal, deletion regime. This can be formulated in a simplified form (Fig. 4), which contains the cyclic change of seasons resulting in seasonal reversible cyclic change of salt regimes and consequently in a seasonal reversible cyclic change in soil salinity.

Soil salinity was monitored before and after irrigation of summer pepper and winter spring barely (Table 3). Result showed that at the end growth season, irrigation

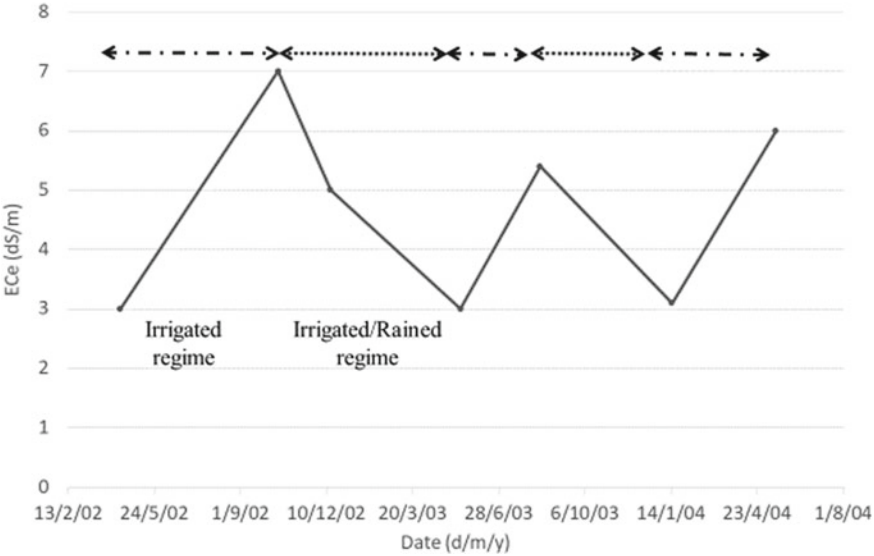
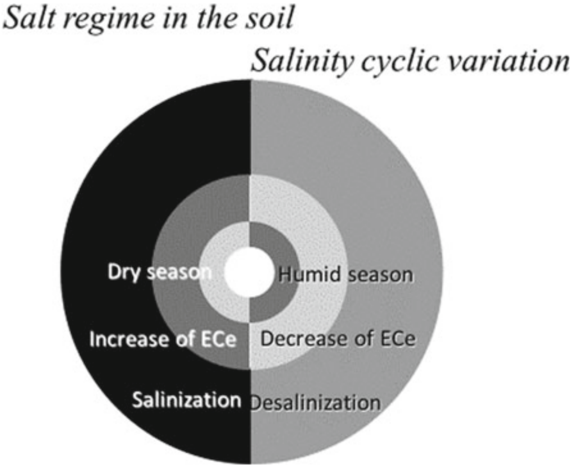


Fig. 3 Seasonal variation of soil salinity in the topsoil (0–1 m): the increase under irrigation regime and the decrease under rainfall regime (Kairouan, 2002–2004)

Fig. 4 Seasonal variation and the corresponding soil salinity cyclic variation



with saline water (6.1 dS m^{-1}) increased soil salinity from 5.7 to 10.2 dS m^{-1} for summer pepper.

The increase of soil salinity could be explained by the salt build up, especially in topsoil, due to evaporation, water absorption by crops and the shortage of rainwater. As for winter/spring barely, although being irrigated with saline water (7.6 dS m^{-1}), the soil salinity decreased from 5 to 3 dS m^{-1} due to the role played by winter rain in the leaching of salt as these rainfalls were sufficient in amount and had long enough

Table 3 Salt balance of a cultivated area with two seasonal crops in Mahdia and Kairouan regions after one year of irrigation

Element	Parameter	Summer pepper	Winter/spring Barley
Water irrigation	Electrical conductivity (dS m^{-1})	6.1	7.6
	Dry residue (g l^{-1})	5.4	5.3
	Total amount of irrigation (m^3)	7333	880
	Salt mass input by irrigation (T ha^{-1})	41.1	3.5
Soil	Salinity before irrigation season (dS m^{-1})	5.7	5.0
	Salinity at the end of irrigation season (dS m^{-1})	10.2	3.0
	Salt balance of soil	1.4	−0.6
Water/Soil	Leached salts mass to the soil profile > 1 m (T ha^{-1})	39.7	4.1
	Percentage	97	118

in duration to bring out the salts from the root zone. It is important to note that although salt accumulated in saline water irrigated soils, leaching of salts was also evident.

3.2 Long-Term Water and Salt Regimes

The long-term sustainability of irrigated agriculture with brackish/saline water is conditioned by maintaining an adequate salt balance in the crop root zone. It is crucial to determine the influence of brackish/saline water irrigation on soil salinity by assessing the accumulation of salts in soil. Salt accumulation can be estimated by the approach of salt mass balance. The approach of salt mass balance in a hydrological representative volume (salt in – salt out = salt stored) has been proposed and applied to evaluate if an irrigation system is at risk of salinization (Runbin et al. 2011). It represents the base of irrigation management strategies implementing the concept of water quantity compensating for water quality (Assouline et al. 2015). Salt mass stored in the soil can be calculated based on the measured salinity of the applied water, the salinity of the topsoil before and after an irrigation season, the total amount of water used for irrigation and the bulk density of the soil. In this way, the salt mass balance was calculated at the end of dry irrigation and rainy winter seasons (Table 3). Changes of salt leaching through soil layers reflect leaching and accumulation. The result of the salt balance calculation showed that during the dry irrigation season with brackish/saline water, salt mass stored in the soil was positive (1.4 T ha^{-1}). In contrast, it became clear that at the end of wet season, the salt balance was negative, with a level of −0.63 T ha^{-1}. The negative salt balance indicated that the mass of salt leached deeper in the soil profile was larger than the mass of salt applied. It has been shown that irrigation water is effective in leaching about 97% of salt (equivalent to 39.7 T ha^{-1}), below the root zone; the common source of this salt being saline irrigation water. It is important to note that under Tunisian conditions, rainfall regime is very effective in leaching to deeper soil not only the salts brought by the irrigation water but also salts stored from the previous irrigation season, which are estimated by about 118% (the equivalent of 4.1 T ha^{-1}).

Processes of salt leaching lead, in the long term, to the transfer of many tons of salt buildup especially in shallow groundwater below the plant root zone, inducing its salinization. This statement was confirmed by the monitoring of soil salinity at depth of 4 m (Fig. 5).

Besides the short- and long-term risks of soil and water salinization, which cause major reductions in crop productivity and quality, social and economic aspects of farmers should be also taken into consideration. Data shown in Table 4 highlight the basic aspects that are considered in carrying out the economic evaluation, where the labor force was estimated at about one-third of the production cost.

As the farmers are self-employed and known for their high productivity, the labor force cost is not included in the total cost of production. Under brackish/saline water irrigation conditions, small-scale family farms tend to be, in the short term, more productive and appear to be more profitable than large farms and more adapted to a bad situation than can be induced by climate change.

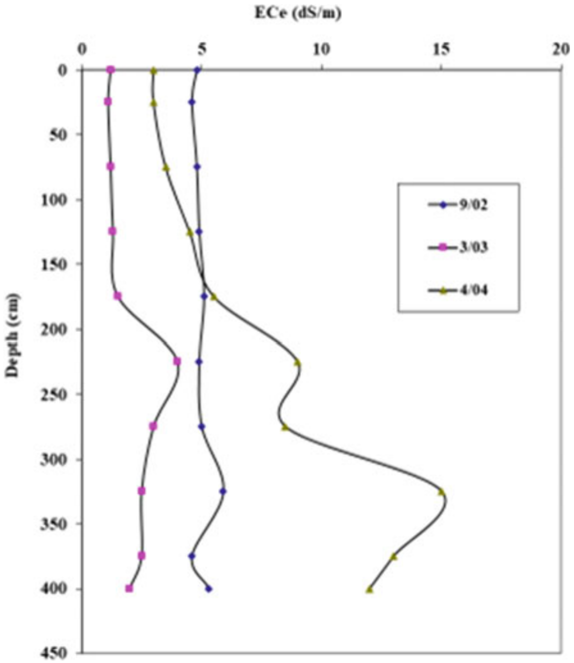


Fig. 5 Annual soil salinity profile at depth of 4 m

Table 4 Profit, Cost of production and proportion of family farms for some crops in Mehdia and Kairouan regions (average of 3 farmers for each region, Tunisian dinar [TND[a]])

Corps	Parameter	Mahdia	Kairouan
Summer peppers	Total profit	1165–363	–
	Total expenses	662–325	–
	Share of family labor costs to total expenses (%)	30–23	–
Greenhouse peppers	Total profit	4069–1093	–
	Total expenses	2048–1440	–
	Share of family labor costs to total expenses (%)	27–24	–
Barely	Total profit	–	1248–766
	Total expenses	–	570–295
	Share of family labor costs to total expenses (%)	–	33–24

[a] Tunisian dinar (DNT) = 0.320 dollar (USD)

4 Discussion

Brackish/saline water is considered a valuable alternative water source when aiming to reduce the risk of water shortages. Several studies indicate that brackish/saline water can be effectively used for production of irrigated crops (Singh et al. 2010; Liu et al. 2016; Di Gioia et al. 2018; Rajesh et al. 2019). However, using saline water for irrigation, under arid conditions with irregular rainfall and high evapotranspiration, may result in salt accumulation in the soil profile and lead to the risk of soil salinization (Verma et al. 2012; Genxiang et al. 2019; Jingang et al. 2019), consequently, soil water-salt movement could be changed, and ultimately crop water uptake could be hindered (Wang et al. 2015; Alharby et al. 2018).

In the Tunisian semi-arid context, soil salinity was monitored when using saline water for irrigation during two different crop seasons (summer pepper and winter/spring barely). In this study, soil salinity (ECe) at the start of the experiment ranged from 5 to 5.7 dS m^{-1}. Soil salinity increased at the end of summer pepper growing season and then decreased at the end of winter/spring barley growing season because of precipitation and leaching. Similar results were obtained by other authors as they showed that, in dry season, soil profile salinity increased under irrigation with 6.1–7.6 dS m^{-1} brackish water but promoted soil salt desalinization in rainy season (Li et al. 2015; Murad et al. 2018). According to Mohamed et al. (2013), by the end of rainy season the salt that accumulated in the soil due to irrigation with saline water leached almost completely out of the top 0–20-cm soil layer. It has been also demonstrated that the total salt load of the soil increases rapidly, especially in the top 0–100 cm soil depth. Salt leaching will depend on the amount of the rain, indeed, as reported by Kaur et al. (1995), some accumulation of salts may occur on an annual basis in years when the seasonal rainfall is below the average. In the short term salt leached from the topsoil layer increases the soil salinity of the 80–140 cm layer (Mohamed et al. 2013). In a similar way, Wenjun et al. (2008) concluded that

150 cm is the maximum salt leaching depth during a wet season with a rainfall precipitation. Overall, in the short run, at least in the eight years of the study, the soil did not become strongly saline (Mohamed et al. 2013).

Irrigation with saline water for many years and without suitable management strategy leads to the buildup of salts in deeper layers. Indeed, the salts will be continuously leached by rainfall from the soil profile and the desalinization process will be more important in the surface layer than in deeper layers. According to Wenjun et al. (2008) about 98.4% of the total salt load, including salt added with saline irrigation and salt which was carried over from preceding years, was moved out of the 0–40, 0–100 and 0–180 cm soil depths. As reported by Mohamed et al. (2013) salinity in the topsoil decreased more rapidly than in the deeper soil, in which the salinity increased initially, as the leached-out salt from the upper layer accumulated in this layer, before it decreased with the infiltrating water. They also mentioned that the salt leaching rate was higher in soil with a higher initial salinity than in soil with a lower initial salinity and this could be explained by the knowledge that at high salt concentration in soil most of the cations (Na^+) remain in the bulk solution outside diffuse double layers around clay particles. In addition, there are several factors that can inhibit leaching: a high clay content of soil; compaction; very high sodium content and/or a high-water table. In the long term, a considerable amount of salt might still remain in the soil, not having been leached by rainfall, indicating that, after several years, irrigation with saline water may cause accumulation of salt in the soil exceeding that washed out by rainfall events. Excess accumulation of salt results in soil salinization which in turn leads to groundwater salinization and crop yield reduction.

Sustainable use of saline water requires suitable management practices to avoid salinization's adverse effects which occur when salts are not dissolved and carried below the root zone. Salinization can be restricted by leaching of salt from the root zone, changed farm management practices and the use of salt tolerant plants (Pooja and Rajesh 2015). The rate of salt leaching depends upon the amount of salts present in the soil, the type of salts, the soil texture and the amount and frequency of the rains (Sharma and Tyagi 2004). Rainfall is well known as a typical natural leaching process that may be effective in leaching of salt out of the root zone to deeper soil layers. Under Tunisian semi-arid conditions, a research study demonstrated that natural rainfall processes resulted in effective leaching of salt out of crop root zone over a certain period while maintaining a favorable salt balance in the topsoil. It has been concluded that increasing intensity and frequency of rainfalls during the subsequent rainy season will generally provide a positive water balance and leach salinity below the main root zone (Liu et al. 2002). Whereas, in the absence of sufficient rainfall, irrigated soil under arid conditions is exposed to salt accumulation. Several studies were conducted to evaluate the effectiveness of the rainfall in saline water management under arid and semi-arid conditions (Sheng and Xiuling 1997; Kafi et al. 2010; Sharma and Tyagi 2004; Kiani and Mirlatifi 2012; Romy 2017). Semi-arid regions are often in a delicate hydrological balance, which may experience prolonged wet or dry sequences that fluctuate considerably over time in response to climate change. Thus, rainfall tends to be more variable in both space and time and the magnitude of these variations differs from one region to another. The effectiveness of rainfall also differs from early to later period of leaching. Thus, although the amount of rainfall was relatively small at the early period of leaching, the rate of salt removal in the soil was high. A substantial amount of rain (1673 mm) could not wash out the salinity from the root zone soil. So, more intense rainfall late in the rainy season, rather than in the early part played only a minimal role in salt leaching since these rainfalls had less opportunity and time to bring out salt from micro-pores of the soil through diffusion (Mohamed et al. 2013). More than that Mojid and Acharjee (2013) suggested that more salt would be leached out of soil with the same quantity of rainfall if the rainfalls were distributed uniformly over the leaching period. Besides amount, frequency and time of the rains, salt leaching is also affected by soil texture. In this way, Kaledhonkar et al. (2020) suggested that a low amount of annual rainfall (<350 mm) in arid regions prevents the use of saline water for crop production on fine texture soil, but not on coarse textured soils. Thus, soil texture and annual rainfall amount play an important role in selection of crops.

Overall, in the case of Tunisian conditions, it is very important to note that for sustainable use of saline water it is important to incorporate the natural rainfall leaching effect into the local irrigation planning and water management. It seems to be that successful use of saline water for irrigation for short-cycle crops can be achieved if rainfall events would occur yearly in the wet season. However, in the long term, rainfall might be insufficient to avoid the risk of salt accumulation. Thus, smart assessment of soil should be applied and innovative water management practices should be adopted.

5 Conclusion

Irrigation with saline water requires effective water management strategies. The challenge for farmers is thus to devise strategies for improving the economic viability while reducing environmental risks and ensuring irrigation sustainability. Irrigation sustainability requires water management practices in order to manage the salt applied from irrigation with saline water, or the native salts in soil in order to control salinity in the root zone. Under Tunisian semi-arid conditions, it has been reported that mechanisms of soil water and salt redistribution are controlled by irrigation and rainfall events. Indeed, irrigation involves inherent physical and chemical processes that can cause salts accumulation in soils (Dennis and Oster 2006) while rainfall induces salts leaching to deeper soil. The dynamics of salt movement in the topsoil soil exhibit a seasonal variation between salt accumulation and leaching in the rainy season which in turn leads, in the long term, to groundwater salinization. Labor force represents an important element in determining the economic feasibility. It seems to be that successful use of saline water for irrigation of short-cycle crops can be achieved if rainfall events occurred yearly in sufficient amount to leach salt from the root zone of sandy soils. Lower supervision costs by employing family farmers are also required. However, in the long term, rainfall would be insufficient to avoid the risk of salt accumulation. Thus, new tools for salinity assessment should be used and innovative water management practices should be adopted.

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Part IV

Land Management When Irrigating with Saline Water

Chapter 11
Do Cultivating Methods Improve Crop Yield Under Saline Conditions in Semi-Arid Areas

Fatemeh Razzaghi, Ali Shabani, and Ali Reza Sepaskhah

Abstract Soil and water salinities in agricultural land increase osmotic pressure and the toxic effect of some ions, disturb the nutrient uptake, restrict plant growth and ultimately, reduce crop yields. During the growing season, the osmotic potential in plant root zone varies due to spatial and temporal variations of salt and water distribution in the soil profile. Planting methods and irrigation regimes are two effective ways to affect salt and water distributions in the soil profile. There are different planting methods including on-ridge planting (single row bed, double row bed, single row sloping bed, double row sloping bed), in-furrow planting and basin planting. Under conditions of irrigation water and soil salinities and in each planting method and irrigation regime, the level of damage caused by salinity stress on plant growth depends on plant position relative to salt accumulation place and soil water content distribution. On the other hand, the variation of salt distribution in the soil results in partial root-zone salinity stress that affects plant growth. Therefore, in this chapter, the effects of different planting methods on improvement or reduction of salinity stress on salt accumulation in soil and on yield, water productivity and relations between yield and soil saturated electrical conductivity of wheat, rapeseed and saffron plants are discussed. Results show that the in-furrow planting method resulted in higher winter wheat, rapeseed grain and saffron yields, higher water productivity and generally higher ECe threshold and ECe for 50% yield reduction compared with on-ridge and basin planting methods under water and salinity stress conditions.

Keywords Wheat · Rapeseed · Saffron · In-furrow planting · On-ridge planting · Water productivity

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1 Introduction

Salinity and water stress are the two major constraints for crop growth and production (Ashraf et al. 2008). It is stated in the literature that around 20% of the total cultivated land and 33% of the irrigated agricultural areas in the world have been affected by high salinity (Jamil et al. 2011; Shahid et al. 2018). Arid and semi-arid regions, which cover one-third of the total world area, face water stress, low precipitation and uneven distribution of rainfall (Mesgaran et al. 2017). The largest area of the world's saline soils is found in the arid and semi-arid regions, where precipitation is lower than evapotranspiration (Nachshon 2018). Iran, as an arid to semi-arid region, is faced with both salinity and water stress due to limited and low quality water resources, low precipitation, low soil quality and high evaporation demand (Ahmadikhah 2009). The rate of agricultural production was already in decline before 2005 (Mousavi 2005). Thirty percent of irrigated land in Iran is salt-affected (Hussain et al. 2019). When water stresses occur, soil water potential, root water uptake, plant photosynthesis and finally crop growth and production are negatively influenced. Hence, finding solutions to overcome this problem is of utmost importance. The most appropriate solutions are: (i) selecting crops tolerant to salinity and water stress, (ii) appropriate planting methods and (iii) managing irrigation amounts and methods.

Irrigation water and soil salinities result in depressed specific metabolic processes and reduced crop growth and yield due to: (1) increase in osmotic stress that limits water uptake by plant roots and (2) ionic toxicity that promotes the imbalance in plant nutrient uptake (Rajpar et al. 2006). As reported by Cebas-Csic et al. (1997), higher salt concentration in soil and higher toxic ions like Na and Cl ions decrease nutrient ions uptake like Ca, K and Mg (Grattan and Grieve 1992). On the other hand, there are spatial and temporal variations of salt and water distribution in the soil profile during the growing season (Liu et al. 2013). These variations resulted from two factors including planting method and irrigation regimes and methods. Some of the planting methods are on-ridge planting (single row bed, double row bed, single row sloping bed, double row sloping bed), in-furrow and basin planting (Fig. 1) (Fahong et al. 2004; Qin et al. 2019; Li et al. 2010). The temporal variation of osmotic potential is related to the soil water-soluble salt concentration variation, which results from soil water content variation between two irrigation events. The level of damage caused by salinity stress on plant growth depends on plant position relative to the salt accumulation place and soil water content distribution (Paranychianakis and Chartzoulakis 2005; Machado and Serralheiro 2017). On the other hand, variation of salt distribution in soils can result in partial root-zone salinity stress that affects plant growth. Planting in-furrow causes salt to accumulate on the ridge and provides a better microclimate for plant growth, due to higher soil water content and lower soil evaporation from soil surface due to canopy cover. In addition, the result of using different planting patterns such as basin, on-ridge and in-furrow showed that the in-furrow planting method stores the rainfall in the soil and enhances water use efficiency (Li et al. 2010).

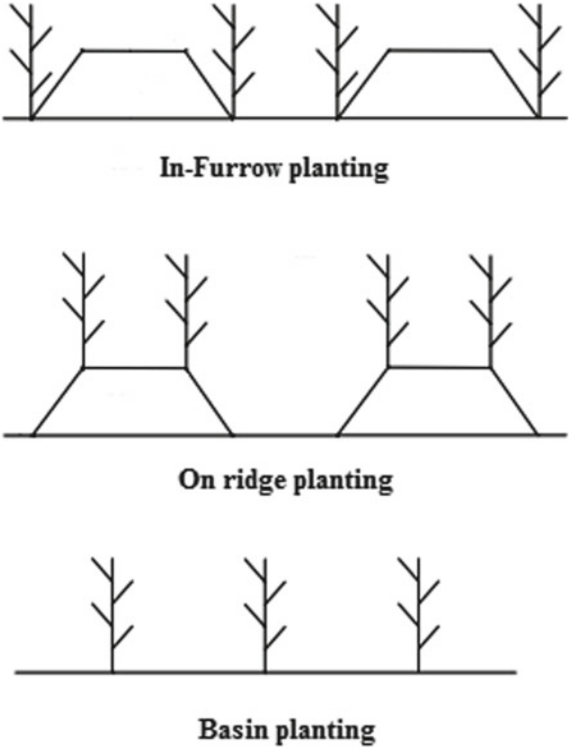


Fig. 1 Schematic of in-furrow, on-ridge and basin planting method (Li et al. 2010)

Application of appropriate levels of amendments in forms of manure, chemical fertilizer and other nutritional residue mitigates the negative effect of salt stress on crop production, increases soil water holding capacity and hydraulic conductivity and enhances water uptake and crop growth and yield (Kanber et al. 2019; Chávez-García and Siebe 2019). However, if the electrical conductivity of the amendment is high, its application with saline irrigation water is not recommended.

In this chapter, the results of 8-year field experiments on the effect of different planting methods and salinity levels on yield and threshold electrical conductivity of rapeseed, saffron and winter wheat are discussed.

2 Materials and Methods

2.1 Site Description

Different experiments were conducted during growing seasons from 2009 to 2017 (Table 1), at the Experimental Station of Agricultural College, Shiraz University, Iran (Fig. 2). The soil at the experimental site is silty clay loam in the 0–1.2 m depth

(Table 2). Cumulative seasonal rainfall depth, irrigation depths for full irrigation and reference evapotranspiration (ET_o) in all growing seasons are shown in Table 3. Reference evapotranspiration (ET_o) was calculated using meteorological data from a standard weather station near the experimental fields and the modified Penman–Monteith equation (Razzaghi and Sepaskhah 2012).

2.2 Experimental Design and Treatments

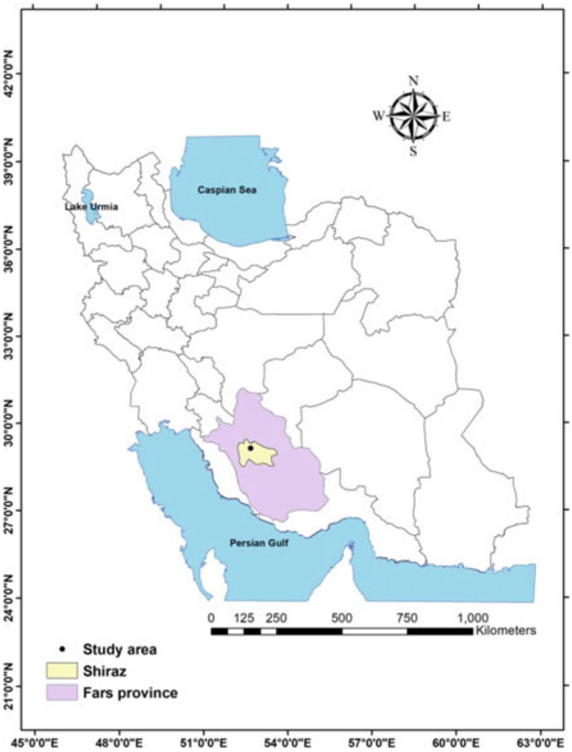
Four different experiments were conducted using rapeseed (Exp 1; Shabani et al. 2013), saffron (Exp 2; Yarami and Sepaskhah 2015), winter wheat (Exp 3; Mosaffa and Sepaskhah 2019) and saffron (Exp 4; Dastranj and Sepaskhah 2019) to investigate whether the planting method mitigates the negative effect of salt stress on plant growth and yield. Hence, different treatments were applied, including different planting methods, irrigation water salinities, and different irrigation regimes and/or fertilizer levels (Table 4). In all experiments, experimental design was a split-split plot arrangement in a randomized complete block design with three replications. In Exp 1, irrigation treatments, water salinity levels and planting methods were considered as the main plot, subplot and sup-subplot, respectively. In Exp 2, salinity levels of irrigation water, cow manure levels and planting methods were arranged as the main plot, subplot and sub-subplot, respectively. In Exp 3, irrigation treatments, salinity levels of irrigation water and planting methods were considered as the main plot, subplot and sub-subplot, respectively. In-furrow planting had two rows at the bottom of each furrow, and on-ridge planting had two rows on top of each ridge with a spacing of 0.15 m. Finally in Exp 4, salinity levels of irrigation water, irrigation water amount and planting methods were performed as the main plot, subplot and sub-subplot, respectively.

In order to prevent water transfer from one plot to another, a 1.0 m distance was considered between two adjacent plots in all experiments. Appropriate fertilizers were added to the soil of each experiment according to performed soil analyses prior to crop cultivation. The saline water in all experiments was obtained by addition of NaCl and $CaCl_2$ to the well water in equal equivalent proportions. In addition, full irrigation was initially applied to all experimental crops to ensure full germination and crop establishment and the saline water and irrigation regimes were initiated afterward.

Table 1 Different experiments that are used in this study

Crop	Years	Code
Rapeseed	2009–2011 and 2010–2011	Exp 1
Saffron	2011–2012 and 2012–2013	Exp 2
Winter wheat	2011–2012 and 2012–2013	Exp 3
Saffron	2015–2016 and 2016–2017	Exp 4

Fig. 2 Location of the experimental site



2.3 Soil Water Content

Soil water content was measured by the neutron scattering method at different depths for each irrigation event, in all experiments. The irrigation depth was calculated according to the following equation:

$$I = \sum_{i=1}^{n} (\theta_{FCi} - \theta_i) \times \Delta Z_i \tag{1}$$

where I is the irrigation water depth (m), $\theta_{\mathrm{FC}i}$ is the volumetric soil water content in layer i at field capacity ($\mathrm{m}^3\ \mathrm{m}^{-3}$), θ_i is the soil water content in layer i before each irrigation event ($\mathrm{m}^3\ \mathrm{m}^{-3}$), Δz_i is the soil layer depth (m) and n is the number of soil layers. Twenty percent, 15, 20 and 15% leaching fraction was added to full irrigation to prevent salt accumulation in root zone in Exp 1, Exp 2, Exp 3 and Exp 4, respectively.

Table 2 Physical and chemical properties of the soil in the experimental site (Shabani et al. 2013)

Properties	Soil depth (cm)				
	0–10	10–30	30–60	60–90	90–120
θ_{FC}[a] ($cm^3\ cm^{-3}$)	0.30	0.32	0.33	0.33	0.33
θ_{PWP} ($cm^3\ cm^{-3}$)	0.16	0.16	0.19	0.19	0.19
ρ_b ($g\ cm^{-3}$)	1.3	1.43	1.43	1.43	1.43
Clay (%)	35	31	39	34	29
Silt (%)	55	57	51	50	53
Sand (%)	10	12	10	16	18
Soil texture	Silty clay loam				
EC_e ($dS\ m^{-1}$)	0.65	0.63	0.6	0.57	0.53
Na ($meq\ l^{-1}$)	0.93	0.85	0.83	0.8	0.76
Ca ($meq\ l^{-1}$)	3.71	3.68	3.72	3.41	3.23
Cl ($meq\ l^{-1}$)	3.23	3.04	2.71	2.3	2.12
Mg ($meq\ l^{-1}$)	3.17	3.11	2.69	2.85	2.71

[a] θ_{FC}, θ_{PWP}, ρ_b and EC_e indicates soil water content at field capacity, soil water content at permanent wilting point, soil bulk density and soil saturated electrical conductivity, respectively

Table 3 Average temperature and relative humidity (T_{ave} and RH_{ave}, respectively), initial salinity of saturated soil extract (EC_e), non-saline water EC, seasonal rainfall, ET_0 and applied full irrigation for different experiments (Exp)

Crop	Exp	T_{ave} (°C)	RH_{ave} (%)	Initial soil ECe ($dS\ m^{-1}$)	Non-saline water EC ($dS\ m^{-1}$)	Applied full irrigation (mm)	Rainfall (mm)	ET_0 (mm)
Rapeseed	1	11.3	62	0.57	0.60	807	298	988
		6.1	42	0.57	0.60	935	258	1048
Saffron	2	8	45	0.58	0.45	207	363	556
		7	55	0.58	0.45	263	445	531
Winter wheat	3	10	44	0.58	0.60	562	363	na
		10	53	0.58	0.60	525	439	na
Saffron	4	na	na	0.64	0.45	324	266	na
		na	na	0.64	0.45	317	367	na

na not available

2.4 Yield and Water Productivity

The crop grain for rapeseed, winter wheat and flowers (stigmas and styles) for saffron and the above-ground dry matter of each crop was harvested and dried [in oven for rapeseed and winter wheat and air-dried for saffron] for each plot and treatment in all four experiments. Water productivity was defined as the ratio of grain or saffron yield to the applied irrigation water.

2.5 Relationship Between Relative Yield and Average Root-Zone Salinity of Soil Saturation Extract

Soil samples were taken from different soil depths after harvest to measure electrical conductivity in soil saturation extract (EC_e). The relationship between relative yield and average root-zone salinity of soil saturation extract was determined by the following equation (Maas and Hoffman 1977):

$$\frac{Y_a}{Y_m} = 1 - b(EC_e - EC_{e\,threshold} \tag{2}$$

in which Y_a is the actual yield, Y_m is the maximum yield, EC_e is the average root-zone salinity of soil saturation extract (dS m^{-1}), $EC_{e\ \mathrm{threshold}}$ is the EC_e value for 100 percent yield potential (dS m^{-1}) and b is the growth reduction coefficient of relative yield (% per dS m^{-1}).

Table 4 Treatments used in different experiments

	Treatment		
	Planting method	Irrigation water salinity, dS m^{-1}	Irrigation water regimes/ fertilizer levels
Rapeseed	On-ridge and in-furrow	0.6, 4.0, 7.0 and 10.0 in first year and 0.6, 4.0, 8.0 and 12.0 in second year	FI, 0.75 FI and 0.5 FI in first year and FI, 0.65 FI and 0.35 FI in second year
Saffron	Basin and in-furrow	0.45, 1.0, 2.0, and 3.0	30 and 60 Mg ha^{-1} of cow manure
Winter wheat	On-ridge and in-furrow	0.6, 5.0, 7.5, and 10.0	FI, 0.65 FI and 0.35 FI
Saffron	Basin and in-furrow	0.45, 1.0, 2.0 and 3.0	FI, 0.75 FI and 0.5 FI

FI full irrigation

3 Results

3.1 Grain Yield/Saffron Yield

The amount of winter wheat and rapeseed grain and saffron yields for different treatments in each study was reported and discussed in previously published articles (Shabani et al. 2013; Yarami and Sepaskhah 2015; Mosaffa and Sepaskhah 2019; Dastranj and Sepaskhah 2019). The maximum and minimum grain yield/saffron yield for different planting methods (averaged over two other treatments: salinity levels and irrigation levels/fertilizer levels) for different growing seasons are presented in Table 5. For rapeseed, in the first year of the experiment, the maximum grain yield in the in-furrow planting method (3.12 Mg ha^{-1}) was similar (P value > 0.05) to that in the on-ridge planting method (3.18 Mg ha^{-1}), while the minimum values of rapeseed yield were higher in the in-furrow planting method in comparison with that in the on-ridge planting method; however, the difference was not statistically significant ($P > 0.05$). In contrast, in the second year of the rapeseed experiment, the maximum yield was higher in the in-furrow planting (3.5 Mg ha^{-1}) method in comparison with that in the on-ridge planting (3.13 Mg ha^{-1}), although the difference was not statistically significant ($P > 0.05$). Similarly to the first year, the minimum rapeseed yield in the on-ridge planting method (1.77 Mg ha^{-1}) was lower than that in the in-furrow planting method (2.04 Mg ha^{-1}); however, the difference was not statistically significant ($P > 0.5$).

Figure 3a and b shows the difference between the rapeseed grain yield of the on-ridge and in-furrow planting methods for different irrigation regimes and salinity levels. In the first year of the rapeseed experiment (Exp 1), the rapeseed grain yield for the on-ridge planting method was higher than in the in-furrow planting method in full irrigation and 0.5 dS m^{-1} salinity level and in 0.35 FI and 10 dS m^{-1} salinity levels (negative values), while for other treatments, the in-furrow planting method had higher rapeseed grain yield than in the on-ridge planting method. In the second year of Exp 1, all treatments had higher rapeseed grain yield under the in-furrow planting method. In general, with an increase in irrigation water salinity and water stress levels, the percent difference between rapeseed grain yield of the in-furrow and on-ridge planting methods was increased (more distance from center, Fig. 3a and b). In other words, under high water and salinity stress conditions, yield reduction in the on-ridge planting method was higher in comparison with the in-furrow planting method. Therefore, the in-furrow planting method provides better conditions for plant growth due to lower salt accumulation, higher soil water content and salt leaching in the plant root zone in the furrow (Zhang et al. 2007; Shabani et al. 2013).

Winter wheat grain yield in the first and second year of experiment (Exp 3) showed a higher value under the in-furrow planting method than under the on-ridge planting (Table 4). The latter results confirmed that the in-furrow planting method produced higher yield than that in the on-ridge planting methods for all interactions of salinity and irrigation levels (Fig. 3e and f). Similar to the results obtained for rapeseed,

Table 5 Maximum and minimum of seed yield/saffron yield for different planting methods in two years of experiments

		Rapeseed Mg ha^{-1} (Exp 1)		Saffron kg ha^{-1} (Exp 2)	
		First year	Second year	First year	Second year
In-Furrow	Max	3.12a[a] (4 dS m^{-1} + FI)	3.5a (4 dS m^{-1} + FI)	12.07a (60 t ha^{-1} + 1 dS m^{-1})	17.34a (60 t ha^{-1} + 1 dS m^{-1})
	Min	2.05b (10 dS m^{-1} + 0.5FI)	2.04b (12 dS m^{-1} + 0.35FI)	7.12b (30 t ha^{-1} + 3 dS m^{-1})	9.40b (30 t ha^{-1} + 3 dS m^{-1})
On ridge	Max	3.18a (0.5 dS m^{-1} + FI)	3.13a (4 dS m^{-1} + FI)	3.89c (60 t ha^{-1} + 0.45 dS m^{-1})	7.35c (60 t ha^{-1} + 0.45 dS m^{-1})
	Min	1.92b (7 dS m^{-1} + 0.5FI)	1.77b (12 dS m^{-1} + 0.35FI)	1.18d (30 t ha^{-1} + 2 dS m^{-1})	1.41d (30 t ha^{-1} + 2 dS m^{-1})
In-Furrow		Winter wheat Mg ha^{-1} (Exp 3)		Saffron kg ha^{-1} (Exp 4)	
		First year	Second year	First year	Second year
	Max	5.41a (0.6 dS m^{-1} + FI)	5.08a (0.6 dS m^{-1} + FI)	10.28a (0.45 dS m^{-1} + FI)	17.27a (0.45 dS m^{-1} + FI)
	Min	2.90b (10 dS m^{-1} + 0.35FI)	2.98b (10 dS m^{-1} + 0.35FI)	5.73c (3 dS m^{-1} + 0.5FI)	7.24c (3 dS m^{-1} + 0.5FI)
Basin	Max	5.30a (0.6 dS m^{-1} + FI)	4.92a (0.6 dS m^{-1} + FI)	6.37b (0.45 dS m^{-1} + FI)	10.2b (0.45 dS m^{-1} + FI)
	Min	2.87b (10 dS m^{-1} + 0.35FI)	2.78b (10 dS m^{-1} + 0.35FI)	1.78d (3 dS m^{-1} + 0.5FI)	3.37d (3 dS m^{-1} + 0.5FI)

FI full irrigation

[a] Means followed by the same letters in columns for each year are not significantly different at 5% level of probability, using Duncan's multiple range test

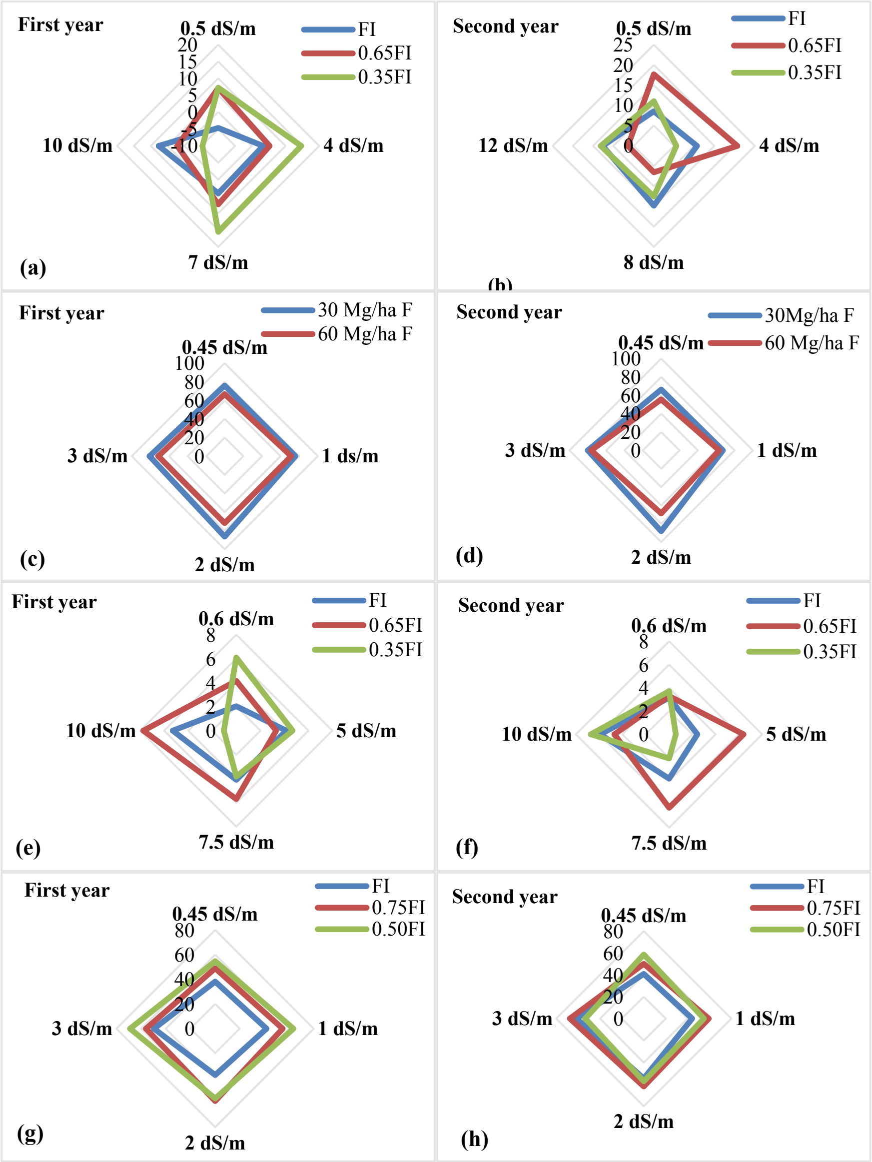


Fig. 3 Percent difference in crop yield for rapeseed (a, b) and winter wheat (e, f) grain yield between the in-furrow and the on-ridge planting methods and for saffron yield and in the in-furrow and the basin planting methods for different irrigation/fertilizer (c, d) and salinity levels (g, h) in two years of the field experiment

differences between the in-furrow and the on-ridge planting methods were larger with higher irrigation water salinity compared with lower irrigation water salinity.

Considering Exp 2 and Exp 4, both maximum and minimum values of saffron yield were higher under the in-furrow planting method than under basin condition in both years of the experiments (Table 5). The percentage difference in saffron yield between the in-furrow and basin planting methods for different salinities and fertilizer levels is shown in Fig. 3. The result showed that saffron yield differences between the in-furrow and the basin planting method were higher for the 30 Mg ha^{-1} fertilizer application and at all salinity levels (Fig. 3c and d). Specifically in the second year, the differences between the in-furrow and basin planting methods were higher for the 2 and 3 dS m^{-1} irrigation water salinity compared with the 0.45 and 1.0 dS m^{-1} irrigation water salinity. This may have been the result of better plant growth conditions in the in-furrow planting method. Figure 3 shows the percent difference in saffron yield under the in-furrow and the on-ridge planting methods, and the results indicate that for all interactions between irrigation and salinity levels, the in-furrow planting produced higher saffron yield than that on the ridge planting method (Fig. 3g and h). Similar to Exp 1 and Exp 2, at higher irrigation water salinity (3 dS m^{-1}), the difference between the in-furrow and on-ridge planting methods was larger. This difference was clearly higher under more severe water stresses in the first year (0.5FI and 0.75FI). The results indicate that salinity stress is more detrimental to saffron yield in in-furrow planting compared with on-ridge planting.

3.2 *Water Productivity*

Maximum water productivity (WP) for rapeseed in the first year was 0.47 kg m^{-3} for 4.0 dS m^{-1} salinity and 0.35 FI for the in-furrow planting and 0.42 kg m^{-3} for 10.0 dS m^{-1} and 0.35 FI for the on-ridge planting method (Exp 1), while in the second year, 0.45 and 0.4 kg m^{-3} were obtained for 0.5 dS m^{-1} salinity and 0.35 FI for the in-furrow and the on-ridge planting methods, respectively. Figure 4a and b shows that the average WP for the in-furrow plants was higher than for the on-ridge planting method for all irrigation and salinity levels in both years. There is no clear pattern for the effect of salinity and water regimes on the percent difference between rapeseed WP in the in-furrow and the on-ridge planting method.

Application of 30 Mg ha^{-1} manure fertilizer led to higher saffron WP under the in-furrow planting method in comparison with that in the basin in both years of the study (Fig. 4c and d). However, the maximum WP for saffron yield in the first year was 5.83 g m^{-3} for 60 Mg ha^{-1} manure fertilizer and 1.0 dS m^{-1} salinity under the in-furrow and 1.88 g m^{-3} for 60 Mg ha^{-1} manure fertilizer and 0.45 dS m^{-1} salinity under the basin planting. In the second year, the WP was 6.32 and 2.81 g m^{-3} for 60 Mg ha^{-1} manure fertilizer and 0.45 dS m^{-1} salinity under the in-furrow and the basin planting methods, respectively (Exp 2). In both years, for application of

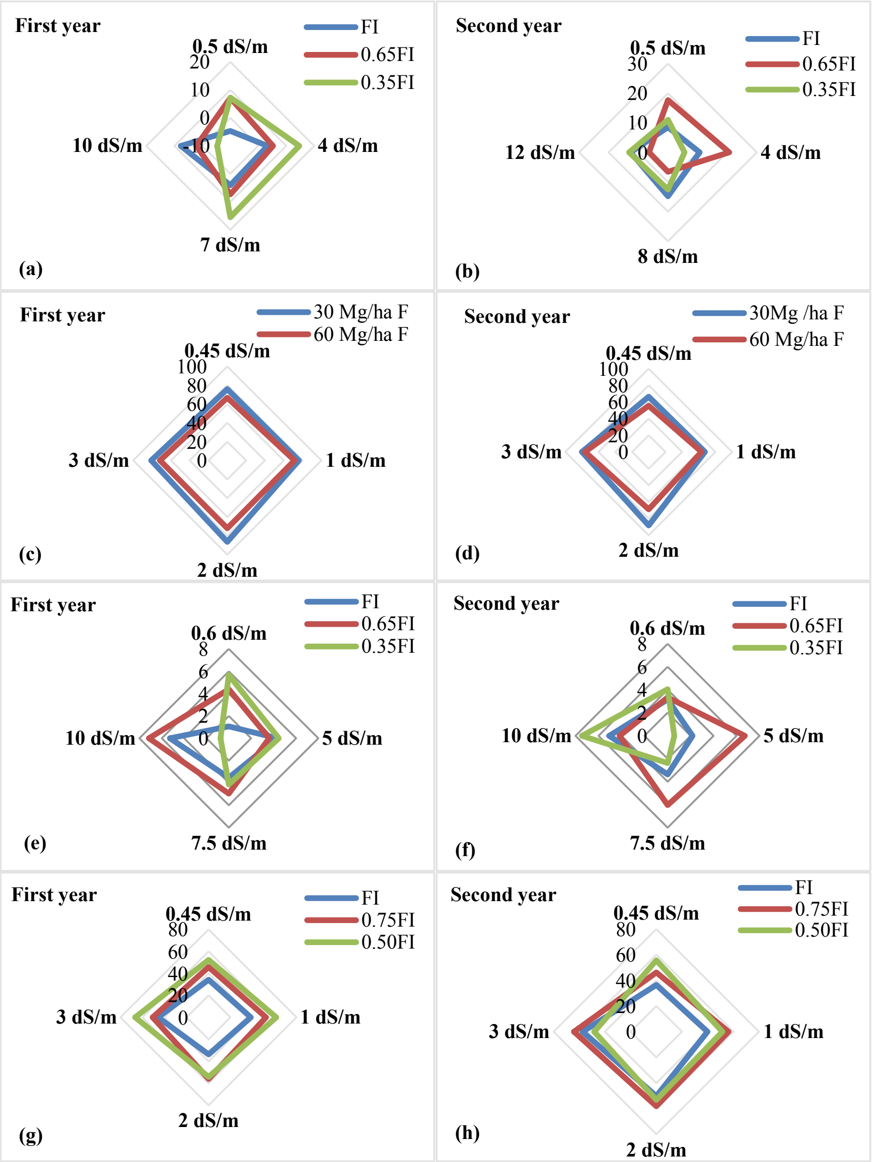


Fig. 4 The differences in water productivity between in-furrow and on-ridge planting methods for rapeseed (a, b) and winter wheat (e, f) and between in-furrow and basin planting methods for saffron for different irrigation/fertilizer (c, d) and salinity levels (e, f) for the 2-year experiments

30 Mg ha^{-1} manure fertilizer, the percent difference between saffron WP in the in-furrow and the basin planting method for 2.0 dS m^{-1} salinity level was higher than values in other salinity levels.

Maximum winter wheat WP in the first year was 1.50 kg m^{-3} for both 0.6 and 5.0 dS m^{-1} salinity levels and 0.35 FI under the on-ridge planting method, and 1.59 kg m^{-3} for 0.6 dS m^{-1} and 0.35 FI in the in-furrow planting method (Exp 3). In addition, in the second year, the WP of 1.69 kg m^{-3} (for 5.0 dS m^{-1} and 0.35 FI) and 1.73 kg m^{-3} (for 0.6 dS m^{-1} and 0.35 FI) for the on-ridge and the in-furrow planting method was obtained, respectively. Considering all interactions, the on-ridge planting method showed higher WP than the in-furrow planting method (Fig. 4e and f).

Saffron reached its maximum WP of 4.61 and 2.2 g m^{-3} in the first year and 7.93 and 3.75 g m^{-3} in the second year (average of salinity and irrigation levels) in the in-furrow and the basin planting methods, respectively (Exp 4). In addition, the percentage of difference between WP in the in-furrow and the basin planting methods clearly showed that saffron had a higher WP in the in-furrow planting method (Fig. 4g and h). These differences were higher with the 2.0 and 3.0 dS m^{-1} irrigation water salinity.

3.3 Relations Between Yield Ratios and Soil Saturated Electrical Conductivity

The relationships between $\frac{Y_a}{Y_m}$ (actual yield/maximum yield) versus the mean soil saturated electrical conductivity for different crops and the planting methods in full irrigation regime were drawn and the threshold EC$_e$ (EC$_{e\text{ threshold}}$), the EC$_e$ for 50% yield reduction and the yield reduction coefficient were determined (Table 6). The results showed that the EC$_{e\text{ threshold}}$ of rapeseed (Exp 1) for the in-furrow planting method was higher than that in the on-ridge planting method. The amount of EC$_e$ to have 50% rapeseed yield reduction was 18.0 dS m^{-1} for the in-furrow planting method, while it was 17.7 dS m^{-1} for the on-ridge planting method, indicating that a higher ECe should be obtained in soil to have 50% yield reduction in the in-furrow planting method compared with the on-ridge method. In addition, the yield reduction coefficient for rapeseed was 3.2% per dS m^{-1} for the in-furrow, while a lower value was obtained for the on-ridge planting method (2.9% per dS m^{-1}). For winter wheat, the in-furrow planting method had a lower EC$_{e\text{ threshold}}$ in comparison with that in the on-ridge planting method (Exp 3). A similar trend was observed for the yield reduction coefficient with 5.2 and 5.4% per dS m^{-1} for the in-furrow and the on-ridge planting methods, respectively.

For the saffron experiments (Exps 2 and 4), the results showed that EC$_{e\text{ threshold}}$ in the in-furrow planting method was higher than that in the basin method. In addition, the percent yield reduction per increase in EC$_e$ was lower in the in-furrow planting method in comparison with that in the basin planting method. Furthermore, a higher

Table 6 Threshold EC_e, EC_e for 50% yield reduction and yield reduction coefficient for different planting methods and crops in full irrigation regime

Planting method/Crop	Rapeseed (Exp 1)	Winter wheat (Exp 3)
	Threshold EC_e (dS m^{-1})	
On ridge	1.02	1.84
In-furrow	1.08	1.56
EC_e for 50% yield reduction (dS m^{-1})		
On ridge	17.66	11.12
In-furrow	18.04	11.16
Yield reduction coefficient (% per dS m^{-1})		
On ridge	2.9	5.4
In-furrow	3.2	5.2
	Saffron (Exp 2)	Saffron (Exp 4)
Threshold EC_e (dS m^{-1})		
Basin	0.76	0.77
In-furrow	0.87	0.86
EC_e for 50% yield reduction (dS m^{-1})		
Basin	1.64	1.90
In-furrow	2.02	2.27
Yield reduction coefficient (% per dS m^{-1})		
Basin	63	44
In-furrow	46	35

EC_e should be reached in soil to have a 50% reduction in saffron yield in the in-furrow planting method compared to the basin method. The latter results showed that saffron sensitivity to saline soil is lower in the in-furrow planting method.

Moreover, the $\frac{Y_a}{Y_m}$ versus the mean soil saturated electrical conductivity equations for winter wheat (Exp 3) and saffron (Exp 4) under different irrigation regimes were determined (Table 7). These equations were not provided for rapeseed (Exp 1) due to different treatments performed in two years of experiment and for saffron (Exp 2), due to use of single irrigation regime. The result showed that application of deficit irrigation under saline conditions reduced the $EC_{e\ \mathrm{threshold}}$ and increased the yield reduction coefficients for both winter wheat and saffron. The latter result occurred due to a decline in soil water potential as a result of both the matric and osmotic potential and hence the sensitivity of crop to saline condition increased under deficit irrigation (Ma et al. 2020).

Table 7 Relationship between $\frac{Y_a}{Y_m}$ fraction versus the mean soil saturated electrical conductivity (dS m^{-1}) for winter wheat (Exp 3) and saffron (Exp 4) under different irrigation regimes

Crop	Treatment	Equations
Winter wheat (Exp 3)	FI	$\frac{Y_a}{Y_m} = 1 - 0.052(EC_e - 1.67)$
	0.65FI	$\frac{Y_a}{Y_m} = 1 - 0.093(EC_e - 1.71)$
	0.35FI	$\frac{Y_a}{Y_m} = 1 - 0.095(EC_e - 1.07)$
Saffron (Exp 4)	FI	$\frac{Y_a}{Y_m} = 1 - 0.39(EC_e - 0.82)$
	0.75FI	$\frac{Y_a}{Y_m} = 1 - 0.59(EC_e - 0.74)$
	0.5FI	$\frac{Y_a}{Y_m} = 1 - 0.84(EC_e - 0.64)$

4 Conclusions

The in-furrow planting method resulted in a higher amount of winter wheat and rapeseed grain and saffron yields, higher water productivity and generally higher $EC_{e\ threshold}$ and EC_e for 50% yield reduction compared with on-ridge and basin planting methods under water and salinity stress conditions. These results are explained by higher soil water content, salt leaching and increases in osmotic potential (lower osmotic pressure) in the plant root zone. Therefore, the in-furrow planting method can be used as a strategy to ameliorate salt and water stress. However, there are some challenges to this planting method such as an increase in roughness coefficient, a decrease in speed of water advances down the furrows and ultimately, an increase in depth of infiltrated water near the furrow inlet and water loss. Solving this problem requires changing the in-furrow irrigation design factors such as furrow length or water discharge to furrows.

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Chapter 12
Phosphogypsum: Properties and Potential Use in Agriculture

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Abstract Phosphogypsum (PG) is a calcium sulphate dihydrate and a by-product of the phosphate fertilizer industry. It is produced in huge quantities (300 MT/year), but only 15% of the PG produced is recycled. Phosphogypsum is valued in several sectors: road construction, building materials and agriculture. In agriculture, PG is used as an amendment for degraded soils (saline, sodic and acid soils) and as a fertilizer because it contains many essential nutrients for plant growth and development such as calcium, sulphur, and phosphorus. The fertilizer industry would be another promising avenue for PG valorization. The objectives of this bibliographic work are to (1) Determine the processes of PG generation and the factors that influence its properties (2) Determine the physical, chemical, and radioactive properties of PG (3) Discuss the potential uses of phosphogypsum in agriculture (4) Define the effects of PG on crop production, soil, water, and the environment. Phosphogypsum contains some heavy metals and radioactive elements that could pose serious environmental risks. Therefore, it is critical to ensure that the exposure to these impurities does not exceed international standards. Hence, the necessity of long-term research projects in this area.

Keywords Phosphogypsum · Properties · Agricultural valorization · Saline soil · Acid soil · Fertilizer · Heavy metals · Radioactive elements

1 Introduction

Phosphorus is among the nutrients necessary for plant growth. Its functions cannot be fulfilled by any other nutrient. Phosphorus fertilizer production is one of the most important tools for providing this essential element to plants. Around 93% of the phosphate rock extracted is used to produce mineral fertilizers (Bejaoui 2016). Phosphorus fertilizer production generates in parallel a by-product called: phosphogypsum (Mesić et al. 2016; Saadaoui et al. 2017). For every ton of phosphoric

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acid, 4–5 tons of phosphogypsum are produced (El Issiouy et al. 2013; Papastefanou et al. 2006). Currently, between 3 and 4 billion tons of phosphogypsum have been produced, with an annual rise of 300 million tons (Cuadri et al. 2021).

The question of considering phosphogypsum as a waste or a resource has been widely discussed in the literature, depending on the regulations in different countries. Despite the restrictions in some countries, phosphogypsum is used all over the world (e.g., Australia, USA, India, Egypt, Spain,…) for different purposes including:

- Agriculture: Several benefits of PG application in agriculture have been reported worldwide. For instance, PG has been used either as a fertilizer or amendment for different types of soils including degraded ones (sodic, saline, and acidic soils). It has also been found that PG increases irrigation/water use efficiency, reduces soil surface crusting, and improves soil water infiltration rate (Al-Enazy et al. 2018; Bouray et al. 2020; Chung et al. 2001; El Rafie et al. 2020; Elloumi et al. 2015; Gharaibeh et al. 2011, 2014; Hassoune et al. 2017; Smith et al. 1994; Turner 2013; Zielonka et al. 2017).
- The manufacturing of fertilizers (ammonium sulphate, potassium sulphate, urea, sodium sulphate and calcium carbonate) (Ennaciri et al. 2016; IFA 2018).
- Composting: PG is widely used as a mineral additive in organic waste composting (Samet et al. 2019).
- Road and building construction (roads, terracing, bricks, plaster…) has been practiced in several countries (USA, Europe, Middle East, Africa); PG has been used as an alternative raw material for cement, to increase the strength of the concrete and as an anti-cracking agent (Al-Hwaiti et al. 2005; El Rafie et al. 2020; Folek et al. 2011; Tayibi et al. 2009; Turner 2013).

Phosphogypsum is currently marketed in Brazil, China, Spain, India, Kazakhstan, the Netherlands, and the United States of America. It is also used in other countries such as South Africa, Syria, and Tunisia. However, the utilization rate is only 15% on the global scale including construction materials, agriculture, and others (Chernysh et al. 2021; El Zrelli et al. 2018) due to several uncertainties and constraints such as:

- Radioactivity, heavy metals, and acidity: The concentrations of radionuclides and heavy metals in PG wastes vary considerably depending on the source and nature of the rock phosphates as well as the extraction processes.
- Transport and application costs: It depends on the distance between the production site and the application site.
- Standards and regulations: The restrictions on PG recycling vary depending on the country and the approach adopted.

Therefore, PG management and utilization are important and adequate research must be undertaken. This chapter aims to analyze and review the existing literature on PG recycling. To achieve this aim, the following objectives were set:

- Determine the processes of PG generation and the factors that influence its properties.
- Determine the physical, chemical, and radioactive properties of phosphogypsum

- Discuss the uses of phosphogypsum in agriculture as a fertilizer, amendment to degraded soils, and as an additive fertilizer industry.
- Define the PG impacts on crop production, soil, water, and environment.

2 Phosphogypsum Generation and Storage Processes

2.1 Phosphogypsum Generation Processes

The wet and dry process are the two main commercial processes used to produce phosphoric acid from natural phosphate. The dry process consists of a thermal reduction of rock phosphate at 2000 °C using an electrical furnace in the presence of coke or silica. The obtained phosphorus is then oxidized to P_2O_5 and hydrated to get phosphoric acid (Pereira 2003).

The wet process is the most used worldwide. It is applied by many countries such as Morocco, Spain, and Tunisia (Bolívar et al. 2009; El Cadi et al. 2014; Ennaciri et al. 2020a; Maazoun and Bouassida 2018). This process consists of attacking the rock phosphate with concentrated sulfuric acid according to the chemical reaction below (Eq. 1) (Mesić et al. 2016), but other acids (hydrochloric or nitric acids) can also be used instead of sulphuric acid (Pereira 2003). Moreover, the temperature of the acid attack is a determinant factor in the degree of hydration of PG (Fig. 1) (Mesić et al. 2016)

$$Ca_{10}(PO_4)_6F_2 + 10H_2SO_4 + 20H_2O \rightarrow 10CaSO_4 \cdot 2H_2O + 6H_3PO_4 + 2HF \quad (1)$$

The wet process is still the most popular one because it is economical and has been proven adaptable to various types of phosphate rocks with different qualities. On the other hand, the production cost in the dry process is much higher. However, the acid produced with the dry process is pure (Al-Fariss et al. 1992).

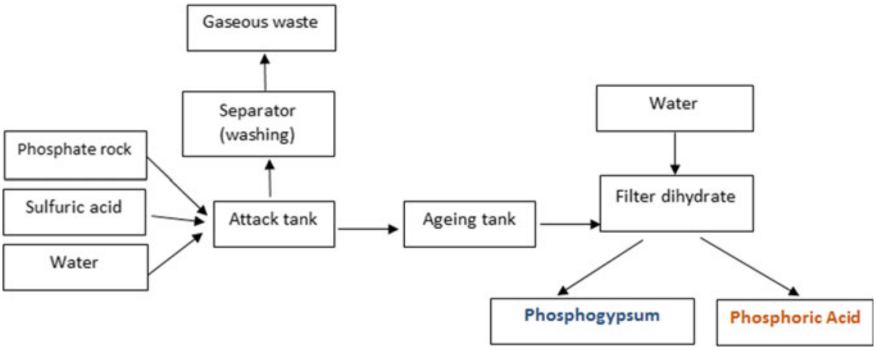


Fig. 1 Diagram of the dihydrate process

2.2 *Phosphogypsum Disposal*

The storage and disposal of PG are essential for many countries around the world and represent a serious concern for the phosphate industry. The management of PG is challenging and governed by current regulations (depending on the country). Almost 85% of the PG produced is discharged into the environment untreated. Phosphogypsum can be disposed of in large stockpiles or discharged directly into the sea (Chernysh et al. 2021). These could represent a threatening source of contaminants for water bodies, soil, and the atmosphere.

2.2.1 Landfill

For companies located far from the sea, landfilling is the only possible option. However, many criteria must be taken into consideration when selecting a landfill site, such as (1) being as close to the facility as possible, (2) the land-bearing capacity must allow for forming a phosphogypsum pile with a maximum height (about 60 m high). And (3) the permeability must be kept to a minimum, with the ideal having a good layer of impermeable clay, which can be added artificially if it does not exist naturally. Alkaline soils are more suitable for landfill sites because the soil acidic conditions increase the solubility and mobility of the pollutants and the risk of their transfer (Motalane and Strydom 2004).

Discharging PG from production sites is one of the most critical operations in the phosphate industry as it requires a large number of tools at a high cost. It can be done dry, with the PG in solid form transported by conveyor belts or trucks. Alternatively, the PG is discharged by pipeline to settling basins where PG decants (wet process) (El Cadi 2013). The dry process is an expensive technique but with less risk of water pollution. However, the conveyors' length and installation are the main limitations. Nonetheless, the second method (wet process) permits recycling the used water. Many issues can result from PG storage, including air pollution (fluorine compounds and other toxic elements), exhalation of radon gas, inhalation of radioactive dust, erosion, and instability of stockpiles. Further details about the ecological impact of PG storage are shown in Fig. 2.

(1) Exhalation of Rn-222 and emission of F (gas), emission of dust; (2) Direct incorporation of trace elements and radionuclides; (3) Leaching of SO_4 and F, acidity, trace elements, and radionuclides; (4) Erosion of stocks; (5) Gamma radiation from stockpiles; (6) Ingestion of trace elements and radionuclides; (7) Inhalation of Rn-222, F (gas) and dust; (8) Dust precipitation; (9) Absorption of trace elements and radionuclides; (10) Percolation or infiltration; (11) Erosion of stocks; (12) Soil erosion; (13) Runoff; (14) Drinking water; (15) Ingestion of SO_4 and F, acidity, trace elements, and radionuclides.

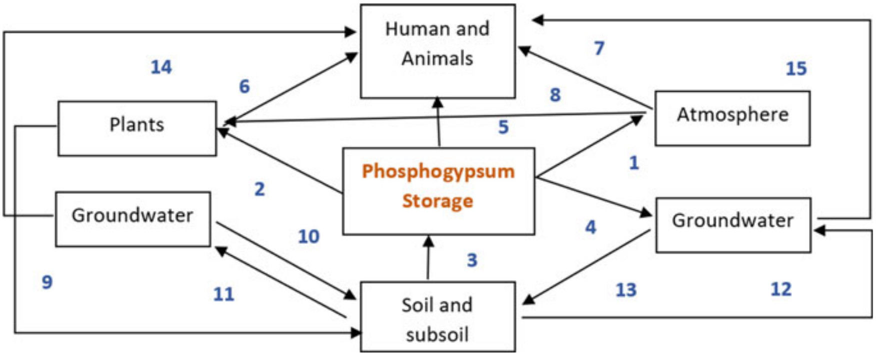


Fig. 2 Diagram summarizing the ecological impacts of phosphogypsum storage (Chernysh et al. 2021; Rutherford et al. 1993; Tayibi et al. 2009)

2.2.2 Discharge into the Sea

Phosphogypsum discharged into the sea dissolves rapidly due to its high solubility. Fluorine, mainly present in the form of H_2SiF_6 precipitates as Na_2SiF_6 after being reacted with sea salts according to the following equation:

$$H2SiF6 + 2NaCl \rightarrow Na2SiF6 + 2HCl \quad (2)$$

Although the sea flow dilutes acids, heavy metals, and radioactive elements, the discharge of PG into the sea is not safe and could be deleterious to the aquatic ecosystems. However, due to new environmental protection regulations worldwide aimed at reducing PG storage/disposal and its eventual negative effects on the environment, several studies are focusing on the valorization and recycling of PG in different fields (Al-Enazy et al. 2018; El Rafie et al. 2020; Gharaibeh et al. 2011; Turner 2013).

2.3 Phosphogypsum Properties

The characteristics of PG vary depending on a range of factors (Fig. 3). For instance, the PG properties are directly affected by the type of rock phosphate and its chemical composition and quality; PG produced from magmatic rock differs from that produced from the sedimentary one. The extraction process also affects PG properties; in fact, the dihydrate process produces less pure PG compared to the hemihydrate or recrystallization processes (Ennaciri et al. 2020a). Furthermore, the PG storage time influences the pH and the amounts of water-soluble impurities.

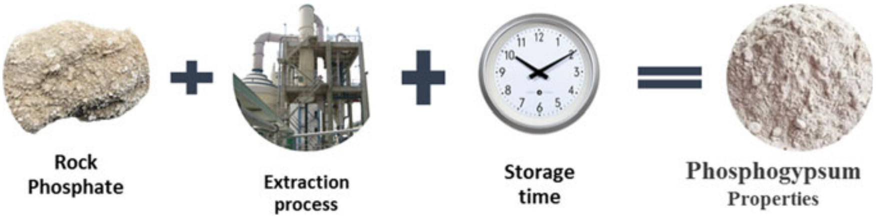


Fig. 3 Factors impacting phosphogypsum properties

2.3.1 Chemical Composition

Phosphogypsum contains soluble and insoluble elements and impurities; it is composed mainly of gypsum ($CaSO_4 \cdot H_2O$), with calcium, sulphur, and water being the major constituents (Table 1). Other elements including phosphorus, fluorine, magnesium, and potassium are also present at variable concentrations. The PG is also known for its heavy metal content (Table 1), almost 3–100% of total heavy metals originally contained in the rock phosphate are transferred to the PG (Ennaciri et al. 2020a). These suggest that PG usage and recycling must consider its chemical composition, especially the impurities that could be associated with environmental concerns.

2.3.2 Physical Properties

Phosphogypsum is greyish and has a granulometry of fewer than 250 microns, 77 μm on average (Lassad et al. 2008). The density of PG is 2.98 g/cm^3, and the surface-specific area is 3 cm^2/g (Charfi Fourati et al. 2000).

The acidic nature of PG ($2 \leq pH \leq 5$) improves its solubility (Ennaciri et al. 2020a), which is about 2.7 g/L (Hammas et al. 2013). Because of its high solubility, PG is a good choice for agricultural soils, especially calcareous soils with high pH levels.

2.3.3 Radiological Characteristics

The content of radioactive elements in PG is strongly related to the origin of the phosphate rock. Table 2 shows the content of radioactive elements in PG of various origins. For example, Bolívar et al. (2009) demonstrated that 90% of polonium and radium initially contained in the imported phosphate rock to Spain are transferred to the PG produced in several phosphate processing plants located on the south-western coast of Spain. This implies that radioactivity is indeed one of the significant challenges to PG valorization. Radioactivity must be carefully considered before, during, and after use.

Table 1 Chemical composition of phosphogypsum from different countries

Element	Morocco[a]	Tunisia[b]	Egypt[c]	Brazil[d]	China[e]
CaO (%)	31.71	31.85	28.31	40.06	38.39
SO_3 (%)	43.40	31.40	40.45	44.5	56.68
H_2O (%)	20.80	7.00	19.71		
P_2O_5 (%)	1.20	0.81	1.98	0.64	2.26
F (%)	1.10	0.92	0.26		
Na_2O (%)	0.27	0.48	0.29	0.03	0.07
K_2O (%)	0.05	0.02	0.02	<0.01	0.12
SiO_2 (%)	0.74	1.86	8.29		1.37
Al_2O_3 (%)	0.26	0.69	0.17	0.30	0.35
MgO (%)	0.08	0.01	0.21	0.05	0.12
Fe_2O_3 (%)	0.07	0.03	0.31		0.45
Ba (ppm)	30.08	30.22	78	1537	
Cd (ppm)	1.34	24.73		<0.1	
Hg (ppm)	0.65	1.99			
Pb (ppm)	0.73	8.06		9	0.3
Cr (ppm)	7.50	6.12	34	11.1	
Zn (ppm)	43.00	93.2	25	<0.1	1.7
Cu (ppm)	55.00	70.82	12	6.3	3.3

[a] Ennaciri et al. (2020b)
[b] Zmemla et al. (2020)
[c] Kandil et al. (2017)
[d] Lütke et al. (2020)
[e] Li et al. (2017)

3 Use of Phosphogypsum in Agriculture

3.1 Use of Phosphogypsum as an Amendment of Degraded Soils

Soil is among the most important natural resources that can be degraded in varied forms. Soil degradation is a change in the soil's health that reduces its ability to provide goods and services (FAO and ITPS 2015). Population and income growth are expected to necessitate a 70% increase in global food production by 2050 and up to 100% in developing countries (FAO 2013). In contrast, the land resources are deteriorating. Indeed, 33% of the land surface is subjected to some form of degradation, whether physical, chemical, biological, or ecological (Lal 2015).

Table 2 Radioactive element content in Bq/kg of phosphogypsum from different countries

Element	Morocco[a]	Brazil[b]	Croatia[c]	Tunisia[d]
^{234}U	143.0			
^{235}U	8.4		7.9	
^{238}U	174.6	18	104	65.9
^{230}Th	546.8			
^{232}Th	133.5	138	7.5	19.7
^{226}Ra	572.7	700	757	209.4
^{210}Pb		1135	746	
^{228}Ra		273		
^{40} K	<15.6	<45	12.7	
^{214}Pb				212.7

[a] Qamouche et al. (2020)
[b] Saueia et al. (2005)
[c] Bituh et al. (2015)
[d] Reguigui et al. (2005)

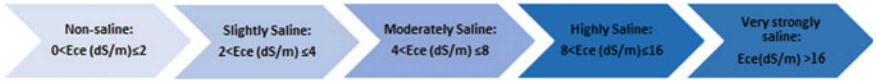


Fig. 4 Standards classification of soil salinity according to Lech et al. (2016)

3.1.1 Reclamation of Saline Soils

Salinity is one of the main forms of soil degradation that impedes food security, particularly in arid and semi-arid regions. Globally, salinity affects approximately one billion hectares with an increasing trend (Ivushkin et al. 2019). Soil salinity affects 20% of cultivated land and 33% of irrigated agricultural land worldwide (Mukhopadhyay et al. 2021).

Salts accumulate in the soil as a result of mineral alteration and marine sedimentation (primary salinity). Secondary salinization occurs when evaporation exceeds precipitation and crop water requirements, and when poor water quality is used for irrigation, especially if water is loaded with electrolytes or total soluble solids that, after evaporation, accumulate in the soil (Dasgupta et al. 2015; Moharana et al. 2019; Tanji and Wallender 2011).

Salinity and Sodicity Diagnosis

Soils are classified for salinity based on their saturated soil paste electrical conductivity (ECe) (Fig. 4). Depending on the ECe value, the soil could be classified as non-saline to very strongly saline.

Fig. 5 Standards for Soil Sodicity Interpretation

Table 3 Classification of soils affected by salinity and sodicity based on ECe, ESP, and SAR (FAO and UNESCO 1974)

Soil class	ECe (dS/m)	Esp (%)	SAR (meq/l.)
Saline	>4.0	<15	<13
Sodic	<4.0	>15	>13
Saline-Sodic	>4.0	>15	>13

Soils are classified for sodicity based on the fraction of exchangeable sodium (Na_{ech}) or the relative amount of Na^+ at the cation exchange sites. The exchangeable sodium percentage (ESP) is calculated using the equation below (Eq. 3) (Qadir et al. 2007).

$$\mathrm{ESP} = 100(\mathrm{Na}_{\acute{e}ch})/\mathrm{CEC} \quad (3)$$

where both Na_{ech} and CEC are expressed in mmolc/kg or cmolc/kg of the soil. The ESP can be calculated by replacing the CEC in Eq. 3 with the sum of the exchangeable cations (Ca, Mg, K and Na) (Qadir et al. 2007).

Sodium adsorption ratio (SAR) is used as an approximation of ESP. An ESP of 15 (SAR ~ 13) is generally considered the limit below which soils are classified as non-sodic, and above which soils are dispersive and have severe physical problems such as compaction due to soil aggregates collapse. The SAR is calculated from the following equation (Eq. 4) (Qadir et al. 2007):

$$\mathrm{SAR} = \left[\mathrm{Na}^+\right]/\left(\left(\left[\mathrm{Ca}^{2+}\right] + \left[\mathrm{Mg}^{2+}\right]\right)/2\right)^{1/2} \quad (4)$$

where Na, Ca and Mg are expressed in meq/l.

The soil sodicity intensity can be evaluated based on the ESP value as per Fig. 5.

Soil classification can also be done by considering three different parameters (ECe, ESP and SAR) (Table 3).

Salinity Effects

There are many perturbations to the water-soil–plant system caused by salinity and sodicity stresses (El hasini et al. 2019). They negatively affect plant development as well as soil physicochemical characteristics which decrease agricultural production and threaten food security in the world (Table 4).

Table 4 Plant and soil Salinity impacts

Level	Effect
Plant	• The rhizosphere's saline solution induces an osmotic effect, which reduces root water uptake (Lamsal et al. 1999; Rahneshan et al. 2018; Sheldon et al. 2017) • High concentration of salts could be toxic and harmful to the anatomy of the roots and leaves (Hasana and Miyake 2017; Läuchli and Grattan 2007) • Salinity decreases chloroplast size and number. It also affects lipid and starch accumulation and leads to chloroplast degradation (Hameed et al. 2021; Mitsuya et al. 2003) • Soil salinization reduces the accumulation of nutrients (N, P, K, and Ca) in plant tissues (Safdar et al. 2019) • Salinity stress decreases plant height and fresh weight that affect yield production (Amirjani 2010) • Salt affects crop germination, density, and vegetative growth (de Souza Silva and Francisconi 2012)
Soil	• Salinization of soil reduces microorganism biomass, genetic diversity, and spore germination (de Souza Silva and Francisconi 2012) • Salinity raises heavy metal mobilization, which contributes to metal pollution (Azadi and Raiesi 2021) • Salinity and sodicity affect soil physique parameters, by causing soil erosion, poor aeration, and slow water infiltration due to soil compaction (Keren and Dagan 2005) • The accumulation of soil-soluble salts has a detrimental effect on structural stability and hydraulic conductivity (Shainberg and Letey 1984) • Sodicity causes pores clogging, surface crusting, and hard-setting (van de Craats et al. 2020) • Salinity reduced soil organic matter and fertility (Mavi et al. 2012; Zhang et al. 2019)

Saline/Sodic Soils Reclamation

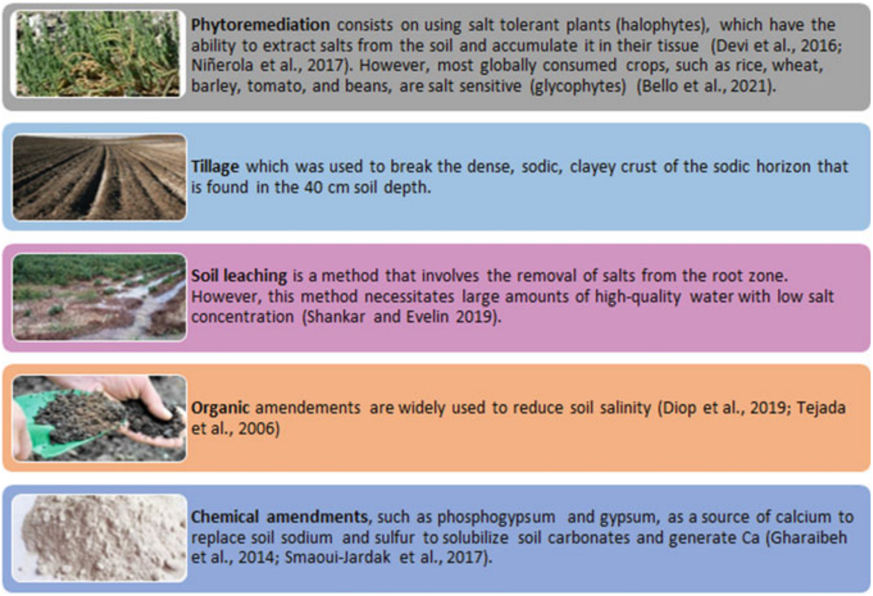
To address soil salinity and sodicity issues, different approaches could be used either separately or combined. Figure 6 shows the most common practices which could be adopted under various soil-climate-plant contexts.

Phosphogypsum is a commonly used amendment for soil salinity reclamation. The theoretical equation for calculating natural gypsum requirement (Eq. 5) can also be used to estimate the PG requirements based on the initial and final soil ESP (Oster and Jayawardane 1998).

$$\text{Gypsum requirement(t/ha)} = 0.86 * D * \rho b * (\text{CEC}) * \left(\text{ESP}_i - \text{ESP}_f\right)/P \quad (5)$$

where D is the depth of the soil to be reclaimed (m); ρb is the soil density (t/m^3); CEC is the soil cation exchange capacity (mmol/kg); ESP$_i$ is the initial ESP and ESP$_f$ is the final ESP and P is the gypsum purity.

Phosphogypsum has been demonstrated to increase quantitative and qualitative crop yields, plant physiological parameters, and soil physicochemical properties. Table 5 depicts the findings of numerous studies on the various effects of PG application on soils and plants under saline conditions.



Phytoremediation consists on using salt tolerant plants (halophytes), which have the ability to extract salts from the soil and accumulate it in their tissue (Devi et al., 2016; Niñerola et al., 2017). However, most globally consumed crops, such as rice, wheat, barley, tomato, and beans, are salt sensitive (glycophytes) (Bello et al., 2021).

Tillage which was used to break the dense, sodic, clayey crust of the sodic horizon that is found in the 40 cm soil depth.

Soil leaching is a method that involves the removal of salts from the root zone. However, this method necessitates large amounts of high-quality water with low salt concentration (Shankar and Evelin 2019).

Organic amendements are widely used to reduce soil salinity (Diop et al., 2019; Tejada et al., 2006)

Chemical amendments, such as phosphogypsum and gypsum, as a source of calcium to replace soil sodium and sulfur to solubilize soil carbonates and generate Ca (Gharaibeh et al., 2014; Smaoui-Jardak et al., 2017).

Fig. 6 Mitigation methods for saline soils

3.1.2 Phosphogypsum as an Amendment of Acidic Soils

Acidic soils (pH $\leq$ 5.5) account for nearly half of arable land area worldwide, steadily increasing due to ongoing soil acidification (Kochian et al. 2015), which mostly occurs in developing countries like Central African, South American, and Southeast Asian countries (FAO and ITPS 2015). Moreover, soil acidity is one of the most critical factors limiting crop yields in the tropics and subtropics, where acidic soils account for 60% of the total land (Kochian et al. 2015). Soil acidification processes can be induced by natural factors (such as long-term rainfall and soil weathering processes) or anthropogenically by human intervention through the excessive use of ammonium-based fertilizers and/or acid-producing fertilizers and phytosanitary treatments). Figure 7 shows the most common causes of soil acidification.

Soil acidification deteriorates soil quality by inducing nutrient loss such as calcium, magnesium, and potassium and by increasing aluminium and manganese concentrations in the soil solution. It also increases the bioavailability of toxic metals such as cadmium and lead (Li et al. 2020). Moreover, acidic soil conditions represent chemical and physical barriers to root growth and cause nutrient deficiencies (such as potassium and molybdenum) and consequently reduce crop yields (Brennan et al. 2004). Soil acidification is often associated with aluminium toxicity. High concentrations of aluminium constrain the plant's physiological and metabolic functions (Singh et al. 2017).

Phosphogypsum has been widely used in the reclamation of degraded acidic soils by reducing aluminium and manganese phytotoxicity and enhancing Ca availability.

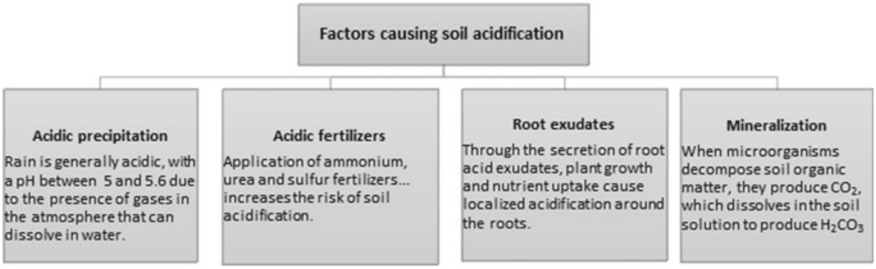
Table 5 The effects of PG application on soils and plants under different saline conditions

Soil salinity (dS/m)	PG Application rate	Results	Reference
$EC_{1/5} = 4.07$	1 t/ha	• The results showed that 1 t/ha of PG with 10 t of manure decreased the electrical conductivity by 45% compared to the control • The soil classification was also modified following the application of PG, in fact, the treatment with 1 t/ha of PG allowed to pass from saline-sodic to normal soil and from sodic to normal soil respectively with or without manure	Diop et al. (2019)
$EC_e = 52$	15, 20, 30 and 40 t/ha	• The application of PG resulted in beneficial effects, as the relative removal of Na (Na/Na_0) was significantly increased. It was 0.80 for the soil leachate at 40 t/ha of PG versus 0.42 under the control • The ESP was reduced from 35.7% to 7% and 5.9% when 30 t/ha and 40 t/ha of PG were applied, respectively	Gharaibeh et al. (2010)
$EC_e = 24.90$	49.14 t/ha	The PG showed its desalinization and desodification efficiencies by reducing residual EC and ESP of the soil	Abdel-Fattah and EL-Naka (2015)
$EC = 5.98$	0, 5, 10, 20, 40, and 80%	• The lower doses (5, 10 and 20% of PG) showed a positive effect on plant development. However, doses higher than 20% of PG caused toxicity issues • The use of 5,10 and 20% of PG results in a significant increase in plant length, leaf number, roots and leaves dry weight, total fruit weight, and chlorophyll content	Smaoui-Jardak et al. (2017)

(continued)

Table 5 (continued)

Soil salinity (dS/m)	PG Application rate	Results	Reference
$EC_e = 1.9$	5 and 10 t/ha	• Phosphogypsum application reduced surface soil pH and ESP, and consequently improved rice and wheat yields • Phosphogypsum ameliorated soil physical properties such as aggregate stability, hydraulic conductivity, and soil moisture retention capacity	Nayak et al. (2013)
$EC_e = 5.89$	5–15 t/ha	• PG enhanced water infiltration in sodic soil. It took 1546 hours in the control to leach 180 cm of water, but only 225 hours in the soil treated with 15 t/ha of PG • Phosphogypsum application reduced soil exchangeable Na	Ağar (2011)
$EC_e = 8.58$	10, 30 and 50 g of PG/kg of soil	• Phosphogypsum raised dry weight by 82–127% compared to the control • Nutrient uptake was significantly higher under PG application	Al-Enazy et al. (2018)
$EC_e = 3.66$	10 and 20 g of PG/kg of soil	• Plant uptake of Pb, Zn, and Cd in soils treated with 10 g of PG/kg of soil was reduced by 19%, 45%, and 39%, respectively, when compared to the control • Following 10 and 20 g of PG/kg of dry soil, the dry weight of rapeseed plants increased by 48 and 54%, respectively	Mahmoud and Abd El-Kader (2015)
$EC_e = 11.17$	0, 15, 30, and 45 t/ha	• Phosphogypsum application increased the number and yield of grains, the shoot's fresh and dry weight, and thousand of grains weight • Compared to the control, 30 and 45 t/ha of PG improved dry grain weight by 52% and 62%, respectively	Outbakat et al. (2022)



Rain is generally acidic, with a pH between 5 and 5.6 due to the presence of gases in the atmosphere that can dissolve in water.

Application of ammonium, urea and sulfur fertilizers… increases the risk of soil acidification.

Through the secretion of root acid exudates, plant growth and nutrient uptake cause localized acidification around the roots.

When microorganisms decompose soil organic matter, they produce CO_2, which dissolves in the soil solution to produce H_2CO_3

Fig. 7 Factors causing soil acidification (Goulding 2016; Ulrich 1986)

Previous studies have shown that when applied superficially or incorporated, phosphogypsum mitigates the harmful effects of soil acidity on plant growth (McCray et al. 1991).

Soratto and Crusciol (2008) conducted a study on sandy-loam soil in Brazil on rice (*Oryza sativa L.*) and beans (*Phaseolus vulgaris L.*), comparing the surface application of four doses of dolomite calcite (0, 1.1, 2.7, and 4.3 t/ha) and two doses of PG (0 and 2.1 t/ha). The results of this study have shown that the combination of PG and dolomite increased the Ca and S contents in the leaves of beans and their dry matter yield. However, a decrease in Zn and Mg contents in the leaves of beans has been observed. This result corroborates with De Oliveira and Pavan (1996) who found that the combination of dolomite and PG improved soil fertility and consequently soybean yield.

The combination of PG with lime in acid soils resulted in a substantial increase in lucerne crop yield and plant P and S uptakes (Bouray et al. 2020). This finding confirms the positive effect of PG on P and S bioavailability. It has also been found, in the same study, that PG application improved the concentration of P and reduced exchangeable aluminium in the soil solution. Additionally, Carmeis Filho et al. (2017) found that the application of PG at 2.1 t/ha combined with lime increased the nitrogen content in the soil by up to 50%. Further, an increase in carbon mineralization and organic matter accumulation has been observed. De Oliveira and Pavan (1996) demonstrated that PG improved soil Ca and Mg concentrations at a depth of 40 cm without influencing soil pH. Nevertheless, In China, PG was compared with other by-products like coal fly ash, red mud, and alkaline slag on tea plants (Li et al. 2010). They found that PG slightly decreased soil pH, whereas the rest of the amendments increased it. All these amendments reduced soil exchangeable aluminium and increased soil exchangeable Ca, Mg, K, and Na which improved the cation exchange capacity of the investigated soils.

In Japan, Toma and Saigusa (1997) conducted a study on the effect of PG on barley in "Andosols". They found that PG application increased the subsoil rooting of barley, particularly in soils poor in humus. A decrease in soil exchangeable aluminium has also been reported and has been explained by the fact that PG has induced the polymerization of aluminium hydroxides, followed by selective and irreversible adsorption to clay minerals.

Xiao et al. (2010) conducted pot trials to compare the effects of lime and PG on the broomcorn crop. The results revealed that broomcorn plants did not develop sufficiently in the absence of PG or lime application. Both amendments increased soil pH in highly acidic soils while decreasing exchangeable Al concentration. Furthermore, a significant correlation was noticed between seed dry weight and PG and lime rates. Compared to the lime treatment, PG increased the P content of the seeds by 1.2–2.4 times. Lime greatly reduced Al toxicity and increased the Ca content in leaves. However, its effect on N, Ps, K, and superoxide dismutase activity in the plant was less than that of PG. According to the findings of this study, PG showed promising remediation effects on highly acidic soils.

Phosphogypsum application rates correlated positively with the concentrations of Ca, Mg, K, P, Na, Si, Mn, F, and SO_4 in the acid soil solution. Also, the aluminium toxicity decreased with the PG rate increase. This has been attributed to the fact that aluminium was complexed by F and SO_4 contained in the PG; at 5 t/ha of PG, 99% and 0.6% of the total Al were complexed by F and SO_4, respectively, while only 0.3% remained in the form of Al^{3+} (Alva et al. 1988). Similarly, in a recent study, Bouray et al. (2022) evaluated the effect of four rates of PG (0, 1, 3, and 9 t/ha) on aluminium speciation in the soil solution of three different acid soils. They have concluded that the PG, when applied at feasible on-farm rates (1–3 t/ha), can significantly reduce the activity of Al^{3+} in acid soil solution through the mechanism of aluminium displacement on soil exchange sites via Ca^{2+}, followed by Al^{3+} complexation with $SO_4{}^{2-}$ and F^-. However, the high rates of PG (9 t/ha) should be avoided on acid soil ($pH < 5$) as this would further acidify the soil causing a release of aluminium and its accumulation unless combined with a pH neutralizing material such as lime.

In summary, PG is widely used in acidic soils because it reduces aluminium toxicity, which is one of the main constraints to crop production on acid soils, increases nutrient availability, and improves soil physical properties. However, its application must be reasonable based on soil properties.

3.2 Use of Phosphogypsum as a Fertilizer

Phosphogypsum contains several nutrients necessary for plant growth and development such as Ca, S, P, Mg, and Mn (Table 6). Therefore, it can be used directly as fertilizer (IFA 2018).

IFA (2018) suggests that using PG as a fertilizer is one of the most promising approaches for saving sulphur and calcium resources. Moreover, Li and Chang (2013) reported that PG positively affected the vegetative development of several important crops including rice, cotton, and soybean. Also, the yields of some of these crops were improved by up to 50% (Table 7). Likewise, Crusciol et al. (2016) claimed that PG application increased the sulphur content of rice leaves, the number of panicles/m^2, and grain yield. Furthermore, Michalovicz et al. (2019) demonstrated that Ca and S content in corn, wheat, barley, and bean leaves was improved, while Mg content

Table 6 Nutrients functions in plants (Alejandro et al. 2020; Chen et al. 2018; Ihsan et al. 2019; Lunt 1967; Shen et al. 2011)

Element	Functions
Calcium	• Membranes and cell walls require Ca to function effectively • Calcium is necessary in large quantities for the roots apex and young shoots as well as for the fruit development • Mitigates the effects of various stresses (salinity, water deficiency, heavy metal pollution…) • Calcium also participates in the activation of certain enzymes
Sulphur	• Sulphur is found in amino acids, proteins, and as a precursor in other sulphur-based compounds such as sulfolipids in membranes
Phosphorus	• Phosphorus is an integral part of the nucleic acids and membrane lipids • It forms adenosine triphosphate (ATP), a source of energy for the various reactions that occur in the plant • Phosphorus is also necessary for several enzymatic activities • It is essential for root development
Magnesium	• Magnesium is an essential nutrient for plant growth, photosynthesis, enzyme activation, nucleic acids, and proteins synthesis • Plant growth and development can be severely hampered when Mg levels are low, resulting in negative effects on crop production
Manganese	• Manganese is involved in many processes in the plant life cycle, including photosynthesis, defense against the pathogen, and hormonal activation

Table 7 Fertilizing effect of PG on several crops (Li and Chang 2013)

Crops	PG rates (kg/667 m^2)	Effects
Rice	75	Developed the stems and reduced the lodging
Cotton	150	Boosted the vegetative development
Soybean	200	The yield increased by 16%
Malten Barley	100–300	The yield increased by 8.3–46.3%
Feed Barley	100–300	The yield increased by 43.3–50.9%

decreased after PG application. In addition, the yields of corn, wheat, and barley were increased by 11%, 10%, and 10% respectively. Yang (2014) tested the combination of PG and compound fertilizers on peanut crops and found that this combination increased the yield by 45% compared to the compound fertilizer alone. Furthermore, the combined application of PG and compound fertilizer increased grain weight, plant height, and the number of nodules. It is also worthwhile mentioning that the PG application has been proven to be economical (Vyshpolsky et al. 2010).

Phosphogypsum application could also serve to (1) improve soil quality by reducing levels of exchangeable sodium and magnesium percentage, (2) improve soil water movement and water storage in the root zone, (3) improve irrigation efficiency, (4) increase crop yields and water productivity (5) enrich the soil with phosphorus, calcium, and sulphur.

The majority of nutrients are available for plants when the soil pH is 5–6. However, this availability decreases with pH increase (Naidu and Rengasamy 1993), the case of calcareous soils. Hence, the importance of using PG for high pH soils, because it dissolves quickly and produces acidic reactions in the rhizosphere, thus decreasing soil pH (Gharaibeh et al. 2014) and therefore improving nutrient bioavailability (Mahmoud and Abd El-Kader 2015).

3.3 *Use of Phosphogypsum in the Fertilizer Industry*

Numerous studies have revealed that PG is used in the fertilizer industry as a source of S, Ca, and P, or as an acid, and as a composting additive.

Potassium sulphate can be manufactured using various raw materials and methods. Sulphate reserves are becoming increasingly limited. The process of using PG, as a sulphur source for potassium sulphate production, reduced the production cost. Furthermore, this method avoids the formation of acidic by-products (such as HCl). According to Eq. 6, potassium sulphate is formed by a decomposition reaction between potassium chloride and PG in an aqueous ammonia solution at low temperatures (Abu-Eishah et al. 2000).

$$2\mathrm{KCl} + \mathrm{CaSO_4} \cdot 2\mathrm{H_2O} \rightarrow \mathrm{K_2SO_4} + \mathrm{CaCl_2} + 2\mathrm{H_2O} \tag{6}$$

The production of 1 t of potassium sulphate requires up to 2 t of PG (IFA 2018). Phosphogypsum can also replace sulfuric acid in the manufacturing process of diammonium hydrogen phosphate. This would improve the quality of the fertilizer, and reduces its production costs (IFA 2018). Additionally, both sodium sulphate and calcium carbonates can be produced, in an environmentally friendly and inexpensive process, through a decomposition reaction between PG and sodium carbonate (Na_2CO_3) (Ennaciri et al. 2016).

Ammonium sulphate is a widely used nitrogen fertilizer by farmers. It is typically produced through chemical reactions involving sulfuric acid and ammonia. Though, it has been suggested that PG can be used to produce ammonium sulphate as well as nitrogen and potassium-based fertilizers, providing that the sulphur conversion efficiency in PG was greater than 95% (IFA 2018).

Using PG as a urea coating material forms a fine film that prevents nitrogen loss through denitrification—a slow-release fertilizer. This ensures continuous and regulated nitrogen supply throughout the crop cycle. Furthermore, this method ensures better resistance to crushing and handling because of the low dust content (Vashishtha et al. 2010).

In addition, PG is widely used in the composting process since it improves compost quality. Samet et al. (2019) confirmed that using PG as a compost additive improved the P and Ca content as well as the microbial diversity of the compost. This latter enhanced potato plant growth as well as the resistance to *Fusarium solani* disease. The addition of PG to compost significantly reduced CH_4, NH_3, and N_2O emissions by 85.8%, 23.5%, and 3.2%, respectively Yang et al. 2015).

4 Environmental and Sanitary Impacts of Using Phosphogypsum in Agriculture

The use of PG, particularly in agriculture, is frequently linked to potential environmental, human and animal health effects. Numerous studies have focused on the transfer of heavy metals and radioactive elements to the soil–plant-water system.

4.1 Heavy Metals Transfer

The geo-accumulation index revealed that the PG-treated soils were not contaminated with vanadium (V), Zn, Cr, Pb, Ni, and Cu. However, slight contamination by Cd was recorded. Zn, Cd, Pb, and Cr contents were lower than the permissible limits for food production. The daily metal intake and health risk index values were <1. This suggests that the consumption of vegetables and fruits cultivated in PG-amended soils could be safe (Al-Hwaiti and Al-Khashman 2015).

Trace elements levels in sunflower plants grown in PG-amended soil were significantly lower than phytotoxicity limits (Elloumi et al. 2015). Moreover, Al-Odat et al. (2004) found that the application of PG at 10 and 40 t/ha did not cause any accumulation of trace elements (Pb, Cu, Zn, and Cd) in the soil and in the plants (*Kochia scoparia*). However, fluorine concentrations in plants increased after PG application but remained below the allowed level.

Furthermore, other authors demonstrated that PG application rather reduces heavy metal uptake by plants. For instance, Mahmoud and Abd El-Kader (2015) reported that PG reduced the content of Pb, Cd, and Zn in canola plants. It was also confirmed that the addition of PG during composting process reduced the content of heavy metals in the final compost product (Kammoun et al. 2017). Besides, Nisti et al. (2015) found that the concentrations of heavy metals in the drainage water of PG-amended soils did not exceed the recommended limits. However, monitoring studies are required to evaluate the accumulation of heavy metals in the soil over time after a repeated application of PG using different crop species. Also, measuring the total amount of heavy metal in the soil or plant tissues may not be the best way to assess the environmental safety of PG use in agriculture, because the risk is rather related to the bioavailable fraction of heavy metal than the total amount. Hence, the necessity of speciation studies.

4.2 Radioelements Transfer

It has been found that the surface application of up to 112 t/ha on loamy soil did not affect radioactivity levels in corn, wheat, or soybean grains (Mays and Mortvedt 1986). Furthermore, there was no increase in Cd levels in grains of the three crops. In addition, El-Mrabet et al. (2003) indicated that the concentrations of ^{226}Ra measured in drainage water and in the cotton (*Gossipium hirsutum L.*) leaves were not affected by PG application. Moreover, Abril et al. (2009a) measured the activity of ^{226}Ra, ^{238}U, and ^{210}Po in 30 samples of a stored PG product and two different PG-amended soil samples. The average of ^{226}Ra concentration in the stored PG was 730 ± 60 Bq/kg (dry weight) which is above the limit of 370 Bq/kg set by the United States Environmental Protection Agency (US-EPA). The ^{222}Rn exhalation rate from PG storage was below the US-EPA limit of 2600 Bq/m^2/h, but slightly higher than that of PG-amended soils. Further, radon exhalation rates were positively correlated with ^{226}Ra concentrations and increased with daily potential evapotranspiration in agricultural soils. However, in another study, Abril et al. (2009b) concluded that the worker exposure risk of ^{226}Ra inhalation either from PG-amended soil or from dust during PG application is negligible.

In Greece, Papastefanou et al. (2006) reported that the radionuclide content of PG-amended soils is 50–479 Bq/kg, compared to 37–54 Bq/kg in non-PG amended soils. The transfer factor of ^{226}Ra (what is taken/what exists in the soil) by rice ranged from 6.5×10^{-3} to 2.0×10^{-2}, but the daily ingestion dose of ^{226}Ra was only 0.86 μSv/y and the effective annual dose for adults was well below the average exposure to different sources of natural radiation (2.4 mSv/y). Mazzilli and Saueia (2010) found that the doses of radioactivity from 50 years of PG use on agricultural soils were of the same magnitude as those from the use of SSP and TSP fertilizers. They concluded that the PG radiological effect is negligible. Furthermore, Lindau et al. (1998) indicated that methane emission, for 84 days, was reduced by 47, 46, and 51%, respectively at 2.5, 5.0, and 10.0 tons/ha of PG. However, ^{15}N uptake by rice grains in plots receiving gypsum was higher than in those receiving PG.

In a greenhouse study where the tomato was grown in soils treated with four rates of PG: 0, 20 (typical dose used in Southern Spain), 60, and 200 t/ha, the concentrations of Cd, Pb, U and ^{226}Ra and ^{210}Po were quantified in the soil, plant and drainage water (Enamorado et al. 2009). The authors found that the Cd concentrations in tomato fruit increased with PG rate increase, reaching up to 44 ± 7 μg/kg, but still below the maximum concentration allowed by the commission regulation (EC) No 1881/2006. The transfer factor of Cd into non-edible parts was also high (4.8 ± 0.5 (dry weight)). However, the concentrations of lead and radium in the fruits were below the detection limit. Furthermore, the concentrations of metals and radionuclides found in the drainage water were less than 1% of the original amount contained in the PG product.

Studying the radioactivity in three Tunisian PG products of different ages (fresh, 10 and 50 years old), showed a decrease in the concentrations of uranium-238 (48% less), actinium-228 (58% less), and thorium-232 (58% less) in the old samples compared to the fresh ones. This reduction could likely be due to leaching after rainfall (Reguigui et al. 2005).

5 Conclusion

Phosphogypsum is a by-product of the phosphate fertilizer industry produced when phosphoric acid is extracted from phosphate rock once digested with concentrated sulphuric acid. The properties of PG depend essentially on the origin of the phosphate rock, the extraction process, the storage duration, and conditions. Phosphogypsum is produced in large quantities (300 MT/year). However, only 15% is recycled in various sectors including construction, building industry, and agriculture. The remaining 85% of the PG produced worldwide is disposed of in stockpiles or discharged into the sea. The agricultural sector has a great potential for PG valorization; PG can be used in numerous areas around the world, including arid and semi-arid regions for the reclamation of saline and sodic soils and tropical and subtropical regions, and as an amendment for acid soils. Phosphogypsum is also used as fertilizer because of its content of several nutrients such as calcium, sulphur, phosphorus, and magnesium which are essential for plant growth development. Moreover, PG can be recycled in the manufacturing process of fertilizers either as a substitute of acids or as a source of nutrients. It should also be stated that the demand for natural gypsum is expanding and PG could be an alternative, providing that PG is more soluble and richer in electrolytes than gypsum. It is also adapted to different agricultural uses. Even though numerous studies have shown that the use of PG in agriculture is relatively safe, there is still a paucity of information about the environmental risks which could be associated with PG use in agriculture, especially in the long term. Further research is required to tackle this aspect so as to accelerate the recycling of PG worldwide.

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Part V
The Challenges Faced When Using of Non-conventional Water in Agriculture

Chapter 13
Status, Drivers, and Suggested Management Scenarios of Salt-Affected Soils in Africa

Fassil Kebede

Abstract Africa with its massive land area covering 3 billion ha and 65% of the uncultivated arable land is a strategic continent that will determine the future of food systems in the world. Therefore, Africa must prepare itself to rapidly modernize its agriculture for unlocking its full potential while maintaining properly the vast expanses, which are currently in use by millions of smallholder farmers. This chapter discusses soil salinity and sodicity, which are types of soil degradation, and widely prevalent in semi-arid and arid regions of Africa. Presumably, salt-affected soils in Africa occupy about 80,000,000 ha of which 69 million ha are found in the Sub-Saharan Africa (SSA). In SSA an estimated 180 million people are affected while the economic loss due to land degradation is estimated at $68 billion per year. The predominant mechanisms triggering the accumulation of soluble salt in the agricultural soils of Africa are seawater intrusion, rising ground waters in low-lying topography from saline aquifers, and irrigation waters. As the soil dries, salts become concentrated in the soil solution, increasing salt stress. Soils, especially in hot and dry areas, are often naturally salty, but inefficient irrigation and poor drainage lead to waterlogging, which raises the water table, bringing salts in the subsoil nearer the surface. When the water evaporates, salt is left around the roots of plants, preventing them from absorbing water and stunting growth. The more that irrigation is used to boost food production, the more soils turn out to be saline. The accumulation of salts in the root zone can have a variety of agricultural impacts. Vitally, salt not only degrades soils and crop productivity but also increases poverty and social instability. Reversing of soil salinity or sodicity is possible although it takes time and is expensive, as well. Solutions include diversifying the land use types, improving the efficiency of irrigation methods with efficient drainage systems, in-situ moisture conservation using mulches to keep the soils cool and moist, and the use of multipurpose salt tolerant crops with a rotation plan.

Keywords Africa · Causes · Impact · Management · Reclamation · Salt-affected soils

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1 Introduction

The increasing global demand for food and agricultural raw materials makes future studies to optimize the utilization of soil resources very important and urgent. In many arid and semi-arid regions, good soils are scarce with their overall productivity declining because of soil degradation and lack of proper soil and water management practices. Salt-affected soils which are widespread in arid, semi-arid, and coastal regions of sub-humid areas have low productivity. Food production in many parts of the world is severely affected by high salt content soils (IPBES 2018).

Africa is the second-largest continent with about 30 billion ha including adjacent islands, it covers 6% of Earth's total surface area and 20% of its land area of which two-thirds are covered with soils (Sayer et al. 1992). The continent measures about 8,000 km from north, *Ras ben Saka* in Tunisia (37°21′ N) to south, *Cape Agulhas* in South Africa (34°51′15″ S); and about 7,400 km from east, *Ras Hafun*, (51°27′52″ E), which is the most easterly projection that neighbours Cape Guardafui, the tip of the Horn of Africa in Somalia to west, Cape Verde, (17°33′22″ W). Moreover, the coastline in Africa is 26,000 km long (Lewin 1924). Besides, the continent is divided in half almost equally by the Equator. The seas that bound the continent are the Mediterranean Sea, the Red Sea, the Indian Ocean, and the Atlantic Ocean (Fig. 1). Moreover, Africa is the second most populous continent on Earth after Asia with a human population of over 1.2 billion. Relative to the rest of the world, Africa has an abundance of the major natural resources necessary for crop and livestock production. Of the world's land area suitable for sustainable production expansion, Africa has the largest share by far, accounting for about 45% of the total (Deininger et al. 2011). Despite this abundance of natural resources, deforestation, desertification, land degradation, water shortage and contamination, threat to biodiversity, and climate change are the major environmental problems that Africa experiences today. Furthermore, sustaining a reasonably high economic growth rate to match the human population growth rate coupled with ensuring the environmental and natural resources integrity is one of the key challenges (UNEP 2008). The combined effects of these multiple crises have serious consequences on its economic development and social welfare (NEPAD 2013).

Agriculture forms a significant portion of the economies of all African countries, as a sector it can, therefore, contribute towards major continental priorities, such as eradicating poverty and hunger, boosting intra-Africa trade and investments, rapid industrialization and economic diversification, sustainable resource and environmental management, and creating jobs, human security, and shared prosperity. Small farms that are dependent on family labour, with very little machinery and several activities, reflect the dominant type of agriculture in Africa. Subsistence farming remains important. To date, Africa has 33 million family farms of less than 2 ha, accounting for 80% of farms. Africa will have a population of two billion people by 2050, the majority of women and youth. This projection alone underscores the scale of agricultural challenges in Africa particularly in connection to feed Africans,

Fig. 1 Map of Africa showing the surrounding oceans and seas (https://images.app.goo.gl/9NSiY1LP5MnzKrZX8)

to create wealth for them, and to conserve resources for future generations (NEPAD 2013).

Africa, in particular, is vulnerable to land degradation and desertification; and is severely affected. Desertification affects around 45% of Africa's land area, with 55% of this area at high or very high risk of further degradation. It is often considered that land degradation in Africa has been vastly detrimental to agricultural ecosystems and crop production and, thus, an impediment to achieving food security and improving livelihoods (UNEP 2015). The annual cost of desertification is estimated at US$ 9.3 billion. Furthermore, water scarcity will affect over 1.8 billion people by 2025 (AWDR 2006). Within the next 15 to 20 years, the areas considered to have relative water security in Africa will fall from nearly 53 to 35%, affecting some 600 million people. According to some estimates, by 2025, up to 16% of Africa's population (i.e., ~230 million people) will be living in countries facing water scarcity, and 32% (i.e., ~460 million people) in water-stressed countries (IAASTD 2009).

Soil salinization and alkalinization are major threats to the soil resource in Africa and are among the most common land degradation processes. Salt is the savour of foods but the blight of agriculture; in excess, salt kills growing plants. Salt-affected soils pose lower agricultural productivity, instable ecology, economic crisis, eventually social unrest, and downfall of human civilization. According to ADR (2012) reports 4–12% of Africa's GDP is also lost due to environmental degradation. Salt-affected soils in Africa are estimated to cover 80,000,000 ha of which the 68.8 million ha are found in the Sub-Saharan Africa (SSA). In SSA an estimated 180 million people are affected (Mirzabaev et al. 2014) while the economic loss due to land degradation is estimated at $68 billion per year (Nkonya et al. 2016).

2 An Overview of the Africa's Physical Geography

2.1 Topography

The African continent can be described as a huge crystalline mass surrounded by a sedimentary fringe (D'Hoore 1964). To the north, these sediments are folded, forming the Atlas chains, the altitude of which is between 1,500 and 3,600 m. The region of the High Plains, which separates the two principal chains is studded with numerous salt lakes, and varies in altitude from 900 to 1200 m. In the extreme south, the Cape system, equally folded but older, has a relief which is lower and more rounded. Elsewhere (i.e., West Africa, North-West Africa, and the Sahara) the sedimentary fringe has not been folded and the relief is less deformed. The continental plateau of Africa is slightly sloping from S.E. to N.W.: in the S.E. its altitude is of the order of 1500 m, whereas in the N.W. it is of the order of 300 m. The highest summits of the continent, covered by perpetual snow, are found there (Kilimanjaro 6010 m, Kenya 5600 m, Ruwenzori 5500 m) (D'Hoore 1964). Vast plains and plateaus are characteristic of Africa's geography. Second only to Asia in size, Africa is structured around three stable zones of ancient mountain formations called "cratons"—the North-West African craton located in the western Sahara desert, the Congo craton roughly corresponding to the Congo Basin, and the Kalahari (Kgalagadi) craton in southern Africa (Summerfield 1996). Rift Valleys starts in Syria, forms the Jordan Valley, the Dead Sea, the Gulf of Akaba, the Red Sea, and penetrate into the African continent by way of the Awash Valley. On leaving the Abyssinian cleft it divides into two principal branches which pass around Lake Victoria: the easterly one, with Lake Rudolf and a string of lakes, the other one to the west, with the Lakes Albert, Edward, Kivu, Tanganyika, and Rukwa. The crystalline plateau is also marked by big tectonic basins which are very extensive, but slightly lower than the sills and domes which separate them. To the north can be distinguished the basins of the low Sahara, Taoudeni, Murzuk, and the Libyan desert; to the south of the Sahara, the Niger, Chad, Bahr-el-Chazal, White Nile and Congo basins, Lakes Victoria and Kyoga, and the two Kalahari basins (D'Hoore 1964).

2.2 Geology

The African continent has remarkable geologic and tectonic features that make the continent not only full of resources but also susceptible to annual hazards. These features include the oldest cratons, plate subdivision below the Eurasian plate at the North, East African Rift System in the East, the African super swell is a region including the Southern and Eastern African plateaus and the South-eastern Atlantic basin where exceptional tectonic uplift has occurred, resulting in terrain much higher than its surroundings) in the Southern and the divergence with the American plates in the West. Parent material is one of the pedogenetic factors that affect soil properties (Burke 2002; Koojiman et al. 2005; Rodrigo-Comino et al. 2018). The greater part of the African continent can be considered as a Precambrian crystalline massif, bounded to the north by the Atlas chain and to the south by the Cape system. This formation crops out over about a third of the surface of the continent. Rocks of Precambrian age underlie large parts of northern and western Ethiopia and smaller areas in the south and east of the country. The lower beds consist mainly of granite, gneiss, and schists. They are covered by more characteristically sedimentary formations (i.e., quartzites, limestones, dolomites, and phyllites). The Upper Precambrian is made up mainly of sandstone but also contains some schistose formations, limestones, and dolomites, the other two-thirds of the crystalline base are covered by various sediments which, except for primary sediments, are of continental origin (D'Hoore 1964; Thomas 2006). Primary sediments are mostly located in North Africa and the Sahara but the extension of their various formations towards the south is patchy. The Cambrian, which followed a glacial period, is indicated by the presence of tillites, and consists of conglomerates, limestones, schists, sandstones, and volcanic veins. These are also found in Mauritania and Mali. The Devonian, containing schists, limestones, and sandstones, goes down as far as the Ghanaian coast (D'Hoore 1964; Thomas 2006). The Carboniferous is limited to North Africa. These outcrops of primary sediments, of which sandstones and schists are dominant, are relatively important in West Africa. In Africa south of the equator and to the west of longitude 30°E extend the Kalahari deposits, consisting of polymorphous sandstones, sands of fluviatile and aeolian origin, and in places, calcareous lenses of lacustrine origin (D'Hoore 1964; Thomas 2006). The Quaternary formation is characterized by important volcanic eruptions, some of which are active, by lacustrine, fluvial, and fluviomarine sediments, and by coverings of colluvial origin. The Volcanic formation covers huge areas on the continental border which include Ethiopia, Kenya, Rwanda, the Cameroons, Central Nigeria, and Uganda whereas the Aeolian sand deposits form the ergs of the Sahara and the South West African deserts, which cover the greater part of the Kalahari and extend towards the north to just beyond the equator, i.e., the east of Angola, the west of the Zimbabwe, the southern half of the Congo basin (D'Hoore 1964; Thomas 2006).

2.3 Climate

Climate is one of the factors governing the distribution of soils in Africa. Rainfall and temperature regimes are the two most important environmental factors that affect both soil characteristics and soil use. The continent of Africa is characterized by several climatic regimes and ecological zones. All parts of the continent, except the Republic of South Africa, Lesotho, and the Mediterranean countries north of the Sahara, have tropical climates. These tropical climates may be divided into three distinct climatic zones: wet tropical climates, dry tropical climates, and alternating wet and dry climates (Huq et al. 1996). Africa is the world's hottest continent; the average annual temperature exceeds 10 °C. The hottest part receives the most solar radiation and lies between the two tropics as a result of the seasonal displacement of the thermal equator or intertropical convergence zone (ITCZ). At a specific time during the season, the air within this region becomes highly heated and rises to condense at high altitudes over the zone of maximum rainfall (Newell et al. 1972; Nicholson 1994). Overland, the ITCZ tends to follow the seasonal march of the sun and oscillates between the fringes of the Sahara in boreal summer and the northern Kalahari Desert in the austral summer. Rainfall over Africa exhibits high spatial and temporal variability. Mean annual rainfall ranges from as low as 10 mm in the innermost core of the Sahara to more than 2,000 mm in parts of the equatorial region and other parts of West Africa. The rainfall gradient is largest along the southern margins of the Sahara—the region known as the Sahel—where mean annual rainfall varies by more than 1,000 mm over about 750 km. The latitude zones of these arid and semi-arid deserts demarcate the tropics from the subtropics. Surface air temperatures over most of Africa display a high degree of thermal uniformity, spatially and seasonally (Riehl 1979). Most of the continent having mean temperatures above 21 °C for nine months of the year (Goudie 1996). The mean temperature in the hottest and coldest months of the year varies little for most of equatorial Africa. For instance, the mean temperature during the summer and winter months at Barumbu, Democratic Republic of the Congo, varies by only 1.4 °C (Griffiths 2005). However, away from the equator and the coast, seasonal variation can be dramatic. In the heart of the Sahara Desert there can be up to a 24 °C difference between the mean temperatures of the coldest and hottest months (Griffiths 2005). Daily temperature variability is primarily influenced by proximity to a coast; generally, the further inland, the more extreme the variation (Griffiths 2005). Rainwater leaches soils and heat triggers chemical processes, hastening the decomposition of minerals.

2.4 Vegetation

Africa's pattern of vegetation zones largely mimics its climate zones (Fig. 2). Areas with the greatest rainfall have the greatest volume of biomass or primary productivity. Accordingly, Africa's equatorial climate zone is its most species-rich area (Meadows 1996). Rainforests in Africa represent slightly less than one-fifth of the total remaining rainforest in the world; Asia and Latin America contain the rest (Sayer et al. 1992). Only about a third of Africa's historical forest extent remains, with West Africa's forests being lost faster than those of any other region. Savannahs with few trees and dry deciduous forests in Africa occur where there are long dry seasons, while dense rain forests occur where rainfall is consistent year-round. Plants characteristic of the Mediterranean region of Africa is drought-tolerant, or xerophytic and able to survive occasional freezing winter temperatures in elevated and inland areas (Stock 2004). The Cape Province of South Africa is famous for its tremendous biodiversity (MacDonald 2003). This region, known as the Fynbos, is considered a distinct floral kingdom and has the highest rate of generic endemism in the world (Allen 1996). The Kalahari and the Karoo in southern Africa and the Sahel in northern Africa fall into the category of semi-desert where short grasses and scattered spiny plants predominate. The halophytes are fairly scattered in the arid and semi-arid regions of Africa. Halophytes occupy salt flats ("sebkhas") bordering the desert, the largest of which are the Qattarah depression in Egypt and the Oum el-Drouss depression in Mauritania. The parts of these depressions which are not too saline and remain sufficiently humid sustain Atriplex and Salsolaceae vegetation (*Salsola foetida*, *S. sieberi*), and *Zygophyllum album.* A large area of this vegetation type occurs in the Danakil depression in Ethiopia and near Lake Al el Bad. In addition, extensive mangrove forests are found on loamy saline soils exposed directly to the tides in the coastal area from the Senegal river on the Mauritania–Senegal border to the Longa river in Angola, and especially in the Niger delta and the islands of the Gulf of Guinea. The stands have *Rhizophora racemosa*, *R. harrisonii,* and *R. mangle* dominants. The mangroves of Madagascar and the east coast of Africa have a strong Asian affinity and comprise *Rhizophora mucronata* (mangrove with prop roots), *Bruguiera gymnorhyza* (semi-circular roots), *Avicennia officinalis* (long narrow pneumatophores), and *Sonneratia alba* (shorter and thicker pneumatophores).

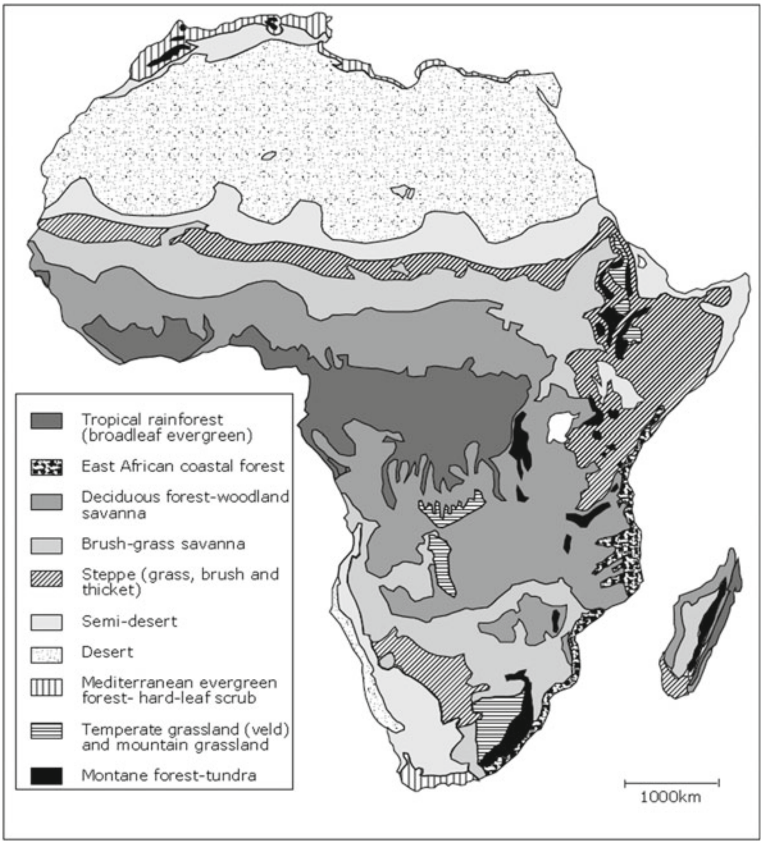

Fig. 2 Principal vegetation zones of Africa (*Source* http://library.berkeley.edu/EART/maps/africa-veg.gif)

2.5 Soils of Africa

Soil is the foundation of many of the Sustainable Development Goals. In addition to providing the medium for food, fodder, and fuel wood production (around 98% of the calories consumed in Africa are derived from the soil), soil controls the recycling of nitrogen, phosphorus, carbon, and other nutrients. Soil reduces the risk of floods and protects underground water supplies. Soil organic matter can store more than ten times its weight of water while the soils of Africa store about 200 Gt of organic carbon—about 2.5 times the amount contained in plants. Aridity and desertification affect around half the continent while more than half of the remaining land is characterized by old, highly weathered, acidic soils with high levels of iron and aluminium oxides (hence the characteristics of colour of many tropical soils) that require careful management if used for agriculture. African soils can be characterized in terms of their relations with water (FAO/UNESCO 1977). Over 60% of the soil types of Africa represent hot, arid, or immature soil assemblages, namely, Arenosols (22%), Leptosols (17%), Cambisols (11%), Calcisols (6%), Regosols (2%), and Solonchaks/Solonetz (2%). A further 20% or so are soils of a tropical or subtropical character, which consists of the Ferralsols (10%), Plinthosols (5%), Lixisols (4%), and Nitisols (2%). The behaviour of these soils is impacted by wide-ranging soil forming processes such as volcanic activity, accumulations of gypsum or silica, waterlogging, soluble salts, etc. (Dewitte et al. 2013).

3 Extent and Distribution of Salt-Affected Soils in Africa

As shown in Table 1 and Fig. 3, salinity and sodicity are the most widespread soil degradation processes on Earth. In Africa salt-affected soils are estimated to cover about 209.6 million hectares of which 122.9 million ha are saline soils and 86.7 million ha are sodic soils (Glenn 2009). However, as irrigated agriculture expands, more salinity problems will develop because there are millions of hectares of potentially irrigable land that could become saline. Seemingly, 200 million ha of land is expected to be potentially salt affected in Africa if the soils of semi-arid regions such as Calcisols (161 million ha), Gypsisols (37.5 million ha), Chernozems (1,039,300 ha), Kastanozems (2,672,400 ha) (Dewitte et al. 2013) are brought under irrigation. Salt-affected soils are prevalent largely in the countries of Eastern Africa, along the coast of Western Africa, the countries of the Lake Chad Basin, and in pockets of Southern Africa. Countries where salt-affected soils are currently widespread are Algeria, Angola, Botswana, Burundi, Cameron, Chad, Congo, Egypt, Ethiopia, Kenya, Libya, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Niger, Nigeria, Rwanda, Uganda, Senegal, Somalia, Sudan, Swaziland, Tunisia, Zambia, and Zimbabwe.

Table 1 Worldwide extent of salt-affected soils

Continent	Saline, Mha	Sodic, Mha	Total, Mha
Africa	122.9	86.7	209.6
South Asia	82.2	1.8	84.0
North and Central Asia	91.4	120.1	211.4
Southern Asia	20.0	–	20.0
South America	69.4	59.8	129.2
North America	6.2	9.6	15.8
Mexico and Central America	2.0	–	2.0
Australia	17.6	340.0	357.6
Global total	411.7	617.9	1029.5

Source Glenn (2009)

Fig. 3 Global distribution of the salt-affected soils 1987 (*Source* Szabolcs)

4 Types and Drivers of Salt-Affected Soils in Africa

Soil salinization, a major soil degradation process, occurs when salts accumulate in the soil to a level where impacts include reductions in crop yields, forest loss, nutrient release from the soil, which can lead to algal blooms and fish mortality, marsh migration inland, expansion of salt tolerant species, loss of critical tidal marsh habitat, soil health issues, change of local climatic conditions, and degraded groundwater (Nachshon 2018; Shrivastava and Kumar 2014). Salinization of soil results from a combination of evaporation, salt precipitation and dissolution, salt transport, and ion exchange (Shimojima et al. 1996). Soil salinity refers to the total salt concentration in the soil solution (i.e., aqueous liquid phase of the soil and its solutes) consisting of soluble and readily dissolvable salts including charged species, e.g., sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chloride (Cl^-), sulphate ($SO_4{}^{2-}$), carbonate ($CO_3{}^{2-}$), bicarbonate ($HCO_3{}^-$), and borates ($B(OH)_4{}^-$) (Corwin 2003). Hypersaline waters may contain trace concentrations of the elements B, Se, Sr, Li, SiO, Rb, F, Mo, Mn, Ba, and Al, some of which may be toxic to plants and animals (Tanji 1990).

When the water evaporates, the salts are left behind. The origin of salts in soil can be natural or anthropogenic, where the former refers to primary salinization and the latter secondary salinization. The primary source of salts in soil and water is the geochemical weathering of rocks from the Earth's upper strata, with atmospheric deposition, seawater intrusion, rising ground waters in low-lying topography from saline aquifers serving as other natural sources, and anthropogenic activities serving as secondary sources. Anthropogenic sources include salts present in irrigation waters, residual salts from amendments added to soil and water, animal wastes, chemical fertilizers, and applied sewage sludge and effluents (Tanji 2002). The predominant mechanism causing the accumulation of salt in the root zone of agricultural soils is loss of water through evapotranspiration (i.e., combined processes of evaporation from the soil surface and plant transpiration), which selectively removes water, leaving salts behind. Salinization commonly occurs on arid and semi-arid zone soils where irrigation and/or rainfall are insufficient to leach salts, where poor drainage and/or shallow water tables exist, where there is an upslope recharge and downslope discharge, and where saline sub-soils formed naturally from marine deposits.

In the African continent as with the rest of the world, the main causes which lead to the development of salt-affected soils are inundation with sea water; mineral/rock weathering; mineral/rock weathering groundwater associated salinity, irrigation-induced salinity and climate change triggered salinity. The brief account of each cause is highlighted below.

4.1 Coastal Salinity

Coastal saltwater inundation is the movement of saline water over terrestrial soils due to rising sea levels. The possible ways sea water can reach the land are flooding during high tide, ingress through rivers and estuaries, groundwater inflows, and salt-laden aerosols. Dry and wet aerosol fallout contributes up to 100 kg/y-ha to 200 kg/y-ha along seacoasts and from about 10 kg/y-ha to 20 kg/y-ha in the interior (Suarez and Jurinak 2012). Rainfall could be another minor source of salinity in agricultural lands. Early showers after a long dry season can add a few kilograms of salts per hectare per annum. Salts influence the chemistry of the soil in which it infiltrates. Once salt-bearing water pushes inland, it may become associated with the soil grains by adsorption or ion exchange, or it may remain in solution. Seawater contains 35 g salt/litre and is typically dominated by chloride and sodium salts with 85% of the salinity derived from these ions (NOAA 2021). Sulfate and magnesium salts account for approximately 10% of the remaining salt content of seawater (NOAA 2021). When water containing salts percolate through soil, positively charged ions (sodium, calcium, magnesium) are attracted and bond with the inherently negatively charged clay mineral surfaces. The extent of bonding depends on the cation exchange capacity and the number of negatively charged sites in the soil.

The coastal zone could be divided therefore into the West and Central African coastal zone, the East African coastal zone, and the Mediterranean coastal zone. The West and Central African coastal zone stretches from Mauritania to Namibia and constitutes 29.5% of the whole area of the African continent. The Eastern African coastal zone can be delimited by latitudes 18°N to 27°S and include coastal areas of the island states Madagascar, Mauritius, Reunion, and Seychelles. A large part of the East African coastal plain which is low-lying is very variable in width. On the other side, the African coastal zone, most of which is very low-lying, consists of the West, Central, East, and Mediterranean coastal zones. Generally, thirty-nine African countries, including the island nations, border an ocean. The continent's coastline is a mix of diverse ecosystems, including estuaries, deltas, barrier islands, lagoons, wetlands, mangroves, and coral reefs (Watson et al. 1997). The depth to water table in the coastal zone is often very shallow and is subject to saline seawater contamination and pollution (Ibe and Awosika 1991).

Over a large area, seawater is in contact more or less directly with the groundwater of the littoral zone. In many arid and semi-arid coastal regions, and sometimes in humid areas, the process of evaporation brings saline groundwater to the surface by capillary movement from shallow water tables, leading to strong soil salinization in countries such as Algeria, Morocco, Senegal, Sierra Leone, Togo, Ghana, and southern Madagascar.

In humid tropical regions, the coastal saline soils of estuaries and deltas, which are rich in organic matter acquire special characteristics where the mangroves (Fig. 4) are associated with Avicennia or Rhizophora vegetation where such soils are drained, they become extremely acidic. They are classified as Thionic Fluvisols and are observed in Sierra Leone, southern Senegal, the Gambia, Guinea Bissan, Guinea, Liberia, Nigeria, Cameron, Gabon, Kenya, Tanzania, Mozambique, and in western Madagascar. Their area is estimated at approximately 3,350,000 ha (CEC 1992). When soluble salts are present, as often in tidal marshes and recently reclaimed sulfidic soils, their osmotic effects can inhibit the uptake of water and nutrients. The toxicity of Na^+ and Cl^{-1} is also common. Within Senegal, the Gambia, and Guinea Bissau, with a pronounced dry season and a decrease of the annual rainfall over the last 20 years, salinity levels with ECe values of 80 dS m^{-1} are not uncommon in the topsoil (Sylla 1994).

4.2 *Weathering of Minerals or Rocks*

Weathering of rocks containing sodium minerals (feldspars, amphiboles, etc.) produces soluble sodium salts, principally carbonates and bicarbonates, often sulfates, sometimes silicates, and rarely chlorides. Through time, saline seas have inundated large areas of present-day continents. These submerged areas have subsequently been uplifted. The resulting geologic formations provide parent material for soils as well as outcrops and underlying saline strata to soils or other formations, all of which are important zones of contact for salt loading of surface and groundwater. The secondary deposits (i.e., sedimentary rocks) formed from inland seas and weathering of continental rock during inundation are the major sources of salinity and sodicity (Suarez and Jurinak 2012).

In sub-humid regions and in certain semi-arid regions where excess water accumulates, the situation is different. Here, the dissolved sodium accumulates as exchangeable sodium in the B horizon, due to vertical or horizontal leaching. The soils which result are sodic soils. These soils are found in Ghana, Togo, Nigeria, Cameroon, Chad, Malawi, Botswana, Zimbabwe, Swaziland, Lesotho, and other tropical countries. Sodic are very susceptible to water erosion. Numerous Vertisols have a B horizon with a very high exchangeable sodium percentage and possess the physical properties of sodic soils. They occur in Tunisia, Kenya, Tanzania, Uganda, Zambia, Lesotho, Swaziland, and South Africa and have been classified as sodic soils.

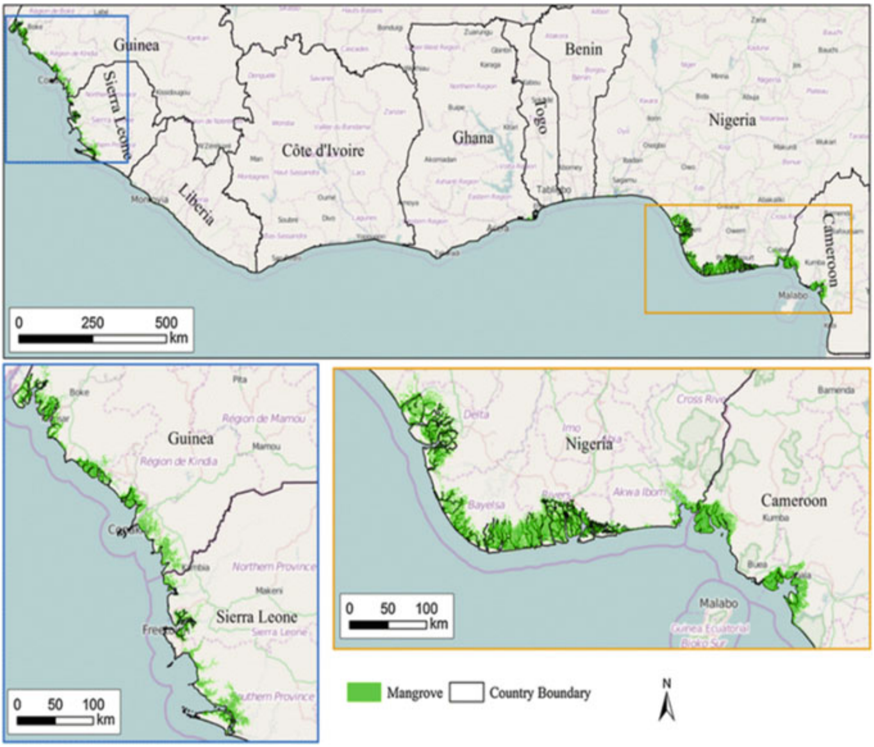

Fig. 4 Map of mangrove coverage in West Africa (*Data Source* USGS; base map: OpenStreetMap)

4.3 Groundwater-Associated Salinity

The water table refers to a saturated zone in the soil (USDA NRCS 2021). The depth of the water table below the surface, together with hydraulic properties of the soil and potential evaporation, control the amount of evaporation at the evaporation front, as they affect capillary water flow from the water table upward (Nachshon 2018). Usually for groundwater levels deeper than 2–3 m, depending on soil properties, evaporation, and resulted salt accumulation will be minor as capillary rise to the evaporation front is negligible (Rengasamy 2006; Salama et al. 1999). In the early stages of saltwater inundation, high freshwater tables in soils tend to attenuate the impact of salts by reducing the movement of saltwater inland (Hussein and Rabenhorst 2001). This eventually leads to lesser impacts from saltwater on soils by lower rates of marsh lateral migration and deforestation (Hussein 2009). When saltwater eventually inundates an upland soil, the amount of soluble salts retained is determined by water table fluctuations (Hussein and Rabenhorst 2001). Utilization of saline groundwater from the saline geologic materials for irrigation is another source of salt-affected soils when drainage is poor, and the climate is arid. Even when the rainfall is as much as 1,000 mm, low-lying impermeable soils may be saline if annual evaporation is high, as it commonly is in tropical Africa. Transported marine salts are often the source of soil salts in Morocco, Algeria, Tunisia, northern Nigeria, Swaziland, Botswana, and South Africa.

Increased groundwater salinity also related to high concentrations of some of the elements like sodium, sulphate, boron, fluoride, selenium, arsenic, and high radioactivity (IAEA 2004). The sedimentary basin with the highest frequency of saline groundwater (EC > 2 dS/cm) is encountered in the North Western Saharan Aquifer underlying Tunisia, Algeria, and Libya and in the North Kalahari Sedimentary basin aquifer in Southern Africa.

4.4 Irrigation-Induced Salinity

Irrigation has contributed significantly to the growth in agricultural production in many countries. However, irrigation-induced salinity is an increasing problem in several of these countries, threatening the productivity of agricultural lands. FAO (1990) reports that about 20–30 million hectares are severely affected by salinity and an additional 60–80 million hectares are affected to some extent. Irrigation-induced salinity can arise as a result of the use of any irrigation water, irrigation of saline soils, and rising levels of saline ground water. When surface or groundwater containing mineral salts is used for irrigating crops, salts are carried into the root zone. The amount taken up by plants and removed at harvest is quite negligible. The more arid the region, the larger the quantity of irrigation water and, water applied in excess of plant evapotranspiration to leach the salt away (Young and Homer 1986). A problem closely related to the problem of irrigation-induced salinity is that of alkalinity or sodicity; its impact is manifested by the degradation of the soil structure. The application of irrigation water to areas with abundant salts (common in arid and semi-arid areas) and more than 15% exchangeable sodium leads to the formation of "alkaline" or "sodic" soils, through the process of alkaline hydrolysis. If the soil has a low chloride and calcium content and if the soil and/or irrigation water applied have abundant exchangeable sodium bicarbonate and/or sodium carbonate (over 15% exchangeable sodium), the clay particles in the soil adsorb the sodium and magnesium salts and swell. The soil loses its permeability (ability to conduct air and water) and filth (friability of the seedbed). Alkalinity may also induce calcium deficiency and various other micro-nutrient deficiencies because of the associated high pH and bicarbonate levels repress their solubilities and concentrations (Kijne and Vander Velde 1992).

According to FAO (2001), the average rate of irrigation development for the Sub-Saharan Africa region (40 countries) over the past 12 years is 43,600 ha/year—an average of 1150 ha/year for each country. Some countries have average rates of development of over 2000 ha/year (e.g., Tanzania, Nigeria, Niger, Zimbabwe, and South Africa). It is well documented that irrigated land leads to increased agricultural productivity, irrigated areas are 2.5 times more productive compared to rain-fed agricultural areas (Stockle 2001). However, the development of an irrigation system can also lead to the build-up of soil salinity when the land is irrigated with poor water quality and water is applied without proper drainage, the evaporation in arid climates can quickly lead to high levels of salt in the soil, reducing the yield potential of the land. Another type of problem that can occur on irrigated lands is known as "waterlogging". This can happen if there is a layer of rock that forms a barrier, through which the water cannot escape. Over time, the water can accumulate and reach the root zone of the plants, making agricultural production impossible.

4.5 Climate Change Triggered Salinity in Africa

Sea level rise associated with climate change includes an increase in coastal erosion and saltwater intrusion. The trend is a result of the coastal degradation and erosion in West Africa. About 56% of the coastlines in Benin, Côte d'Ivoire, Senegal, and Togo are eroding, and this is expected to worsen in the future (Mafaranga 2020). Two of the most salient facts about climate change and Africa are that the continent contributes an insignificant amount to global greenhouse gas emissions (less than 1%), and that it is likely to be the area most affected by climate change. Soil salinization plays a role in global biogeochemical cycles, but its significance is still not as well understood, particularly in regard to different potential management opportunities (e.g., small vs large holder farms). Soil salinization is a key regulator of plant/soil nitrogen pools and, by altering soil electric conductivity and affecting the functioning of soil microorganisms, it impacts nutrient cycling and global fluxes. Moreover, soil salinity may increase N_2O emissions, but the underlying regulatory mechanisms are complex. Soil salinity generally reduces plant productivity in croplands and, consequently, soil carbon storage. Furthermore, the decomposition of soil organic carbon is limited because salinity reduces soil microbial function. Climate change-induced sea surface rise will lead to saltwater intrusion in coastal areas. Moreover, when groundwater is overused, inland aquifers can also be affected, increasing risks of soil salinity. Under climate change scenarios, salinity in drylands can increase due to higher rates of evapotranspiration of shallow groundwater.

5 Impact of Salt-Affected Soils in Africa

5.1 Impact on Soil

A problem closely related to the problem of irrigation-induced salinity is that of alkalinity or sodicity; its impact is manifested by the degradation of the soil structure. The application of irrigation water to areas with abundant salts (common in arid and semi-arid areas) and more than 15% exchangeable sodium leads to the formation of "alkaline" or "sodic" soils, through the process of alkaline hydrolysis. If the soil has a low chloride and calcium content and if the soil and/or irrigation water applied have abundant exchangeable sodium bicarbonate and/or sodium carbonate (over 15% exchangeable sodium), the clay particles in the soil adsorb the sodium and magnesium salts and swell. The soil loses its permeability (ability to conduct air and water) and filth (friability of the seedbed). When this occurs, water infiltration is hindered, and plant roots/soil organism may be starved of oxygen (Rhoades 1990). Alkalinity may also induce calcium deficiency and various other micro-nutrient deficiencies because of the associated high pH and bicarbonate levels repress their solubilities and concentrations (Kijne and Vander Velde 1992).

5.2 Impact on Plants

Excessive soluble salt concentrations or salinity affects plant growth and production primarily by increasing the osmotic potential of the soil solution (Bernstein 1961). Under some conditions, (Bernstein 1974; Bernstein et al. 1956), specific ion toxicities can also be important for some crops, particularly for woody species. The physiological effects of excess salinity are many, but visual symptoms generally do not become evident until salinity conditions are extreme. Plants affected by excessive soluble salt concentrations usually appear normal, but there is a general stunting of growth, foliage may be darker green than for normal plants, and sometimes leaves are thicker and more succulent. Woody species often exhibit leaf burn, necrosis, and defoliation resulting from toxic accumulations of Cl or Na. Chlorophyll formation is inhibited in citrus by specific ion toxicities (Carter and Myers 1963). Occasionally, nutritional imbalances caused by salinity produce specific nutrient-deficiency symptoms (Lunin and Gallatin 1965; Ravikovitch and Porath 1967). The osmotic effect of salinity is to increase the osmotic potential of the soil solution, thereby making soil water less available for plant uptake. Therefore, salt-affected crops often appear the same as crops suffering from drought. As the salt concentration in the soil solution increases, both the growth rate and ultimate size of most plant species progressively decrease. Salinity effects are frequently not recognized, even though yield reduction may be 20–30% because of the general decrease in growth rate and plant size. Not all plant parts are affected the same way, and any relationship between growth response and soil salinity must take this into account (Bernstein and Pearson 1954; Meiri and Poljakoff-Mayber 1970). The leaf-to-stem ratio of alfalfa is affected, influencing forage quality (Hoffman et al. 1975). Vegetative production is decreased more than seed or fibre production for crops such as barley, wheat, cotton, and some grasses (Ayers et al. 1952). Root yields of root crops are generally decreased much more than top yields (Pearson 1959; Hoffman, and Rawlins 1971). The impact of reduced plant production caused by salinity depends upon the purpose for which the plants are grown.

5.3 Impact on the Socio-Economy

Soil salinity is one of the biggest threats to our global agricultural soils, the world's largest industry, and the wider food system. In 2018, the Intergovernmental Science Policy Platform of Biodiversity and Ecosystem Sciences (IPBES) completed a global assessment of land degradation. The report revealed that soil salinization was one of the main factors reducing plant growth and agricultural productivity worldwide. The annual global economic cost of lost crop production is US $27.3 billion. Land affected by high levels of salinity totals 1 billion hectares. That farmland generates 40% of the planet's food. The UN university states that since the 1990s, 2500 ha have been lost, daily. We must urgently find cost-effective solutions for salinization to ensure we have enough to eat, to protect our environment, and ensure our very existence on earth. In Sub-Saharan Africa (SSA) an estimated 180 million people are affected, (Mirzabaev et al. 2014) while the economic loss due to land degradation is estimated at $68 billion per year (Nkonya et al. 2016). The socioeconomic impacts of land degradation vary with the geographical, political, and economic context.

6 Suggested Management Scenarios

Every year new salinity problem areas develop and are identified. Salinity is the most important problem facing irrigated agriculture; and solving salinity problems is one of the greatest challenges to agricultural scientists. Use and reclamation of salt-affected soil for agricultural purposes requires a combination of approaches and technologies and the consideration of socioeconomic aspects under local conditions. Agricultural production in salt-affected soils is largely dependent on water availability, climatic conditions, crop, and the availability of resources. In this section, relevant options for reclamation and management of salt-affected soils in the African context are identified and presented below.

6.1 Use of Salt Tolerant Crops

Although several reclamation and management practices can reduce salt levels in the soil, there are some situations where it is either impossible or too costly to attain desirably low soil salinity levels. In some cases, the only viable management option is to plant salt-tolerant crops. Actual yield reductions will vary depending on the crop variety and the climatic conditions during the growing season. Moreover, plants are usually most sensitive to salt during the emergence and early seedling stages. Tolerance usually increases as the crop develops. Most of the major cereal crops exhibit high tolerance to soil salinity, which are grown in Africa are sorghum, wheat, triticale, rye, oats, barley, maize, and rice (Maas 1990). Virtually, Africa is the centre of origin and also a major producer of several cereals like sorghum, pearl millet, finger millet, teff, and African rice where these cereals are grown over an area of 98.6 m ha. Breeding of indigenous cultivars to develop salt tolerant varieties that suit the wide-ranging agroecology of Africa will be the most cost-effective technology for managing of salt-affected soils. Besides, because of their fibrous roots, grasses alone or in combination with forage legumes are frequently used in the reclamation of saline and sodic soils to restore good soil structure (Bernstein 1958). Under non-irrigated conditions, grasses that accumulate significantly high concentrations of Na^+ and Cl^- in the shoots may be used to restore soil structure and also to remove these ions from the soil profile (Sandhu and Malik 1975). Furthermore, in typical aridic or semi-aridic environment where salinity is prevalent a wide-ranging salt tolerant perennial plants can be grown. For example, date palm is most frequently cultivated by improving through breeding in Egypt, Sudan, and the other countries of North Africa. The fig and olive are also successful trees, which are grown in the saline environment of North Africa, with about two-thirds of the olive production being processed into olive oil. And orange, which is tolerant to a chloride ion, can be grown in the regions of the southern coast of South Africa and the Mediterranean coast of North Africa, as well as Ghana, Swaziland, Zimbabwe, the Democratic Republic of the Congo, and Madagascar. Sugarcane is also frequently grown perennial grass on saline estates in South Africa, Egypt, Mauritius, and Sudan with a possibility of improved productivity with a reasonable reclamation to lower down the alkaline soil pH through the application of either mined gypsum or phosphogypsum.

6.2 The Irrigation Method

The irrigation method and volume of water applied have a pronounced influence on salt accumulation and distribution. Flood irrigation and an appropriate leaching fraction generally move salts below the root zone. With furrow and pressurized irrigation, soluble salts in the soil move with the wetting front, concentrating at its termination or at its convergence with another wetting front. In drip-irrigated plots, water moves away from the emitter and salts concentrate where the water evaporates. In furrow-irrigated plots, water movement is from the furrow into the bed via capillary flow. When adjacent furrows are irrigated, salts concentrate in the centre of the intervening bed. Manipulating bed shape and planting arrangement are strategies often used to avoid salt damage in furrow-irrigated row crops. Moreover, canal water is of excellent quality, and has, obviously, tremendous value for farmers who are dealing with salinity and/or sodicity. When dealing with genetic salinity, they use canal water for reclamation purposes, while they mitigate the effect of poor-quality tube well water by applying it in conjunction with canal water. The importance of canal water for farmers was substantiated in a survey conducted by Kielen (1996), where farmers singled out canal water as the most important factor for salinity management. In a modelling exercise, the importance of canal water was further confirmed in ensuring a long-term salinity equilibrium at reasonable levels (Smets et al. 1997). Making more canal water available to farmers would, therefore, help them in their salinity management.

6.3 Salt Leaching and Drainage

Salinity problems can be either potential or actual. Both types of problems can be solved by drainage, but they differ with regard to the purpose and requirements of the drainage. Therefore, it is useful to distinguish between two types of salinity drainage: "salinity prevention" and "salinity reclamation" (Van Beers 1966). *"Salinity prevention" drainage* is designed to prevent salinization after the establishment of irrigation facilities in a non-saline area. Therefore, the amount of salt supplied by irrigation water and by capillary rise from the groundwater must be in equilibrium with the amount of salt leaving the root zone by drainage. Salinity prevention drainage generally requires low rate of discharge (about 1–2 mm per day) and deep drains. The depth of the drains is determined mainly by the permissible depth of the groundwater in relation to salinization dangers, the so-called "critical depth", which depends on the type of soil, groundwater salinity, and evaporation. This depth is generally greater than that required for crop-drainage under humid conditions. Because the drainage rate is much smaller, the spaces between drains needed for this type of drainage are much larger. Whereas "*salinity reclamation" drainage* is used to reclaim saline soils by leaching and drainage using large quantities of water. After reclamation, re-salinization has to be prevented by means of a salinity prevention drainage system. Efficient salt leaching by shallow drainage is the most effective way to decrease salinity levels to acceptable limits. Leaching can also increase the pH, lower the specific conductance and the concentration of Al and other salts as well as the partial pressure of CO_2 (Pounamperuma 1972). In Senegal, Béye (1973) observed the beneficial effect of shallow drainage in acid sulfate soils. Sylla and Touré (1988) showed that ridging by plowing as done in the Diola zone is efficient to control salinity as well as iron toxicity. Detrimental acidity and salinity can be overcome by daily leaching with brackish to freshwater tide in Sierra Leone (Sylla et al. 1993).

6.4 Use of Organic Matter

To improve sodic soils, heavy dressings of organic matter have sometimes been applied. It is stated that a heavy dressing of organic matter results in the formation of a more stable structure. The second effect is that, with the decay of the organic matter, CO_2 is produced, as a consequence of which the solubility of $CaCO_3$ is increased. When gas exchange processes in the soil are impeded, the CO_2 concentration may rise considerably and an increased solubility of $CaCO_3$ can be expected. Besides, some green manures, in particular, *Sesbania aculeata* and *Argemone mexicana*, are found to be highly effective in the improvement of sodic soils (Uppal 1966). Both green manures upon decay produce a large amount of organic acids which depress the pH of the soil. Moreover, heavy dressings of molasses, containing large quantities of organic acids, have been reported to be very effective in reducing the alkalinity of the soil (Prettenhoffer 1964).

6.5 Use of Chemical Ameliorant

Phosphogypsum is an almost unused by-product of phosphate fertilizer production, which includes several valuable components—calcium sulphates and rare-earth elements. Phosphogypsum (PG) was found to be better at reclaiming materials than mined gypsum. Application of PG results in a greater decrease in surface soil pH and ESP, resulting in a greater yield of rice and wheat over the equivalent dose of mined gypsum. The contents of soluble P, calcium P, and Fe–P were greater in PG-treated soil than the initial soil and mined gypsum–amended soil. Beretka (1990) reports positive results with the application of 3–5 t/ha of phosphogypsum every 3–5 years. After such applications of phosphogypsum the improvement of soil structure at surface layer and better water infiltration were recorded in unstable structure soils and soil management was easier and faster. Nayak et al. (2011) conducted a research in India on agricultural soil without vegetation, with the addition of 5–20% phosphogypsum and they found that with the increasing amounts of phosphogypsum applied, pH was reduced from 7.9 in control to 5.1 in treatment with 20% phosphogypsum. According to Vyshpolsky et al. (2010) by using phosphogypsum in irrigated areas, the effects of excess Mg^{2+} in soil, which are negative regarding soil structure and ultimately plant growth and yield, are mitigated. Dimitrijević et al. (2010) conducted an experiment with different varieties of wheat on solonetz, with the application of phosphogypsum as a reclamation agent in the amount of 25 t/ha and 50 t/ha, and they found an average yield of 5.17 t/ha (25 t/ha PG) and 3.81 t/ha (50 t/ha PG). According to the aforementioned studies, positive effects of phosphogypsum on soil, water, and plants are prevailing. However, for the sustainable use of phosphogypsum in the reclamation of salt-affected soils, agroecology-based research is imperative.

6.6 Fertilizers

Fertilizers like ammonium sulphate, superphosphate, and calcium nitrate have a favourable effect on sodic soils. In addition to providing an increased fertility, ammonium sulphate tends to lower the pH of the soil. Studies on soil salinity–fertility relationships indicate a positive effect of fertility on crop salinity tolerance. Among the most striking data are those published by Ravikovitch and Yoles (1971). The yields of clover (*Trifolium alexandrinum*) and millet (*Setaria italica*) growing in pots in a greenhouse experiment were greatly increased by the addition of N and particularly P to saline soil. Lüken (1962) reported that positive effects of N and P application on the yield of wheat (*Triticum aestivum* L.) growing on saline soils under dryland conditions were detected. The addition of P improved the yield from tomato (*Lycopersicon esculentum* L.) growing under saline conditions (Cerda and Bingham 1978). Kafkafi (1984) concluded that the use of saline water for irrigation should be combined with a continuous supply of nutrients in the proper concentration. The yield of beans (*Phaseolus vulgaris* L.) was increased by P fertilization for the salinity range studied by Lunin and Gallatin (1965). The addition of P fertilizer (15 and 40 mg P l^{-1}) to pepper plants (*Capsicum annum* L.) during the first 55 days of growth increased the per cent germination of seeds obtained from these plants in the presence of 0.5% NaCl solution, in comparison with untreated plant.

6.7 Reclamation Using Rice Cultivation

Rice cultivation is very effective for improving sodic soils, particularly for leaching soluble salts. On sodic soils with extremely high pH values the growth of rice is stunted. Green manuring with *Sesbania* or an application of a small dressing of sulphur or gypsum promotes the growth of rice on these soils (Uppal 1966). Moreover, rice straw mulching experiments in Senegal proved to be an efficient practice to avoid salinity build-up during the dry season (Béye 1974). Thus, the most important rice-producing countries such as Egypt, Guinea, Senegal, Mali, Sierra Leone, Liberia, Cote d'Ivoire, Nigeria, Tanzania, and Madagascar can tackle soil salinity build-up via rice straw mulching.

6.8 Use of Crop Rotations in the Reclamation

Crop rotation is an agricultural practice, which implicates the cultivation of different crops on the same field. Selection of suitable crop rotation at farmer field is very intricate decision. When the good quality of water supplies is limited a suitable crop rotation is the only means for managing salt-affected soils and maintaining crop yields (Kaur et al. 2007). Crop rotation resulted in several improvements, in soil physical and chemical properties and is also suggested for salt-affected soil, especially when crops with varying degrees of salinity tolerance are used (Lacerda et al. 2011). For suitable crop rotation in salt-affected soils, selected crop should be either salt tolerant or tolerant cultivars must be selected from sensitive or medium tolerant crops with high economic value (Ouda et al. 2016). Abro and Mahar (2007) reported that in rice–wheat cropping system, salinity indicators like soil ECe, pH, and SAR were significantly lowered after the rice harvest, however, a minor increase in ECe and pH were recorded whereas, the SAR levels dwindled further after wheat harvest. Similarly, in a study Liu et al. (2013) reported that the rice-barley crop rotation lowered soil ECe after a reclamation time of more than 10 years. The paddy soil management for 50 years favoured the enhancement of soil organic carbon and decreased the concentrations of Ca, Mg, and Na (Chen et al. 2011). Fu et al. (2014) found that rice-barley crop rotation had more ameliorative effect on soil properties and significantly decreased the pH value than cotton-barley crop rotation system in the same year.

7 Conclusion

While soil salinization may occur naturally, it has been highly exacerbated by a combined anthropogenic and climate change activities in Africa. Land degradation and soil fertility decline in Africa are deeply complex. Now it is clear that salinization and alkalinization of agricultural soils become a threat to the African continent as it visibly impacts food production, the livelihood of millions of smaller holder farmers, and social stability. Sustained and profitable land use systems on salt-affected soils are possible if appropriate decisions on soils, climatic, and landscape characteristics in view of the current and future use of the land are considered intrinsically. Besides, "prevention is better than cure", so does the same concept apply to solving the worldwide problem of soil degradation through salinization. The costs of preventing salinization are incredibly cheaper than the reclamation projects in salinized areas. Thus, it is high time now for the African countries that are threatened by the gravity of salinity and sodicity problems to prepare their respective national plans of actions for managing and versatile use of salt-affected soils both at large and small-scale farming taking into account cost-effectiveness and sustainability.

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Chapter 14
The Use of Non-Conventional Water Resources in Agriculture in the Gulf Cooperation Council Countries: Key Challenges and Opportunities for the Use of Treated Wastewater

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Abstract The Gulf Cooperation Council (GCC) countries are situated in a region of severe water poverty characterized by harsh climatic conditions. The average per capita share of natural freshwater resources is among the lowest in the world at about 120 m^3/year; much less than the recognized absolute water scarcity limit (500 m^3/capita/year). On the other hand, the average per capita annual water consumption is about 800 m^3/capita/year, putting the GCC region within the world's highest water consumers. This huge deficit in their natural water resources, reaching over 15 BCM, is met mainly by extensive over-abstraction of the limited groundwater resources, vast installation of expensive desalination plants, and to a lesser extent, the reuse of treated wastewater. Treated wastewater has the potential to play an important role as a non-conventional water resource, especially for the agricultural sector, the biggest water consumer (77%), reducing pressure on the depleted groundwater, matching the continuous increase in water demand, minimizing contamination, conserving energy, and reducing the environmental footprint of wastewater treatment. However, treated wastewater still accounts for only 3% of the total GCC water demand. The wastewater sector faces three key challenges that must be carefully managed to reach full utilization, these are: public perception, health and environmental risk, and economic and cost recovery. For this to be accomplished, developing a reuse strategy/policy is a necessity for promoting the treatment efficiency and maximizing the treated wastewater reuse. Sustainable water systems can be entirely realized if everyone begins thinking about wastewater differently.

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Keywords Water scarcity · Water management · Wastewater treatment · Reclamation benefits · Reclamation constraints · GCC

1 Introduction

Water is an invaluable resource, and is essential for human development, well-being, and survival. It maintains the health of our ecosystems, keeps our communities running, and our economies developing. Water resources are widely considered as the most critical natural resources. Essential freshwater resources are relatively scarce, of the 1,400 million km^3 of water on Earth, 97% is in oceans, 2% is freshwater in ice, 0.6% is underground water, less than 0.3% is readily available for humans to use, with huge geographical variations even of this small fraction[1] (Pidwirny 2006; PwC 2012). Moreover, by 2050, global water demand is estimated to grow by 20–30%, due to the increased water use mostly in the agricultural sector followed by domestic and industrial sectors (WWAP and UNESCO 2019). Yet, water is often taken for granted and poorly valued, not all people recognize what it takes to deliver or produce freshwater every day or to treat wastewater so that it can be safely reused or returned to the environment. Benjamin Franklin stated that "We will never know the true value of water until the well runs dry" (IPCC 2018). Due to its importance, the UN-Water choose "valuing water" as the theme of the 2021 World Water Day (UN-Water 2021). Water resources are only sustainable if they are properly managed.

Securing freshwater availability has become one of the main challenges at national, regional, and global levels due to various factors such as population boom, climatic conditions, and the mismanagement and overuse. In a world where freshwater demand is continuously increasing, and limited water resources are progressively depleted due to over-abstraction, pollution, and climate change; reusing wastewater has become an important option to counteract these conditions. To ignore the benefits of wastewater reuse is nothing less than a lost opportunity in the perspective of a circular economy and water sustainability (UN WWAP 2017).

Six countries in the Arabian Peninsula, namely, Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and United Arab Emirates (UAE), constitute the Gulf Cooperation Council (GCC), which was founded in 1981. The cooperation is based on their geographic proximity, common political, socio-economic, and cultural affairs, natural resources from oil and gas, joint destiny, and shared objectives. The GCC countries are located in the southwestern region of the Asian continent, bordered by the Arabian Gulf in the east, the Red Sea in the west, the Arabian Sea in the south, and Iraq and Jordan in the north (Fig. 1). The GCC countries cover an area of nearly 2,410,737 km^2, about 83% of this area belongs to Saudi Arabia (GCC-STAT data

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[1] Ten countries (Brazil, Russia, USA, Canada, Indonesia, China, European Union, Colombia, Peru, and India) are the world giants in terms of natural water resources, accounting for about 60% of the world's freshwater. At the other extreme, the water poorest countries, usually the arid and smallest ones, include Bahrain, Kuwait, Jordan, Libya, Maldives, Malta, Qatar, United Arab Emirates, Yemen, and Saudi Arabia (FAO 2003).

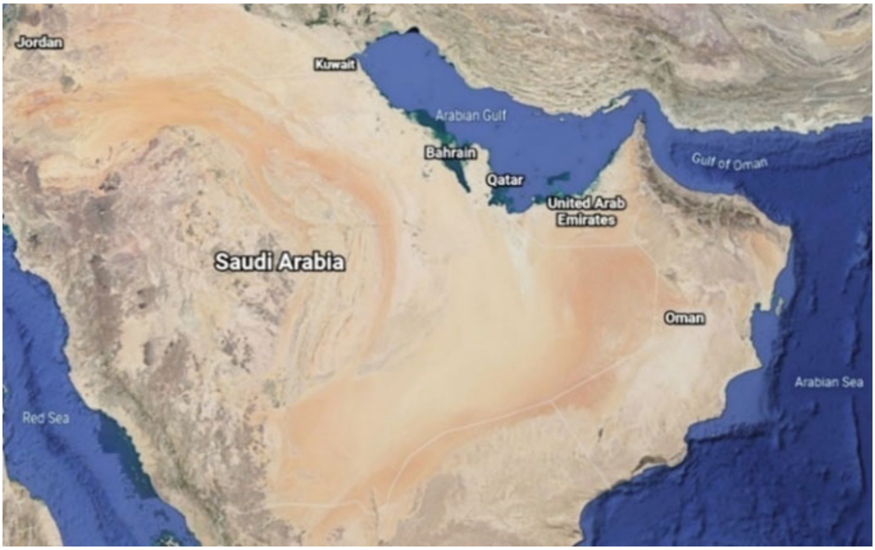

Fig. 1 Geographical location map of the GCC countries (Google Earth)

2018). Since the discovery and the start of intensive exploitation of oil fields in the middle of the twentieth century, these countries have experienced an unprecedented fast-paced transformation resulting in a rapid change in socio-economic development, an improvement in the standard of living and an increase in consumption patterns, mainly due to the sharp increase in income, which continues to this day (Al-Badi and AlMubarak 2019). The human development index (HDI), which is based on indicators such as life expectancy, education, and gross national income, for the GCC countries is 0.84/1, which is higher in rank than that for most developing countries and is continuously improving (UNDP 2020). In addition, GCC countries had a relatively high per capita GDP of USD 55,137 in 2018, approximately 20% higher than the average of the world advanced economies, ranging from USD 41,400 in Oman to USD 115,900 in Qatar (Alpen-Capital 2019). These high living standards have been associated with high per capita water consumption, putting major stresses on the limited water resources (Droogers et al. 2012).

GCC countries have the lowest water endowment of natural water resources in the world due to their location in one of the driest regions of the world. The GCC area is characterized by extreme temperatures (reaching more than 50 °C during summer daytime), low and irregular rainfall (ranging from 70 to 150 mm/year), and high evaporation rates (>3,000 mm/year). This is aligned with an annual average per capita share of natural water resources of about 119 m^3, making the GCC countries among the lowest in the world and way below the absolute water scarcity limit (<500 m^3 per capita per year, compared to a world average of 6,000 m^3)[2] and will

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[2] Globally, 1,000 m^3 of water per person per year is considered the minimum amount to sustain life and ensure industrial development and agricultural production in countries where climates require

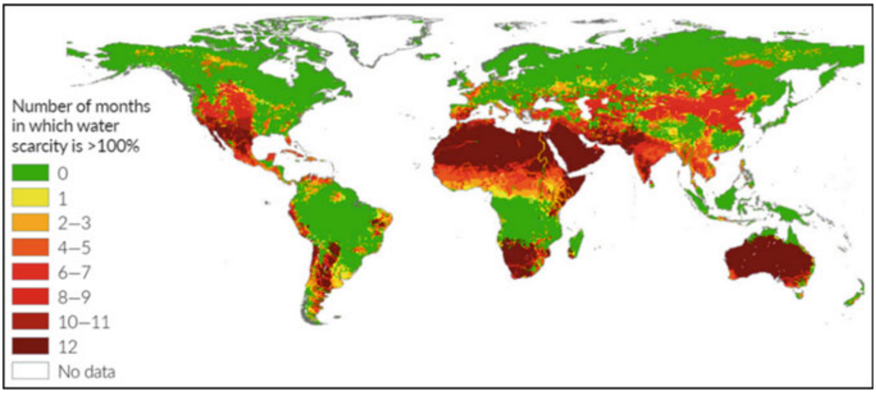

Fig. 2 Number of months per year where surface water and groundwater is withdrawn and not returned exceeds 1, at 30 × 30 arc min resolution (1996–2005) (UN WWAP 2017)

continue to decline because of the increasing population growth (Qureshi 2020; Parimalarenganayaki 2021). Figure 2 shows, on the world map, how many months per year water scarcity is > 100% (UN WWAP 2017). As can be seen, the Gulf region is characterized by water scarcity all year around. Moreover, it is evident that the climate is changing and rising temperatures are affecting the hydrological systems, like water availability and extreme events, which is expected to have an impact on communities, the environment, health, water supply, food security, human security, and economic growth (IPCC 2018).

On the other hand, the GCC total per capita water consumption is one of the highest in the world reaching about 800 m^3/capita/year (GCC-STAT data 2018), which is primarily attributed to wasteful consumption due to low water use tariffs resulting from government subsidies (Economist 2010). In addition, the per capita domestic water consumption is also considered very high, ranging from about 250 l/day (in Oman and Saudi Arabia) to more than 600 l/day (in Qatar and UAE) (Al-Zubari 2017). It should be noted that the value adopted internationally for basic human water needs is about 50 l/capita/day (Gleick 1996; Cosgrove and Loucks 2015). According to the World Health Organization (WHO), between 50 and 100 l/person/day is the optimal requirement of water to ensure basic needs, including drinking, personal sanitation, personal and household hygiene, food preparation, and washing clothes (WHO 2003a). People's feeling of this apparent water abundancy instead of real-water scarcity may arise from the expansion of constructing desalination plants and providing water all days of the year without interruption.

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irrigation, based on the Falkenmark index. This index is the most widely used tool for classifying the per capita available renewable water resources, in regions with no stress (>1,700 m^3), water stress (<1,700 m^3), water scarcity (<1,000 m^3), and absolute water scarcity (<500 m^3) per capita per year (Falkenmark 1986; Darwish et al. 2014; Gampe et al. 2016; Kummu et al. 2016).

Due to rapid population growth, expanded urbanization and industrialization, improvement in living standards, low water tariffs and governmental subsidies, relatively high distribution network losses, climate change, rising food demand, and agricultural policies of food self-sufficiency; the demand for water has dramatically increased in the past four decades in all the GCC countries (Al-Zubari 2017). As a food importing region, the GCC food imports constitute approximately 60–90% of the total food consumed (Economist 2019). Alpen-Capital (2019) indicated that about 85% of food consumption in the GCC region is imported, with 3.1% annual growth rate, and it reached USD 36.4 billion in 2015 and estimated at USD 53.1 billion in 2020 (Ben Hassen and El Bilali 2019). Moreover, a study for the MENA region (Droogers et al. 2012) expected that by 2041–2050, climate change would be responsible for 10% of the change in water demand and 22% of the water shortage. The study also revealed that there will be a 50% increase in water demand with a 12% decrease in water supply by 2050. Therefore, one of the greatest challenges facing the GCC countries is providing water to meet the domestic, agricultural, and industrial sector demands. In more detail, these challenges will be manifested in: (1) increasing pressure on the region's scarce and limited groundwater resources that are being depleted and whose quality is deteriorating due to over-exploitation; (2) heavy reliance on the energy-intensive desalination; (3) inadequate reuse of treated wastewater; (4) the import of virtual water via agricultural goods; and (5) the projected future impacts of climate change (Saif et al. 2014). It is important to point out that the report for climate change in the Arab Region (Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region [RICCAR]) indicated that the Arabian Gulf has moderate vulnerability to climate change, although remaining among the hottest areas in the Arab region and signaling rising temperatures, due to their financial capabilities (ESCWA 2017).

Under such conditions, it is expected that there will be an increase in the demand for water (i.e., groundwater and desalinated water), and treated wastewater has a great potential in supplementing the ever-growing water demand (Jasim et al. 2016). Wastewater reuse can be the predominant water supply for agriculture in the GCC countries, if treated properly and used safely. It will continuously increase with population growth and water consumption and can be considered as a renewable non-conventional water resource, especially because the agricultural sector is considered the largest consumer of water, accounting for more than 77% of the total water use (AQUASTAT data 2017) and is primarily met through the massive exploitation of groundwater (Fig. 3). This high percentage is caused by low irrigation efficiencies mainly resulting from the dominantly practiced traditional flood irrigation method, unmonitored groundwater abstraction, cultivating high-water consuming crops such as fodders, and lack of groundwater tariff in agriculture (Al-Zubari et al. 2017). Although wastewater reuse has started in the GCC countries in the early 1980s (Al-Zubari 1998), only small percentage of the large volumes of collected or treated wastewater is being reused, while the rest of both treated and untreated wastewaters is disposed to the coastal and marine environments, which represents a major lost opportunity under the GCC scarcity conditions. Additionally, the current wastewater

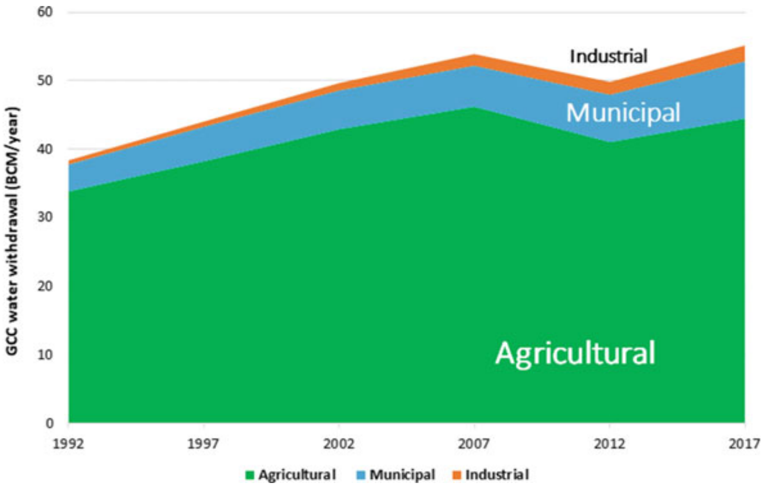

Fig. 3 Water uses in the GCC countries (AQUASTAT data 2017)

system is experiencing frequent hydraulic loadings due to lagging wastewater infrastructure behind that of the water supply, which is decreasing treatment efficiency and increasing insufficiently treated carryover volumes to the surrounding environment, negatively affecting biodiversity and threatening ecosystems. Likewise, most of the sludge generated during wastewater treatment ends up in landfills without any beneficial utilization, although it could be used in the production of energy or as fertilizers (Al-Zubari and AlAjjawi 2020).

Wastewater reuse can contribute to meeting this ever-increasing demand for water and closing the gap between demand and supply. Indeed, wastewater is regarded as a resource that is too valuable to throw away, especially in an increasingly water-scarce world. Moreover, the motivation for advanced wastewater treatment is not only providing an alternative water source when coping with water scarcity by reducing freshwater abstractions, but also conserving environmental quality by minimizing pollution, recycling nutrients, and increasing resource efficiency (UN WWAP 2017). Dr. Tedros, Director-General of WHO, stated that “Sanitation saves lives, but history teaches us that it is also one of the key building blocks of development” (WHO 2018).

This chapter aims to present the GCC’s current water resources status, outline the main benefits and constraints of wastewater reuse with a focus on its reuse in agriculture, with some recent examples. Then it explores the potential future contribution of wastewater in the Gulf region and ends with recommendations for the way forward.

2 Water Resources in the GCC Countries

Most of the land in the GCC countries is classified as arid to extremely arid, with harsh weather and is mostly desert. Due to low rainfall and high evaporation rates, they are poor in natural water resources and have very limited surface water (lakes and rivers), except for Saudi Arabia, Oman, and UAE. Surface water contributes to only 0.5% of the total GCC water supply (Fig. 4). Until the early 1970s, the GCC had relied on groundwater as the primary source for all their water requirements. Currently, water demands are being met by three sources: (1) Groundwater abstraction (traditional and heavily exploited); (2) Desalination (introduced in the 1950s and expanded rapidly in the 1970s); and (3) Treated wastewater (introduced in the early-1980s) (Al-Zubari 1998). In 2018, the total water resources used had reached 36 billion cubic metres (BCM), including 28.34 BCM from groundwater and surface water (most of the groundwater used is non-renewable), and 7.6 BCM of non-conventional resources (6.5 BCM of desalinated water and only 1.11 BCM of treated wastewater) (GCC-STAT data 2018). These water resources are used to meet the demands of three main sectors: municipal, agricultural, and industrial sectors. The water requirements for the agricultural sector, the main water consumer in the GCC countries, account for 77% of the total water budget. These are being met mainly by groundwater abstraction (94%) and are complemented by desalinated water (3%) and treated wastewater (3%). The main water resource for the municipal sector, the second main consumer (18%), is from expensive desalination (>74%) of seawater to satisfy almost all of its water demands and is complemented by small quantities from groundwater (26%). Lastly, the industrial sector's water needs (5%)[3] are met primarily by groundwater abstraction (96%) and desalination (4%). Water demands from these three sectors are expected to increase in the future.

The Gulf region has witnessed an escalation in water demand during the past years, with an annual increase of 10% (Dutch Economic Network 2018). The main drivers for this increase are rapid population growth, improved living standards, and the remarkable development of various economic sectors (industry and commerce) throughout the six countries. Moreover, the free or low-priced water supply causes people to waste water without considerable concern in the UAE (Yagoub et al. 2019) and this also applies to the other GCC countries. Figure 5 shows the rapid population growth associated with the growing water supply during the period 2012–2018. There are more than 56 million inhabitants across the GCC today (GCC-STAT data 2018), with an annual population growth rate for the period from 2011 to 2017 is nearly 3.1% (Statista 2021). As the population, living standards, and water-intensive lifestyle in the GCC continue to rise, more pressure will be added on their limited water resources and the demand–supply gap is going to further widen in the future. Wastewater reuse can provide a valuable opportunity that must not continue to be wasted, to supplement the water supply, and to minimize the disposal of this water to

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[3] It is important to note that this percentage does not account for the exact water utilization of the industrial sector, because the industrial sector relies on its own desalination plants.

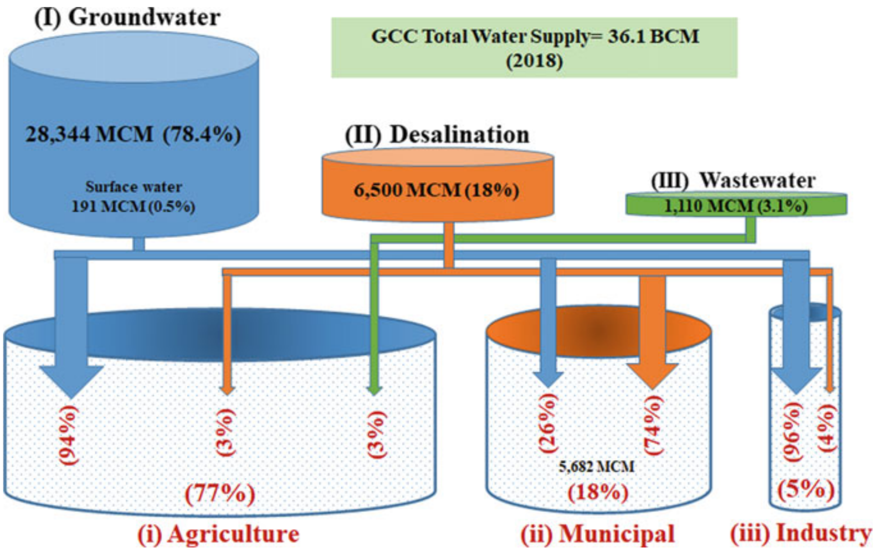

Fig. 4 GCC water resources: (I) Groundwater, (II) Desalination, (III) Wastewater (GCC-STAT data 2018), and GCC water uses: (i) Agriculture, (ii) Municipal, (iii) Industry (Al-Zubari et al. 2017) based on 2010/2012 data

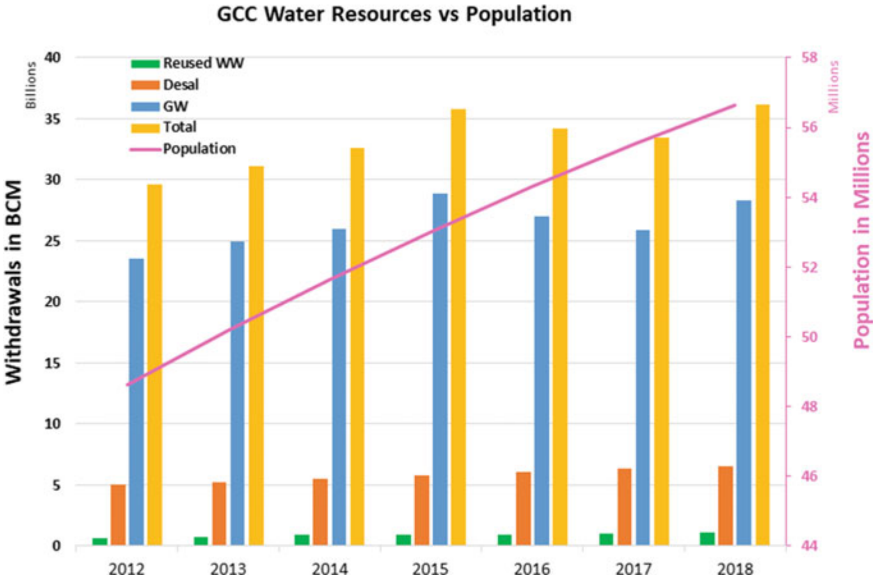

Fig. 5 Water resources (GCC-STAT data 2018) versus population (World Bank data 2020) in the GCC during the period 2012–2018

the environment without benefit. A detailed discussion of the GCC water resources is given hereafter.

2.1 Surface Water and Groundwater Resources

The GCC countries have surface water that is insignificant and cannot be relied on, except for the mountainous areas in Saudi Arabia, Oman, and UAE; it accounts for 0.5% of the total GCC water supply. The total surface water generated from rainfall, captured in dams and used, is estimated to be 191 million cubic metres (MCM) in 2018, of which 102 MCM/year are generated in Saudi Arabia, 89 MCM/year in Oman and UAE (GCC-STAT data 2018). Groundwater is the main source of water in the GCC that extends almost over all the six countries. Major shared aquifers include the Neogene Aquifer (Kuwait, Saudi Arabia, Iraq), Dammam Aquifer System (Bahrain, Saudi Arabia, UAE, Oman, Yemen), and Umm Er Radhuma aquifer (Bahrain, Saudi Arabia, Qatar). Groundwater resources in the GCC countries are classified into renewable resources and non-renewable (or fossil) resources. The renewable groundwater resources are relatively small depending on the rainfall events and surface runoff and mostly encountered in shallow alluvial aquifers, whereas the non-renewable resources are found in the deep aquifers and were formed thousands of years ago during the rainy Pleistocene and Pliocene geological periods. They cover about two-thirds of the Arabian Peninsula (Al-Rashed and Sherif 2000). Generally, it is believed that the status of aquifers depends on their renewability and storability, and that the main groundwater reservoirs are old and were recharged during the past pluvial periods. Owing to the absence of present-day recharge, sustainable development of aquifer systems is not feasible, so their exploitation must be carefully undertaken and must be within their safe yield (Alsharhan and Rizk 2020a).

All GCC countries are utilizing hundreds to thousands of times more groundwater than sustainable recharge would allow (Saif et al. 2014). The majority of groundwater resources in the GCC region, which are non-renewable, are being extensively mined and over-abstracted. The drive to achieve food self-sufficiency and maximum food production by providing generous subsidies had led to over-exploitation of these groundwater resources. While some countries were successful in achieving these goals, such as Saudi Arabia as it became the sixth largest wheat exporter in the 1980s, it was at the expense of its water resources. These agricultural policies coupled with inadequate water management had created an unsustainable water usage culture (Baig et al. 2020). Moreover, this had resulted in major groundwater depletion, while the remaining limited renewable groundwater resources are being over-abstracted beyond their replenishment rates, leading to reduction in the quantity and degradation in quality with high salinity levels due to significant saltwater intrusion (Al-Zubari 2017; Mohamed et al. 2021). During the period 2012–2015, the total groundwater recharge rate was estimated to be about 5.2 BCM (Table 1), while groundwater abstraction was estimated to be 19.8 BCM. Groundwater has been heavily over-exploited by amounts that considerably exceed their recharge rates,

Table 1 The conventional groundwater resources availability in the GCC countries, in MCM

	Groundwater (MCM)			
Country	Groundwater abstraction[a]	Groundwater Recharge[b]	Non-renewable reserve	Water Deficit from natural resources
Bahrain	103	110	Negligible	7
Kuwait	496	160	Negligible	– 336
Oman	1,215	900	102,000	– 315
Qatar	250	50	Negligible	– 200
Saudi Arabia	15,450	3,850	428,400	– 11,600
UAE	2,300	190	Negligible	– 2,110
GCC	19,814	5,260		– 14,554

[a] Groundwater abstraction average rates represent the years 2012–2015

[b] Recharge represents shallow alluvial aquifers; recharge to Kuwait and Bahrain aquifers occurs by the underflow from equivalent aquifers in Saudi Arabia and recharge is variable depending on the hydraulic gradient between the two countries. All indicated figures represent steady-state conditions (Al-Zubari et al. 2017)

resulting in a huge deficit ranging from nearly 15 BCM (Al-Zubari et al. 2017) to 20 BCM (Dutch Economic Network 2018). The large deficits in the GCC countries' water budget have not changed much since the 1990s, where it was around 13,436 MCM/year (Al-Zubari 1998), except for Bahrain that currently experiences no deficit in groundwater, mainly due to the major dependency on desalination. One of the key reasons for this unsustainable exploitation of groundwater resources is the existence of direct and indirect subsidies to well drilling, absence of monitoring metres and/or tariffs on groundwater pumping, increase of food demand, and unplanned agricultural expansion. Obviously, this has resulted in a significant decline in groundwater quantity manifested by water level drop, and quality levels represented by salinity increase, being suitable for domestic use in few areas and used mostly for agricultural activities. Such a situation necessitates an alternative approach.

2.2 *Desalination*

The massive imbalance between groundwater discharge and recharge, due to overpumping, is causing seawater intrusion and deterioration of groundwater. This deterioration, coupled with the prevailing freshwater scarcity condition that exists in the arid Gulf region, had forced the GCC countries to find alternative ways to satisfy the demand for freshwater. This is being met by investing heavily in non-conventional water resource, namely desalination. Desalination, both thermal and reverse osmosis (RO), was first introduced in the region in the mid-1950s (Al-Shuwaikh desalination plant in Kuwait to produce drinking water), and then increased considerably in the 1970s in all the GCC countries (Al-Mutawa et al. 2014; Alsharhan and Rizk 2020a).

The reason for the sudden expansion in desalination was the spike in oil prices that provided the required funds for water and energy infrastructure investments (Saif et al. 2014). Since then, desalinated water has proven to be a practical solution for the water-shortage problem for domestic and industrial water supply. However, desalination's relatively high cost is the main reason for not using produced desalinated water in the agricultural sector. Growing food needs water and energy at much higher price than the imported food available at the market. For instance, producing one kg of potato, which usually costs ~USD 1.5, will cost USD 3.5 when using water produced by thermal desalination (Darwish et al. 2014).

Currently, most of the freshwater demand for domestic (74%) and industrial (4%) sectors in GCC is met by desalination (accounting for 18% of total water supply) with a total capacity of 8.2 BCM in 2018 (GCC-STAT data 2018). The GCC is currently producing 5.75 BCM of desalinated water annually, from around 439 desalination plants distributed on the coast of the Arabian Gulf and inland (Qureshi 2020), which constitutes around 60% of the world's desalination plants (Mu'azu et al. 2020). Kingdom of Saudi Arabia (KSA) is the highest producer of desalinated water in the world, followed by the UAE (Ouda 2014). While UAE and KSA rely on desalinated water, to meet their municipal water supply by nearly 70 and 60%, respectively; Qatar, Kuwait, and Bahrain rely totally on desalination (Zekri and Al-Maamari 2020). So far, GCC countries have their own energy resources, i.e., oil and gas, needed for sea and brackish water desalination. However, desalination is an expensive and energy-intensive process accompanied by a significant environmental impact that is evident from the negative effects of desalination brine discharge on marine life, air pollution by gaseous emissions, as well as noise (Dawoud 2012; Yagoub et al. 2019). Moreover, given its high energy requirements, water produced by desalination is considered unsustainable, as natural gas prices and thus production costs increase, which necessitates an alternative approach (Kajenthira et al. 2012). Therefore, it is essential to lower the rate of desalination expansion to conserve the GCC countries' income of these non-renewable fuel resources and to save the environment (Darwish et al. 2009). One of the options to do this is to use renewable energy in desalination. Sustainable and long-term solutions are required to shift to renewable energy resources for saving energy and consumption of fossil fuels, something that has not been accomplished yet. Wastewater is another option that can provide cheaper alternatives than desalination, to be used at least for the agricultural and industrial sectors.

2.3 Wastewater

Treating wastewater, by building and running wastewater treatment plants (WWTPs), was introduced in the early 1980s in most of the GCC countries (Al-Zubari 1998). A correlation was found between the level of high per capita GDP and water treatment because of the higher demand for raising safety and water quality concerns (Liao et al. 2021). There has been a dramatic change in the reuse of wastewater. For example, Saudi Arabia banned importing some Jordanian fruits and vegetables, because of concerns about the use of wastewater in irrigation during the early 1990s (Lazaridou et al. 2019). However, the reuse of treated wastewater is currently receiving remarkable attention in the Gulf countries as a possible source to bridge the ever-increasing water demand–supply gap and to reduce the pressure on the fast-depleting groundwater and the energy-intensive desalination. Nearly 99% of the matter presented in wastewater is water, so treating and reusing this could be a more sustainable alternative than desalination or long distance water transfers (Kehrein et al. 2020). Great efforts were made in providing access to basic sanitation services and establishing many WWTPs.

As a part of implementing the objectives and indicators of the sixth goal of sustainable development goals (SDGs), almost 100% of the population benefit from improved and safe sanitation services (Indicator 6.2.1) in all the GCC countries (GCC-STAT 2021). Actually, this had started even before the SDGs, as the water decade (1981–1990) and the millennium development goals (MDGs) phase (2001–2015) also focused on safe water and sanitation for all. Specifically, treating wastewater and increasing its reuse (SDG 6.3.1), reducing the pressure on other water resources (SDG 6.4.2) that is groundwater in the case of GCC countries and eliminating the negative environmental impacts on the marine environment (SDGs 6.3.2 and 6.6.1) can be counted as an important incentive for considering the treatment and reuse of wastewater. Currently, by law, wastewater must be treated before reuse or disposal in the surrounding area in all the GCC countries to protect the people and environment from contamination. Saudi Arabia is currently operating modern treatment facilities with secondary and/or tertiary treatment capabilities for all types of wastewater such as domestic, industrial, and agricultural with the governmental decision (Alkhudhiri et al. 2019). In some countries wastewater is treated to advanced levels using ultrafiltration through the reverse osmosis, RO membranes, such as the Sulaibiya plant in Kuwait (Abusam and Shahalam 2013). The continuous increase in the treated wastewater flow, proportional to the growth in the population and municipal water supply rates, has encouraged the GCC countries to increasingly rely on treated wastewater as a non-conventional water resource besides desalination.

There are about 295 wastewater treatment plants in the GCC countries, most of them (102 WWTPs) are in Saudi Arabia, followed by 86 WWTPs in UAE, with mostly tertiary (activated sludge followed by disinfection) and advanced treatment capabilities. The total WWTPs designed capacity in the six GCC countries has expanded from 2.4 BCM in 2010 to about 3.7 BCM in 2018 (GCC-STAT data 2018). The majority of these WWTPs are centralized and are operated by the government, with fewer recently decentralized and run by the private sector. Treated wastewater is used to meet the non-potable water requirements such as agricultural production, landscaping, forestry, recreational, commercial, and industrial uses. However, its reuse is constrained due to health, religious, social, and environmental concerns. Wastewater can be used as long as its treatment meets the requirement for the intended use. Substantial research evidence exists that, after adopting proper management measures, treated wastewater can safely be used to grow food and forage crops under the agro-climatic conditions of the GCC countries (Qureshi 2020).

3 Current Status of Wastewater in GCC

While the produced volumes of treated wastewater have increased over the past three decades, their reuse has not reached its potential to contribute significantly to the water budget in the GCC countries. Currently, wastewater reuse accounts for only 3–4% of the water demands in all GCC countries, mainly in the agricultural sector. Table 2 displays the currently available capacities of wastewater treatment plants, collected, treated, and reused volumes of wastewater. In 2018, the total municipal water consumption was about 5,682 MCM and the total collected wastewater volume was 3,276 MCM (i.e., 57%). The total GCC-designed treatment capacity of the major WWTPs facilities was 3,730 MCM/year. The UN World Water Development Report (UN WWAP 2017) indicated that high-income countries treat about 70% of their generated municipal and industrial wastewater. Although the GCC rate of wastewater treatment of the collected rates is very high reaching more than 95%, only 35.6% (1,110 MCM) of these volumes are reused (GCC-STAT data 2018). The remaining unused treated wastewater are discharged unused to the sea, wadis, and artificial lagoons, especially on days with heavy rain because the rainwater drainage channels are connected to the wastewater network (KSA-MEWA 2018). Although there is a steady increase in the reuse wastewater as volumes, the percentage increase is lagging behind and is much less than the percentage increase in the collected and treated volumes, indicating the inadequate utilization of the potential of the treated wastewater. These figures indicate that wastewater reuse is still at its initial stages in the GCC countries. However, the expansion in utilization of the treated wastewater as a strategically alternative source to meet the GCC countries' future demands is one of the main strategic objectives and policies in the 2016–2035 GCC Unified Water Strategy (UWS) (Al-Zubari et al. 2017) as well as all their future plans. It is also part of the commitments toward some of the UN's Sustainable Development Goals by meeting a number of wastewater treatment and reuse objectives.

The average percentage of collected wastewater to generate municipal water is about 60% in the GCC countries. Analysis of wastewater volumes at the countries' level indicates that volumes of municipal consumption have increased dramatically in KSA and UAE in recent years (Fig. 6), and also the volumes of collected and treated wastewater are the highest in these two countries, followed by Kuwait and Qatar. Saudi Arabia, Qatar, UAE, and Oman are treating almost 100% of their collected wastewater, while Kuwait and Bahrain are treating 85 and 50%, respectively. The percentage of total wastewater reuse is the highest in UAE, with a volume of 513 MCM in 2018 representing 70% from collected wastewater, followed by Oman (64%), Qatar (59%), Bahrain (55%), Saudi Arabia (18%), and finally Kuwait with only 15%. In addition, the percentage of treated wastewater share in the total water budget is currently 15% in Qatar and 10% in Bahrain and UAE. The increasing reuse gives an indication of a higher level of awareness about the importance of this resource to minimize the depletion of groundwater in particular, and to reduce the fast rate of the loss of agricultural lands due to the salinization of groundwater.

Table 2 Annual total GCC wastewater collection (compared to municipal consumption), treatment and reuse volumes (in MCM), WWTPs design capacities, and percentages of collection, treatment, and reuse (GCC-STAT data 2018)

Year	Municipal consumption (MCM)	WWTPs design capacity (MCM)	Collected wastewater (MCM)	Treated wastewater (MCM)	Reused wastewater (MCM)	% Collected to municipal generated	% Treated to collected	% Reused to treated
2011	4,167.3	2,925.1	2,174.5	2,036.3	697.6	52.2	93.6	–
2012	4,409.5	2,943.1	2,410.6	2,259.8	681.3	54.7	93.7	30.2
2013	4,697.7	3,253.7	2,576.1	2,428.9	724.6	54.8	94.3	29.8
2014	4,903.8	3,300.0	2,823.2	2,652.5	879.9	57.6	94.0	33.2
2015	5,089.7	3,413.4	2,918.6	2,777.6	884.5	57.3	95.2	31.8
2016	5,171.3	3,548.3	3,112.5	2,977.3	907.2	60.2	95.7	30.5
2017	5,406.6	3,664.8	3,101.5	2,912.4	1,010.8	57.4	93.9	34.7
2018	5,682.7	3,730.5	3,276.7	3,119.5	1,110.3	57.7	95.2	35.6

Considering that lagging wastewater reuse plans will intensify financial, economic, and environmental burdens, the GCC countries have prepared ambitious plans to expand the reuse of treated wastewater as a strategic alternative resource, especially in the agricultural sector, to reduce groundwater stress and replace the deteriorating groundwater. A National Water Strategy 2030 was developed in both Saudi Arabia (2018) and Bahrain (approved recently in February 2021) that recognized treated wastewater as one of the main water sources. Moreover, Saudi Arabia's Vision 2030 identified treated wastewater reuse as a sustainable source to diminish the water demand–supply gap and also, in a complete shift in water management policy regarding wastewater reuse, the government targets privatization of its major WWTPs and achieving 100% of reuse for agricultural and other purposes in the near future (Ouda 2016; Mu'azu et al. 2020). About 120 MCM in the city of Riyadh (50% of its treated wastewater) had been used for various applications, including agriculture, recreational and ecological, landscaping activities, and industrial and groundwater recharge. It is predicted that reuse of municipal wastewater will increase in Saudi Arabia to reach 5,090 MCM by 2050 (Alkhudhiri et al. 2019). It is worth noting that this amount is more than the annual surface water volume received by Saudi Arabia (2,400–3,700 MCM). Similar strategies for increasing wastewater utilization exist in other GCC countries, such as the 4th phase of expansion in Tubli WWTP in Bahrain that will be able to double its average daily flow capacity and it is expected to be completed in 2022 (Al-Zubari et al. 2017).

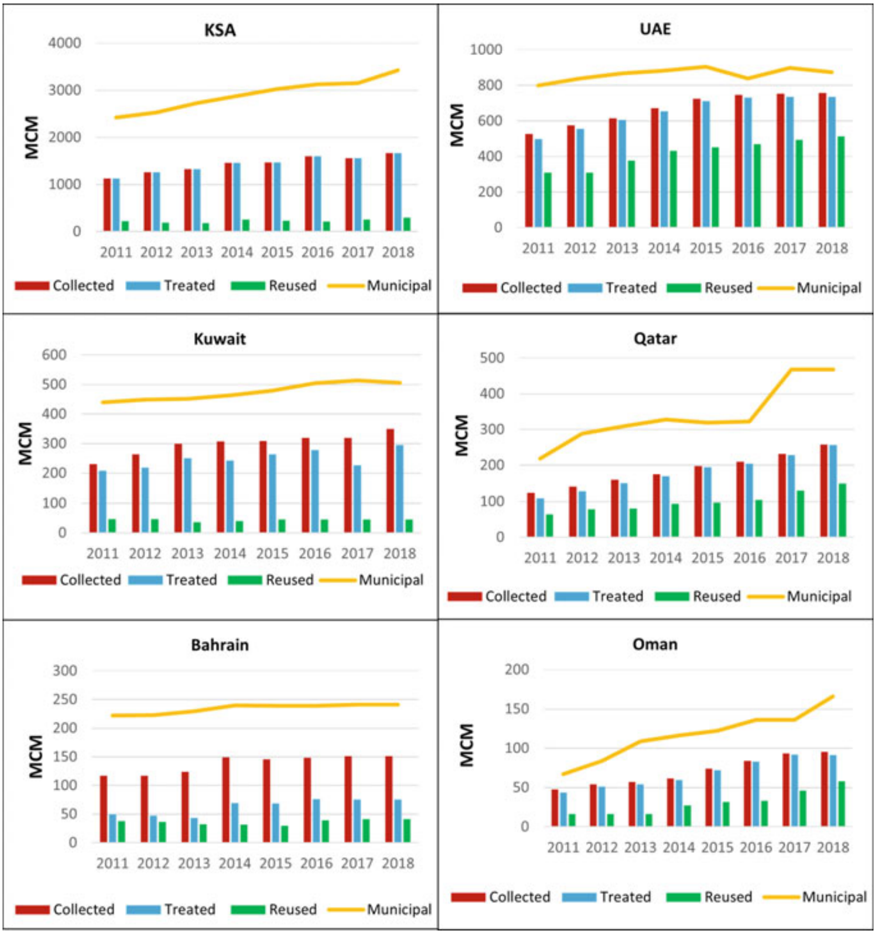

Fig. 6 Municipal consumption (line), wastewater collection, treatment, and reuse volumes (bars) in each GCC country (GCC-STAT 2018). KSA: Kingdom of Saudi Arabia, UAE: United Arab Emirates

4 Major Benefits of Wastewater Reuse

It is a major challenge to recognize the significance of treated wastewater as an important water resource. Despite some constraints that must be carefully managed to protect the public and environmental health, which will be discussed in the next section, there are various environmental, social, and economic benefits from reusing treated wastewater for non-potable purposes (Shoushtarian and Negahban-Azar 2020). FAO (2010) stated that recycling of wastewater is a major link in Integrated Water Resource Management (IWRM) and considered as a "win–win" situation, in which many different aims can be achieved, that is a solution to water demand, while additionally providing the agricultural and environmental advantages outcomes. Simultaneously, this can benefit several stakeholders: urban authorities, farmers, and the environment. Furthermore, using wastewater in irrigation can make a substantial contribution in lessening stresses of water demand by reducing the need to pump groundwater, adding/recycling nutrients, increasing crop yields, enhancing soil microorganism activities and soil health conditions, and avoiding pollutants to be disposed into the environment. In addition to energy savings and economic savings resulting from saving fertilizers and from avoiding desalination production and groundwater abstraction, reducing the carbon footprint, and contributing toward climate change adaptation and mitigation (Dery et al. 2019; Lazaridou et al. 2019). What follows is a brief discussion of the main benefits of the wastewater reuse in the GCC countries.

4.1 Matching Demand and Promoting Agriculture

The reuse of treated wastewater can be an important substitute for freshwater, creating supply-side benefits, protecting groundwater resources, and offering an additional source of water. With increasing water consumption, because of rising population and urbanization, the amount of domestic wastewater generated is expected to increase proportionally, providing additional water volumes that can match the rate of development. Due to quality considerations, this non-conventional water resource can be used especially for irrigation of agricultural lands and in industry, reserving freshwater resources for priority uses, reducing pressure on the deteriorating groundwater, and helping alleviate water scarcity in the GCC region. Complete reuse of treated wastewater can substantially reduce the country's reliance on costly desalinated water and depleted groundwater, to be used for wider purposes (Alkhamisi and Ahmed 2014).

Since agriculture is completely dependent on irrigation in the GCC countries, which consumes nearly 80% of the total water demands, reusing treated wastewater can help in expanding agriculture, diminishing the imbalance between available water resources and the need to grow more food. This can result in promoting projects that can contribute to economy investments in the agricultural sector, creating job opportunities, and can significantly improve the food security situation (Qureshi 2020).

4.2 Environmental Benefits

The UN world water report (UN WWAP 2017) indicated that over 80% of wastewater globally is discharged to the environment without treatment. Produced wastewater should be treated, due to environmental considerations, irrespective of whether or not it is going to be used. Reuse is a better option than disposal from economic and environmental perspectives to minimize contamination and reduce the environmental footprint of wastewater treatment. However, large portions (>2 BCM) of treated wastewater in the GCC countries are discharged into the sea, representing about 40% of the total groundwater recharge rate in the region. Saudi Arabia discharges >1.3 BCM of treated wastewater, this is over 60% of the total amount of treated wastewater in the GCC countries, next is Kuwait with >300 MCM, UAE (>245 MCM), Qatar and Bahrain (>100 MCM) and less than 40 MCM are being discharged to the sea and wadis in Oman (GCC-STAT data 2018).

In addition, Hanjra et al. (2012) indicated that wastewater reuse in agriculture can contribute toward climate change adaptation and mitigation by saving fertilizer use, preventing mineral fertilizer extraction from mines, and savings in energy which would reduce the carbon footprint.

4.3 Economic Benefits

By 2030, the energy consumption for producing water and recycling in the GCC countries will have tripled (Qureshi 2020). However, in comparison with desalination, it is more economical to reuse treated wastewater than produce costly desalinated water, because it is less expensive and consumes less energy (Jasim et al. 2016). The electricity demand for desalination in the MENA region (of which 70% is in Saudi Arabia, UAE, Kuwait, Algeria, and Libya) is expected to reach 122 terawatt-hour (TWh)[4] by 2030, three times higher than in 2007 (Al-Saidi and Saliba 2019). In Saudi Arabia, about 3.7 million barrels, or 30% of daily crude oil production, were consumed in 2018 for power generation, transportation, and operating desalination plants (Mu'azu et al. 2020). In the near future, the use of thermal desalination may become unsustainable since energy prices increase to represent production costs. Darwish et al. (2009) warned that more than one-tenth of oil production in Kuwait was used in the desalination plants in 2003 and that this number is almost doubling every 10 years. If this trend prevails, the country's total production of oil (or total Kuwait's income) will not be sufficient to desalt seawater for providing drinking water for its population in about thirty years, assuming constant oil production and water consumption trends. This trend in energy consumption is growing with alarming rates in all the GCC countries and is threatening the main source of income of these countries.

Typical market prices for desalinated water, based on fossil fuels, range between USD 1 to 2/m^3 for RO and thermal desalination plants. This can fall to be as low as USD 0.5/m^3 for large-scale plants, referring to economies of scale, when the capacity of the plant reaches $\gtrapprox$100,000 m^3/day (IEA-ETSAP and IRENA 2013; Zotalis et al. 2014). However, in Qatar, the actual cost rose above USD 3/m^3 (electrical cost USD 0.12/kWh and energy cost USD 2.4/m^3). Moreover, the total GCC energy cost for thermal desalination in 2012 was USD 1.552 billion. Meanwhile, the treatment of

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[4] Terawatt-hour (TWh) is a measure of electrical energy, equals one trillion (10^{12}) watt-hours.

wastewater is far less costly. While costs vary according to quality, treating one m^3 of wastewater in Kuwait to potable water quality using advanced levels through ultrafiltration and RO, costs about USD 0.66, which is one-third of the cost of thermal desalination (Darwish et al. 2014). Furthermore, the estimated cost of tertiary and secondary wastewater treatment is USD 0.317 /m^3 and 0.067 /m^3, respectively (Aleisa and Al-Zubari 2017). In Bahrain, tertiary treatment of wastewater costs USD 0.53/m^3, its collection costs USD 0.4/m^3, and its distribution reuse costs USD 0.13–0.27/m^3. Kajenthira et al. (2012) indicated that reusing treated wastewater had resulted in saving USD 225 million, in six main cities of Saudi Arabia, and conserving 2% of Saudi Arabia's annual electricity consumption and 29% of total water withdrawals, as well as reducing CO_2 emissions by 1.75 billion kg CO_2. Recently, Thakur et al. (2020) reported that microalgae would be a promising treatment technology in the future, reducing the energy cost.

With respect to the wastewater nutritional value, economic savings resulting from providing higher levels of nutrients to soil and plants will reduce the need for additional chemical fertilizers, in terms of nitrogen and phosphorus (Dery et al. 2019). In fact, lowering the treatment level decreases fertilization needs and costs due to the increased levels of available nutrients left in irrigation water (Alkhamisi and Ahmed 2014). This is beneficial particularly for the soils in the GCC countries, which have a sandy texture and are deficient in organic matter and/or nutrients. Thus, using treated wastewater in irrigation will increase the economic return to farmers and farming productivity, providing another incentive for agricultural reuse.

4.4 Other Benefits

Treated wastewater can also be used in other sectors such as the industrial sector, or for enhancing groundwater storage by artificial recharge. Groundwater artificial recharge, using surplus tertiary treated wastewater, can reduce declining groundwater levels and reduce seawater intrusion. However, such reuse needs risk assessment and management studies to prevent the migration of treated wastewater to groundwater wellfield used for drinking water supply, which is site-specific. In addition, this requires the determination of safe injection locations for ensuring the removal of pollutants or pathogens in the underlying geological formations, if they exist (WHO 2003b). In fact, after some time (<400 days), a natural self-treatment process, termed soil aquifer treatment (SAT), can occur to the recharged treated wastewater, with a low spending of energy and a low carbon footprint (as result of aquifer natural processes and gravity flow). However, aquifer adequate thickness, lateral distance, and slope are required for natural treatment to occur (Missimer et al. 2012).

In Australia, a recent study on groundwater recharge (Vanderzalm et al. 2020) demonstrated that total nitrogen removal reached 40 to 60%, with 95% removal for ammonia, and total phosphorus removal was also observed to be around 90%, after 18 months from injecting two cycles of treated wastewater. Similar studies were performed in the Gulf region, particularly in Saudi Arabia and Oman. In Saudi

Arabia, wadi aquifers showed to have a major role in additional treatment, storage, and recovery of wastewater when required for areas in demand, i.e., aquifer recharge and recovery (ARR) (Missimer et al. 2012). Moreover, treated wastewater from Salalah WWTP was recharged/injected through several tube wells along the coast of Oman, and this increased the level of groundwater and reduced the intrusion of seawater from 3.4 to 2.7 km, pushing back the saline zone by 700 m (Shammas 2008).

Generally, treated wastewater can be used in the industrial sector since they do not require high-quality water. In 2009, oil refining and natural gas processing sectors were responsible for almost 40% of water withdrawals in Saudi Arabia. Riyadh Refinery can be considered as one of the best case studies of reusing secondary treated wastewater, rather than desalinated water, by the industrial sector in the GCC countries. Rather than relying on desalination, this refinery substantially reduced the water withdrawals from 12,200 m^3/day to 3,800 m^3/day, by the reuse of wastewater, reducing the cost by half and using 66% less energy compared to reverse osmosis desalination (Kajenthira et al. 2012). The case study also indicated that if similar water reuse measures are applied for all other refineries in Saudi Arabia that rely on desalinated seawater, this would save approximately 199 MCM annually, as well as savings of about USD 105 million annually, and lowering energy consumption and CO_2 emissions by 1.79 billion kWh and 1.75 billion kg CO_2, respectively. Moreover, industrial wastewater is also being treated and reused in the GCC countries. For example, Qatar Gas, the world's largest natural gas company, has increased its wastewater recycle rate to 70% (Jasim et al. 2016). Moreover, another success story is the Gulf Petrochemical Industries Company (GPIC) in Bahrain, with total water needs of 341 MCM/year, approximately recycle 66% of the total water used in the operations and the rest of the water requirements are met by the desalination unit (VNR 2018). Unfortunately, there are not many data on the use or treatment of industrial wastewater.

5 Major Constraints of Wastewater Reuse

Although treated wastewater reuse is valued as a strategic opportunity in increasing agricultural water supplies, a number of bottlenecks limit its full utilization in the GCC countries. These include social (public attitudes, reliability), health and environmental (quality of produced treated wastewater by adopting standards for reuse), and economic considerations (transportation and cost recovery), which should be considered in any reuse strategy. The following are the details of the main constraints for reusing treated wastewater in the GCC countries.

5.1 Public Acceptance

The success of planning, implementing, and attaining long-term wastewater reuse programs depends primarily on the acceptance and readiness of the public as one of the major stakeholders, especially the potential end-users for accepting reusing treated wastewater as an alternative water resource. Therefore, it is extremely crucial to explore people's attitudes and identify the factors affecting their perception, such as age, educational level, knowledge, gender, income, religious views, culture, emotional or psychological disgust, trust, health risk perception, treated wastewater quality, residential location, willingness for paying for various purposes, and many other factors (Zimmo and Imseih 2010; Fielding et al. 2018). Understanding the factors is vital for developing effective stakeholders' engagement in wastewater reuse programs and achieving the country's reuse targets (Dolnicar et al. 2011).

Logically, higher education and more basic knowledge about water scarcity threats, water production and supply costs, cleanness of wastewater treatment, and the benefits of reusing treated wastewater are associated with higher acceptance (Garcia-Cuerva et al. 2016; Akpan et al. 2020). However, this can differ between countries. Public acceptability of reusing treated wastewater has started to increase among the farmers in most of the GCC countries (Alkhamisi and Ahmed 2014). Abdelrahman et al. (2020) concluded that the majority of respondents in a survey, from 1304 UAE residents, supported the use of treated wastewater in irrigation, irrespective of their educational level, age, and income. This positive perception was observed in the UAE for outdoor activities that do not involve physical contact (Cristóvão et al. 2012). Public acceptance and willingness to implement reuse projects in the UAE are highly connected with the grade of awareness of water scarcity in the country (Kretschmer et al. 2000). Moreover, a study in Kuwait with 75% of respondents did not object to use the reclaimed water, from the advanced Sulaibiya WWTP, for agricultural irrigation, car washing, and domestic cleaning. However, 78, 77, 60, and 52% refused this water to be used for cooking, drinking, showering, and clothes washing purposes, respectively, even the ones that possessed enough knowledge, regardless of its quality and cost (Alhumoud and Madzikanda 2010). Ouda (2013) indicated that the majority of the community in Saudi Arabia is unaware about water production and distribution costs, water shortages, and water resource problems. Furthermore, a survey for studying public attitude toward wastewater reuse practices (Alataway et al. 2011) on 400 consumers in two main agricultural cities in Saudi Arabia, namely Al-Hassa and Tabouk, concluded that Al-Hassa residents were more supportive than those in Tabouk. The reason attributed to that experience or familiarity with wastewater reuse, i.e., in Al-Hassa, reduced the level of people's concern.

Some studies showed that acceptance was low with great opposition among people other than farmers, which poses a serious challenge toward efficient and sustainable reuse of treated wastewater. For instance, Dare and Mohtar's (2018) study revealed that the preference in Qatar was for fresh or desalinated water rather than treated wastewater in agriculture, as a result of being a wealthy country with high living standards. In addition, consultations with Qatari experts indicated that most people view wastewater unsafe for reuse in agriculture, and they also feel oversight and monitoring were insufficient. In Saudi Arabia, a recent study (Mu'azu et al. 2020) was conducted on 624 households to assess public perceptions investigating the socio-demographic variables influencing the reuse of wastewater and recycling of greywater for non-domestic uses, such as firefighting, swimming pools, and car washing. The results indicated that the acceptance of reusing treated wastewater, even among educated people, was low even after treatment no matter what the treatment level was and regardless of the technologies employed. However, the study indicated more acceptance of greywater recycling. The study indicated that the reasons behind this were psychological repugnance and the relatively large subsidy for freshwater supplies. It concluded that key factors for the success of large-scale adoption of treated wastewater are high literacy rate, intensive awareness campaigns for changing behavior, and the capacity for detecting pollutants and germs in the reused wastewater.

There are some indications that public awareness toward wastewater is changing positively with time in the region. For example in Bahrain, a relatively old study assessed the public's knowledge toward wastewater along with public attitudes of reuse and revealed that most of the surveyed individuals were not aware of the simple basic aspects concerning wastewater (Madany et al. 1992). The respondents strongly opposed using reclaimed water regardless of their conditions and were willing to pay in order to avoid using it. Another study, nearly twenty years later, showed that the psychological factor became the main barrier to not using treated wastewater, after the health risk factor, which means greater confidence in the efficiency of the wastewater treatment technology and its ability to eliminate microbes. Despite this, the psychological factor remained a major obstacle to the utilization of this water resource, and this was not related to gender or age, but it was often related to the level of education. This rejection decreased whenever the use was far from the human body, as in irrigating freshly eaten vegetables and gardens as well as in industry. It was also found that most of the individuals are still willing to pay more to avoid using treated wastewater under any circumstances (Al-Malood et al. 2010).

Most likely, religion is one of the main reasons for opposing the use of treated wastewater, especially in the GCC countries. Many are unaware that Islam does not contradict reusing wastewater, provided that it presents no health risk and will not cause harm (Faruqui et al. 2001) and the Quran indicates that impurities in water can be diluted to be made more pure (Wilson and Pfaff 2008). Indeed, Islam is supporting the preservation of water cleanliness and this advocates capturing, treating, and reusing wastewater (Amery and Haddad 2015). In 1978, a fatwa (Islamic juridical declaration) had been issued by Scholars of Islam in Saudi Arabia stating: "Impure wastewater can be considered pure water and similar to the original pure water, if its complete advanced treatment is capable of removing impurities with regard to taste, color and smell, as witnessed by specialized, knowledgeable and honest experts. If there are negative impacts from its direct use on human health, then it is better to avoid its use, not because it is impure but to avoid harming human beings." This fatwa lessened any religious concerns and paved the road of reusing treated wastewater in Saudi Arabia, Gulf, and Islamic countries (Ouda 2016; Dare and Mohtar 2018).

In order to make farmers and all people rethink the different aspects of wastewater and raise their acceptance toward reuse practices; awareness and education programs are needed (Dawoud 2017) to improve their knowledge of the capabilities of treatment methods and accurate detection of pollutants before reuse (Mu'azu et al., 2020). In addition, gaining public trust by assuring the good quality of treated wastewater (Alsharhan and Rizk 2020b) and establishing a technical guiding framework for implementing reuse programs are needed to reduce public concerns and guarantee reliability or steadiness of continuous supply of treated wastewater. Moreover, applying economic tools, such as tariffs, on the heavily subsidized current freshwater supplies (i.e., groundwater and desalinated water) would help convince users to accept treated wastewater and in achieving the target of full reuse of wastewater (Qureshi 2020).

5.2 Environmental Health Concerns: Standards and Regulations

While wastewater has numerous positive economic, environmental, and security benefits, and contributes considerably to decreasing the burden on the threatened groundwater, its reuse remains subject to physical, chemical, and biological restrictions and concerns. Risks to human health and environmental quality are a serious bottleneck for reusing wastewater in agriculture (Kehrein et al. 2020). Wastewater treatment is designed to eliminate long-term chemical risks, such as suspended solids, dissolved and particulate organic matter, nutrients (mainly nitrates and phosphates), and heavy metals and immediate microbial risks. Regulating wastewater reuse and discharge depends on microbiological and physical–chemical standards. Poor treatment and inadequate management guidelines can result in pollution with microbial pathogens and toxic chemical components, even if discharged to the environment without reuse affecting marine organisms and mangroves. Therefore, it is critical that wastewater effluents are effectively treated, and then monitored to ensure a safe supply and reuse.

In order to ensure the safe use of wastewater for workers as well as consumers, sanitation standards and health guidelines within the requirements of the WHO must always be followed (WHO 2018). All GCC countries are strictly following national and international low-risk guidelines and quality standards, based on high technology and high-cost approach, (e.g., California and USEPA standards) to eliminate those impacts. The quality of treated wastewater is typically defined in terms of its regulations set (Alkhamisi and Ahmed 2014). Table 3 shows the guidelines for wastewater reuse in agriculture in GCC countries for restricted agriculture. These standards and regulations outline the degree of wastewater treatment levels and the irrigation methods to determine the compatibility of reuse in crop production (Lahrich

Table 3 Standards of reuse of treated wastewater for restricted irrigation in the GCC countries

GCC country	Chemical and Microbial parameters											
	pH	Turbidity	TDS	TSS	BOD	COD	NH_4	NO_3	Phosphate	Fecal Coliforms	*E. coli*	Helminth eggs
		NTU	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	Count/100 ml	Count/100 ml	Egg/L
Bahrain[a]	6.5–9	2	3,500	10	10	40	1	10	1	<1,000	<2.2	<0.1/1000
Kuwait[b]	6.5–8.5	–	1,500	15	20	100	15	–	30	400	20	<1
Oman[c]	6–9	–	2,000	15	15	150	5	50	30	200	70	<1
UAE[d]	6–8	5	2,000	20	10	150	–	–	–	<1,000	–	<1
Qatar[e]	6–9	2	2,000	50	50	150	1	–	30	0	–	<1
Saudi Arabia[f]	6–8	5	2,000	10	10	50	5	10	1	1000	23	1

Data Sources [a](Government of Bahrain, 2020); [b](Abusam and Shahalam 2013); [c](Baawain et al. 2012); [d](Dalahmeh and Baresel 2014) representing Abu Dhabi; [e](Darwish et al. 2015); [f](Al-Jasser 2011) et al. 2021), in order to be free from health hazards. However, inadequate operational experience, high operational and maintenance costs, regulatory control, limited monitoring and evaluation of wastewater quality, and overlapping roles of organizations involved in the collection, treatment, monitoring of quality, and public health protection may have adverse effects and sometimes restrict its use in agriculture in the GCC countries (Qureshi 2020).

In arid and semi-arid zones, salinity can be considered the most significant environmental risk and heavy metals are a potential health risk (Elgallal et al. 2016). In Bahrain, infiltration into the old wastewater collection or distribution infrastructure network by shallow water levels resulted in increased salinity levels of the produced treated water, affecting the suitability of its reuse (Al-Zubari et al. 2017). The risk of heavy metals accumulation in soil could also be critical under the prevailing alkaline soil conditions in the GCC, increasing the probability to be immobilized and exceeding the maximum allowable limits (Al-Zubari 1998). Therefore, it is important that industrial wastewater, as a source of heavy metals, be kept separately and prevented from entering or mixing with domestic wastewater network, affecting the efficiency of treatment and eventually reuse.

The occurrence of diseases, caused by pathogens particularly bacterial (as fecal coliforms and *E. coli*), helminth eggs, protozoa, and viral pathogens can be associated with wastewater. Research conducted in UAE (Khan and Dghaim 2016) examined the risk of contamination from microbial pathogens of four public parks in Dubai irrigated by treated wastewater. Most of the tested samples (total 96 samples) were found contaminated with bacterial indicators and protozoan parasites. The study results indicated that microorganisms are surviving in treated wastewater, soil, and in the irrigation network system, and recommended that further monitoring of treated wastewater at the point of end use is vital to avoid the risk from microbiological contamination. In Bahrain, helminthic infections had posed a great risk that prevented the authorities from distributing treated wastewater to farmers (WHO 2004). Moreover, emerging concerns, of pharmaceuticals, antibiotics, disinfectant by-products, and personal care products in wastewater pose an additional threat (Jasim et al. 2016) and should be studied and considered carefully in the design of WWTPs (Ouda 2016).

Additionally, the COVID-19 pandemic, caused by coronavirus (SARS-CoV-2) spread, has also raised several concerns and revealed the world's under-preparedness to tackle incidents of disease outbreaks. The COVID-19 outbreak, emerged in China, was declared by the World Health Organization (WHO) in March 2020. This pandemic had caused turbulence to the GCC economies and major downfall in oil demand across the globe (Al Rashdi et al. 2020). The pandemic had led to the emergence of a number of previously unexperienced risks, affecting the water supply and wastewater sectors in an exceptional way and highlighting the importance of sufficient safe water supply, proper sanitation, and sound Water, Sanitation, and Hygiene (WASH) services, along with awareness, as necessary issues to reduce the spread of the SARS-CoV-2 virus. To combat the COVID-19 virus and limit its spread, all the GCC countries had implemented partial and/or complete curfews, by closing many sectors including governmental, educational, industrial, and commercial, or at least restricted their operations and to continue their responsibilities from home. These conditions had affected the water supply, the volume of generated wastewater and altered the peak periods of both. To overcome the challenges and mitigating risks associated with the pandemic, the GCC Secretariat General conducted several virtual workshops. Personal attendance of workers in the water supply and sanitation sectors was considered essential, allowing them to go to work during curfew hours. Moreover, shortage of spare parts and chemicals, due to the closures of borders, had a direct impact on the operation and maintenance of water supply stations and wastewater systems in terms of capacity and quality. In response, some GCC countries have begun to increase their dependence on locally produced materials or materials produced in other GCC countries (Al-Zubari and Al-Rashidi 2020). This indicates the significance of localizing the water technologies, wastewater besides the desalination, at least spare parts, in the region.

The virus cannot only affect the respiratory system, but also the gastrointestinal tract. Recently, several studies reported the existence of the genetic material, ribonucleic acid (RNA), of the virus in wastewater treatment plant samples. Research on the removal of coronavirus in municipal and hospital wastewater, by disinfection technologies, is required to reduce the risk associated with the virus. Lack of a standardized protocol for detecting SARS-CoV-2 in wastewater is a crucial challenge because there is limited knowledge on how to do this efficiently. However, no additional measures specific to COVID-19 were recommended by the WHO. Tertiary or advanced treatment with the final disinfection step, such as chlorine, ozone, and ultraviolet light should be used to produce water free of viral pathogens (Lesimple et al. 2020; Lahrich et al. 2021). The only concern in the GCC countries is about the safety of the workers in the WWTPs, since wastewater is treated at the tertiary level before being reused, and this needs precautions that later became standard practices, as wearing appropriate personal protection equipment (PPE); frequent applying hand hygiene; avoiding touching their faces; and practicing social distancing (Al-Zubari and Al-Rashidi 2020).

It is important to mention that the use of wastewater as a tool to detect COVID-19 prevalence, known as wastewater-based epidemiology (WBE), is not widespread, but it is beginning to expand. The presence of SARS-CoV-2 RNA in municipal wastewater may predict the virus occurrence qualitatively and quantitatively. This has the potential to give an alert and an early sign to monitor COVID-19 spread within a community, if the virus rises above the threshold, allowing for quicker action and containing the infection before its spread at an alarming rate (Al Huraimel et al. 2020; Mandal et al. 2020). A few articles reported a correlation of the viral genetic material concentration in wastewater with the number of COVID-19 confirmed cases. The United Arab Emirates was the first Arab country to detect SARS-CoV-2 in wastewater samples (Albastaki et al. 2021; Hasan et al. 2021). A large number of municipal wastewater samples (2940) and aircraft wastewater samples (198) were tested in the Albastaki et al. (2021) study, and the results showed a direct correlation between cases of COVID-19 recorded in Dubai and the viral load. It is important to point out that eleven WWTPs influents in UAE tested positive for SARS-CoV-2 on different dates, however, none of the 11 WWTPs effluents tested positive during the entire sampling period, indicating that wastewater treatment is efficient in removing the virus, and confirming the safety of reusing treated wastewater (Hasan et al. 2021).

These constraints could be minimized by risk assessment where barriers are added to reduce both the possibility and severity of contamination. Treated wastewater should be used for irrigation under controlled conditions after ensuring no health risks arising from potential pathogenic and toxic pollution to the users, agricultural products, soils, surface, and groundwater (Alkhamisi and Ahmed 2014). In addition, developing a framework on wastewater, which highlights the implementation of sanitation safety plans that minimize the risks of reuse and enhance the trust in treated wastewater, is urgently needed and essential, to secure the long-term sustainability of the system.

5.3 Economic Constraints

Although most of the central cities in the GCC have WWTPs generally built near the residential domestic areas to reduce the infrastructure cost of transferring the untreated wastewater to those WWTPs, their established infrastructures do not cover all of the expanding areas, especially in the big areas of Saudi Arabia and Oman. WWTPs are sometimes far away from the agricultural areas and transportation costs of treated wastewater to the crop production areas could be an economic constraint. For example, the Al-Ansab treatment plant, the largest wastewater treatment plant in Muscat, Oman, is about 100 km from Al-Batinah agricultural area where the treated wastewater is needed, and Sulaibiya WWTP in Kuwait is about 120 km far from Al-Abdali agricultural area. Along those distances, treated wastewater is transferred through pipes and may have to be stored (Abdul-Khaliq et al. 2017). In response to the high transportation costs, there has been a growing emphasis on the potential advantages of adopting “decentralization approaches” to sanitation management, which are believed to be appropriate for peri-urban areas (areas with a mix of rural and urban characteristics and land uses). This will offer opportunities for wastewater reuse and also offer increased improvements in the environmental health conditions (Parkinson and Tayler 2003; Capodaglio 2017), and most importantly, has a considerable security effect.

There is a growing trend toward decentralization worldwide and large-scale centralized wastewater treatment systems may no longer be the best option for urban water management. Recently, GCC countries have moved to the decentralized wastewater system (Al-Zubari and AlAjjawi 2020). They allow for the recovery of nutrients and energy, save freshwater, and help secure access to water in times of scarcity (UN WWAP 2017). Internal decentralized treatment facilities in different industries will reduce the pollution load to domestic WWTPs, and then they can use their own treated wastewater, principally in cooling, sand washing, and construction purposes (ACWUA 2010). A study in Saudi Arabia (Kajenthira et al. 2012) indicated that the potential for expanding urban wastewater reuse in high altitudes and/or inland cities is effective, and can result, if applied in only six cities, in financial cost and energy savings of about USD 225 million (2009 dollars) and $4*10^9$ kWh annually.

As indicated earlier, water tariffs are generally very low, heavily subsidized by the governments, and are widely seen in the GCC as an economic right and a basic human need (Economist 2010), but this situation has a negative impact on the full utilization of treated wastewater. Currently, wastewater collection, treatment, and even distribution services are provided free of charge (with literally zero cost recovery) in the majority of the GCC countries (except for Oman, and recently in Saudi Arabia and Qatar), which does not provide an incentive for water savings, especially in the agricultural sector, and lowers the probability of large investments in wastewater projects. This will increase the financial burden on the government budget. Therefore, applying a proper tariff, which is lower than other water resources, on sanitation services linked to domestic water supply bills can reflect the economic value of the service and provide some cost recovery and financial stability. The funds generated could then be used to expand plants' capacities, ensure their adequate maintenance and operation costs, collection and transportation of the water (Abdul-Khaliq et al. 2017). Moreover, adding tariffs as a percentage of the domestic use can also be used as an economic tool to lower water consumption. The National Water Company in Saudi Arabia had completed a comprehensive study to evaluate the willingness and ability to pay for treated wastewater and to identify treated wastewater tariff for various sectors. The industrial and commercial sectors had the highest willingness to pay. Accordingly, a new wastewater tariff was introduced for the government, commercial and industrial sectors in December 2015, raising the potable water cost to USD 1.6/m^3 and introduces a wastewater service cost of USD 0.8/m^3 (Ouda 2016).

5.4 Other Constraints

The wastewater sector has zero control on the driving forces or the direct pressures of the wastewater system inflow and outflow and is considered as a reactive sector to the municipal water supply sector. Hydraulic loadings, which occur on some occasions as a result of rapidly increasing municipal water demands and overwhelming generated wastewater volumes beyond the TWWP capacity, decrease the efficiency of wastewater treatment and increase the carryover volumes, leading to the discharge of untreated or partially treated wastewater into the environment and increasing pollution. The capability to deal with these hydraulic loadings depends mainly on the integrated planning and cooperation between the water supply and wastewater sectors as well as other relevant agencies (Al-Zubari and AlAjjawi 2020). Therefore, institutional arrangement, between the water supply, wastewater, health, agriculture authorities, is needed in all the GCC countries to ensure the coordinated and effective utilization of the treated wastewater. Moreover, many of the GCC countries face fragmentation of legislation that is scattered among agencies, overlapping responsibilities (e.g., water resources authorities and agricultural authority), and weak enforcement of water regulations. Currently, no country, except Saudi Arabia, has a comprehensive "Water Law." Nevertheless, the majority of the GCC countries have a policy for expansion of the reuse and incentivizing farmers, like Bahrain, that provides free delivery of treated wastewater to 92% of all agricultural lands (Al-Zubari and AlAjjawi 2020).

6 Potential Future Contribution of Wastewater

The population of GCC countries is projected to reach 68 million by 2035 (UN 2019), which will increase domestic water consumption and subsequently wastewater generation rates. Dawoud (2017) indicated that the production of wastewater has been increasing by 11% annually in the GCC countries, and by 2030 volumes of treated wastewater would reach about 17 BCM. Future potential for increasing the reuse of treated wastewater is recognized as one intervention strategy for developing unconventional water resources in the GCC countries. Hence, the expansion of the reuse of treated wastewater for irrigation and other activities could contribute greatly to reducing water scarcity in the region. For this to be accomplished, adequate political will, sound laws, policies, strategies, and frameworks, private sector participation, intensive public awareness campaigns, and finance plans are necessary for successful achievement of this goal. Meeting the country's increasing water demands necessitates adopting a national sanitation law or strategic wastewater reuse policy that includes regulations not only for enhancing the treatment efficiency, but also for maximizing the reuse of treated wastewater. Such initiatives can conserve non-renewable oil and gas resources consumed in desalination.

This was clearly reflected in the strategic objectives (SOs) of the Unified Water Strategy (2016–2035) for the GCC countries (GCC-UWS), which has been approved by the GCC Supreme Council in 2016 during their 37th Gulf Summit. Treated wastewater reuse in agriculture has been emphasized in a number of strategic objectives that have been formulated to address this topic (Table 4). SO3 is dedicated to wastewater and targets to increase the collected wastewater to reach at least 60% of the municipal water supply, to maximize wastewater treatment and reuse up to 90% by 2035 in each GCC country. Moreover, it aims to raise the WWTPs capacities, the level of treatment, treated wastewater reliability, decentralization, and privatization, in order to expand the reuse plans and reduce the environmental impacts of wastewater disposed without utilization and/or treatment. In addition, the GCC-UWS aims to protect groundwater resources from depletion and deterioration, increase water efficiency in the water-consuming sectors, localize desalination and water treatment technologies in the region, improve water governance, and increase economic efficiency. Furthermore, the overall strategic objectives are to help guarantee achieving long-term level of water security and sustainability to the water sector in the GCC countries (Al-Zubari et al. 2017).

With the aim of highlighting the numerous benefits of implementing the GCC-UWS targets, three management intervention future scenarios were modeled using

Table 4 Strategic Objectives (SO) of the GCC-UWS (Al-Zubari et al. 2017) related to the wastewater sector

SO1:	**To Acquire Technology Development and Manufacturing of Desalination and Water Treatment Plants and Diversification of Energy Resources**	
	1.1	Establishing joint GCC desalination and water treatment industry
	1.2	Establishing an advanced joint GCC R&D base in desalination and water treatment
	1.3	Developing professional and technical capacity in desalination and water treatment in the GCC
	1.5	Mitigating the impacts of desalination and water treatment practices on the environment
SO3:	**To Maximize Municipal Wastewater Collection, Upgrade Treatment, and Increase Economic and Safe Use of Treated Wastewater and Sludge**	
	3.1	Increasing wastewater collection rates, treatment capacities, and treatment levels
	3.2	Increasing treated wastewater reuse in all appropriate sectors
	3.3	Enforcing legislation related to the protection of health and environment in all stages of collection, treatment, and reuse of domestic wastewater
	3.4	Maximizing the beneficial use of wastewater sludge
SO4:	**To Achieve the Highest International Standards of Water and Wastewater Services**	
	4.1	Ensuring the highest international standards of water supply and sanitation services to all populated areas in the GCC countries
	4.3	Achieving the highest management standards for sanitation utilities
	4.4	Enhancing the capacity and performance of Water Supply and Sanitation personnel
SO6:	**To Establish a Water-Efficient and Rational Agricultural Sector Compatible with the Available Water Resources**	
	6.1	Improving water use efficiency and increasing water productivity in the agricultural sector
	6.2	Increasing the use of treated wastewater in agriculture in conformity with reuse standards
SO8:	**To Improve Governance in the Water Sector to Achieve Effective and Integrated Water Resources Management**	
	8.1	Ensuring integrated planning and coordination among water-related sectors in each GCC country
	8.2	Ensuring water sector regulation
	8.5	Providing water data and information for decision-making support

(continued)

Table 4 (continued)

	8.6	Customizing water-related standards compatible with the GCC countries conditions
SO9:	**To Achieve Water-Oriented Society in the GCC Countries**	
	9.1	Building water importance and value awareness for the future generation
SO10:	**To Minimize Water Supply Economic Costs and Increase Cost Recovery while Maintaining the Quality of Service**	
	10.1	Giving water an economic value in the GCC countries
	10.3	Increasing public–private partnership in the water sector
	10.4	Adopting and implementing “polluters pay” principle in the water sector

WEAP[5] Modeling System (Al-Zubari et al. 2017). These management scenarios were: (1) increasing wastewater collection rate to 60% (currently averaging 57% but varies among the countries), (2) increasing irrigation efficiency to 60% (from the low level of 35–40%), and (3) decreasing per capita water consumption to 250 l/day. The results were then compared with the reference (2012 data) scenario that represents the Business-As-Usual conditions (Fig. 7). The simulation results indicated that the potential of the generated wastewater, if properly treated and fully reused, would completely fulfill all the agricultural water needs in Bahrain, Kuwait, and Qatar (averaged 50% of the total water demands in the GCC countries). These countries would also have a surplus of treated wastewater, which can be used for expanding agriculture or for other purposes. However, for Oman and Saudi Arabia, the generated wastewater will contribute to only about 15% of the requirements of the agricultural sector, because the municipal sector has a small share of their total water demands (12%) while the agriculture sector represents around 84% of the total water consumption. It should be noted that these figures can be achieved taking into consideration the per capita use reduction to 250 l/day, and without this scenario more wastewater will result in more recovery in agriculture. Moreover, these management scenarios are associated with potential savings in financial, economic, and environmental costs. Consequently, the reuse of treated wastewater should be integrated into the water management and security strategies for all the GCC countries, side by side with the water conservation plans (reducing the consumption of water, reducing the water losses, improving the efficiency in the use of water, and raising awareness). It is important to mention that the study projected the increase in the GCC water demands. Under the current (Business-As-Usual) conditions, total municipal water supply requirements in the GCC countries are expected to increase from 5.7 BCM in 2015 to about 11 BCM in 2035 (50% more in 20 years), however, when implementing a management intervention scenario, the increase will reach about 7.3 BCM in 2035 (with 3.7 BCM reduction).

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[5] WEAP (Water Evaluation And Planning) dynamic modeling software that takes an integrated approach to all water resources.

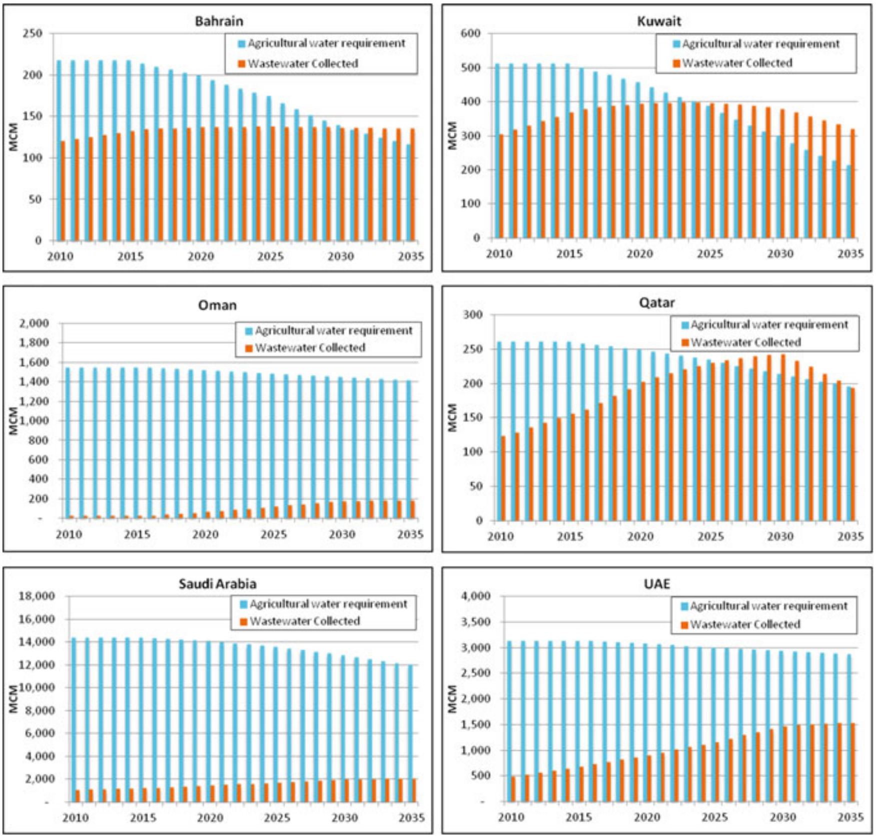

Fig. 7 Potential of wastewater contribution to the agricultural sector in the GCC countries, after implementing three scenarios representing the GCC-UWS targets, i.e., increasing wastewater collection to 60%, increasing irrigation efficiency to 60%, and decreasing per capita water consumption to 250 l/day (Al-Zubari et al. 2017)

7 Conclusion and Recommendations

Currently, the GCC countries' water requirement (around 32 BCM) is met by groundwater abstraction and surface water harvesting (79%), desalination (18%), and very limited reuse of treated wastewater (3%). Water demand in the GCC countries is predicted to rise dramatically and, consequently, municipal wastewater generation will increase steadily. Treated wastewater has been adopted in the GCC countries as a non-traditional alternative water resource among other water resources. Great efforts have been made to provide access to sanitation services, and establish many of modern wastewater treatment plants, with mostly tertiary and advanced treatment capabilities, in all the GCC countries. Although the GCC countries treated about 95% of the collected municipal wastewater in 2018, the reuse of this treated wastewater was only about 35%. Much of this treated wastewater is discharged into the marine and coastal environment without being used, even when treated to a tertiary level. As a result, the potential for reusing this generated wastewater is not fully developed until now and the reuse of treated wastewater is still in its early stages of development, representing a major untapped opportunity under the current water scarcity conditions of the GCC countries. However, many ambitious plans have been announced in all the six countries to increase the reuse share in their total water budget and water supply portfolio, in order to meet their future demands for irrigation water and other purposes. In response, the following should be kept in mind to ensure complete utilization of treated wastewater:

- The produced wastewater will be treated, due to environmental considerations, irrespective of whether it is going to be used or not. Therefore, maximizing the reuse should be addressed as a much better option than discharge, from environmental and economic perspectives to minimize the contamination and reduce the environmental footprint of wastewater treatment.
- The evolving necessity to conserve valuable groundwater and energy resources require policymakers to give more consideration to the potential benefits of wastewater, such as: (1) Reuse will protect groundwater from depletion and from deterioration in water quality. (2) Reuse is a better choice than desalination, at least for non-potable water needs, because it consumes less energy and at the cost is much lower than that of desalting seawater. (3) Reuse can reserve freshwater resources for priority uses and help alleviate water scarcity in the region. (4) Reuse can contribute significantly to cover the water needs of the agricultural sector, the GCC's biggest water consumer. To achieve these benefits tertiary treatment should be increased, and 100% reuse should be accomplished.
- Monitoring and enforcing strict standards and legislation to ensure proper wastewater treatment, avoid health risks and environmental impacts and guarantee wastewater reliability, requires more consideration and should be addressed as a priority.
- Decentralization and privatization policies will marginally guarantee the security and safety of treating and reusing wastewater and will also reduce the financial and environmental costs.
- The reuse potential can be increased if coupled with demand management in the agricultural sector. Therefore, a policy to shift toward demand management by improving water use efficiency, especially in irrigation systems, controlling collection and distribution networks, leakage and rehabilitation are all of interest to the sector.
- Complete utilization of treated wastewater can only succeed with a positive public perception toward reusing. Therefore, there is a necessity to launch awareness programs and campaigns for farmers, as well as for the public, to address the water scarcity problem and water supply costs, and to overcome social and religious concerns regarding the use of treated wastewater in agriculture, landscaping, and other purposes.

- Reducing the large government subsidy of water supplies by revising and restructuring the water tariff is an important step for raising people's perception toward the importance of wastewater. In addition, developing an effective cost recovery mechanism (tariff on wastewater reuse) to fully recover the cost will reduce the burden on governments and ensure the long-term availability of this water resource.
- Institutional arrangement, or at least integration and strengthening institutional cooperation between the water supply, wastewater, health,and agriculture authorities is required in all the GCC countries to avoid fragmentation of legislation, weak enforcement of water regulations, and to ensure effective utilization of the treated wastewater.
- Finally, all the GCC countries are considering the wide-scale expansion in the reuse of treated wastewater as a major part of their Integrated Water Resources Management policies, plans, and investments to overcome the constraints and the main management challenge in the wastewater sector, which is the large mismatch between treated and reused wastewater quantities.

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Part VI
Use of Models as Management Tools

Chapter 15
SALTMED Model as a Tool for Water, Crop, Field, and N-Fertilizers Management

Ragab Ragab

Abstract In recent years, models attracted more attention and once calibrated and validated using field observations, they were used as management tools for the estimation of crop water requirements, expected yield under different irrigation systems, when using different water qualities and different land and fertilizers managements. SALTMED is an example of such management models. The model has been developed over four European Commission funded projects (SALTMED, SWUP-Med, SAFIR, and Water4Crops) and tested using field observations over a number of years (Ragab et al. 2005a, 2015; Ragab 2020). The SALTMED model simulates the crop growth and dry matter, water and solute movement under various irrigation systems (surface and subsurface) and under full and deficit irrigation including the Partial Root Drying Method, PRD. The model also simulates drainage flow to open and tile drains, shallow water table height, nitrogen cycle, and estimates the actual and potential evapotranspiration as well as the water use efficiency and crop water productivity. SALTMED model can simulate up to twenty fields or treatments simultaneously. The model also simulates crop rotations. The model has been tested against a number of field experiments in different countries such as: tomato and potato under drip irrigation in Syria, Egypt, Crete, Serbia, and Italy (Ragab et al. 2005b and 2015; Afzal et al. 2016), in Iran, sugar cane under sprinkler irrigation (Golabi et al. 2009), in Greece, cotton under drip irrigation (Kalfountzos et al. 2009), in Denmark, quinoa irrigated with saline water (Razzaghi et al. 2011), in Morocco, quinoa, sweetcorn, and chickpea under drip irrigation (Hirich et al. 2012), in Brazil, vegetable crops (Montenegro et al. 2010), in Italy, quinoa and amaranth using saline water (Pulvento et al. 2013, 2015b), in Portugal, rainfed and irrigated chickpea (Silva et al. 2013), in Morocco, quinoa under deficit drip irrigation (Fghire et al. 2015), in Turkey, sweet pepper in green houses using saline water (Rameshwaran et al. 2015, 2016b), in

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Syria, legumes (lentil, chickpea, and faba bean) using saline water (Arslan et al. 2016; Rameshwaran et al. 2016a), in Turkey, quinoa using fresh and saline water (Kaya and Yazar 2016), and in Egypt, potato using gated pipes furrow irrigation (El-Shafie et al. 2017). The abovementioned studies illustrated the capability and reliability of the SALTMED model in simulating the field observed yield and dry matter, soil moisture, and salinity concentration of the root zone. In addition, the model was also able to derive an important relation commonly known as the salinity-yield response function (Arslan et al. 2016; Rameshwaran et al. 2015, 2016a, b). SALTMED was also used to study the possible impact of climate change on yield, dry matter, crop water requirements, harvest and sowing dates, and length of the growing season of amaranth and corn crops in Italy and Morocco (Pulvento et al. 2015a; Hirich et al. 2016). The model has been intensively used in Egypt on a variety of field crops (Abdelraouf and Ragab 2017, 2018a, b, c; Abdelraouf et al. 2020; Dewedar et al. 2021; Marwa et al. 2020; El-Shafie et al. 2017), in Pakistan (Chauhdary et al. 2019, 2020), in Iran (Basiri et al. 2020; Dastranj et al., 2018), in Portugal (Silva et al. 2013, 2017), and in Morocco (Hirich et al. 2012, 2016, 2020; Filali et al. 2017; Fghire et al. 2015). The model has also been used to derive some parameters that are not easy to measure (e.g., Leaf Area Index, LAI, Salinity tolerance index π_{50}, etc.) More details about the applications are published in a Special Issue of Journal of Irrigation and Drainage (Ragab 2020).

Keywords SALTMED model · Salinity · Soil moisture · Crop growth · Dry matter · Yield · Agricultural water management · Nitrogen fertilizer management · Irrigation · Drainage · Deficit irrigation · Partial root drying · PRD · Crop rotation · Evapotranspiration · Nitrogen dynamics

1 Introduction

Globally, irrigation consumes about 70% of the fresh water resources. Although, rainfed agriculture globally represents 75% of total agricultural area, it produces 60% of the food production; while irrigated agriculture globally represents 25% of the total agricultural area, it produces 40% of the global food production. This fact highlights the importance of irrigation and its positive impact on food production. For this reason, farmers in rainfed areas learned to apply supplemental irrigation after observing the advantage of additional supplemental irrigation on the yield.

Deficit irrigation is currently practiced more than in the past due to climate change's negative impact especially the more recent frequent drought events on water resources availability. The deficit irrigation principle is to apply less water than the full water requirement resulting in subjecting the plant to mild water stress only during the growth stages where the plant is less sensitive to water stress.

In addition, due to the fact that irrigation requires a large amount of water and as food demand is on the increase to feed the ever-growing population using the same limited amount of water, deficit irrigation and drought tolerant crops are now more attractive options in arid and semi-arid regions. In addition to the use of deficit irrigation, the use of non-conventional water resources (saline/brackish), treated waste water, drainage water, agro-industry waste water, mining water, desalinated water, etc., as well as the less water consuming crops and drought tolerant crops are becoming increasingly attractive in water stressed regions. The SALTMED model is designed to simulate crop growth and yield under deficit irrigation, non-conventional water resources and includes a database for conventional crops and drought tolerant (non-conventional crops).

Due to the strong competition among different sectors for fresh water resources, the use of non-conventional water resources is on the increase for irrigation. However, when using such water resources, a careful management should be in place to safeguard the environment from any negative impact (salinization, heavy metals, microbes, etc.) and protect the soil from degradation (Ragab 1995, Ragab et al. 1997; Ragab 1998, 2002, 2004; Hamdy et al. 2003; Malash et al. 2008; Choukr-Allah 2010, 2012).

Models are particularly important to predict the long-term impact of using poor quality water especially saline water on soil, crop growth, and the environment, as most of the field experiments do not last long enough to show the impact after a long period of application.

SALTMED model is a comprehensive model for generic applications. The model accounts for most of the common irrigation systems (drip, sprinkler, furrow, basin, border, subsurface drip, Center Pivot, rainfed), irrigation application/strategies (deficit irrigation, DI, Partial Root Drying, PRD, surface, and subsurface irrigation), the presence of shallow water table and open and tile drains, salt and nitrate leaching, and nitrogen cycle. The model has a database for soils, crops, and irrigation systems parameters (Ragab 2002, 2005, 2015, 2020). The model is user friendly using the WindowsTM environment (Windows 7, 10, and 11). SALTMED is a physically based model using the well-known equations for water and solute transport, crop growth, nitrogen cycle, evapotranspiration, and water uptake.

The SALTMED model can be freely downloaded from the links provided at the end of this chapter.

2 Brief Description of the Main Processes in the SALTMED Model

The SALTMED model includes the following key processes: evapotranspiration, plant water uptake, water and solute transport under different irrigation systems, nitrogen dynamics, and dry matter and biomass production. A brief description of the abovementioned processes will be given in the following sections.

2.1 Evapotranspiration

Evapotranspiration has been calculated using the Penman–Monteith equation according to the modified version of Allen et al. (1998) in the following form:

$$\mathrm{ET}_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1a}$$

where ET_o is the reference evapotranspiration, (mm day^{-1}), R_n is the net radiation, (MJ m^{-2} day^{-1}), G is the soil heat flux density, (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height, (°C), Δ is the slope of the saturated vapor pressure curve, (kPa °C^{-1}), γ is the psychrometric constant, 66 Pa °C^{-1}, e_s is the saturated vapor pressure at air temperature (kPa), e_a is the prevailing vapor pressure (kPa), and U_2 is the wind speed at 2 m height (m s^{-1}). The calculated ET_o here is for short well-watered green grass. In this formula, a hypothetical reference crop with an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23 were considered.

In presence of stomata/canopy surface resistance data, one could use the widely used equation of Penman–Monteith (1965) in the following form:

$$\lambda E_p = \frac{\Delta R_n + \rho C_p \frac{(e_s - e)}{r_a}}{\Delta + \gamma \frac{(1 + r_s)}{r_a}} \tag{1b}$$

where "r_s" and "r_a" are the bulk surface and aerodynamic resistances (s m^{-1}).

The r_s can be measured or calculated from environmental and meteorological parameters or from the leaf water potential and Abscisic Acid, ABA concentration.

In the absence of meteorological data (temperature, radiation, wind speed, etc.) and if Class A pan evaporation data are available, the SALTMED model can use these data to calculate ET_o according to the FAO procedure Allen et al. (1998). The model can also calculate the net radiation from solar radiation according to the FAO procedure if net radiation data are not available. The crop evapotranspiration ET_c is calculated as:

$$\mathrm{ET}_c = \mathrm{ET}_o(K_{cb} + K_e) \tag{2}$$

where K_{cb} is the crop transpiration coefficient (known also as basal crop coefficient) and K_e is the soil evaporation coefficient. The values of K_{cb} and K_c (the crop coefficients) for each growth stage and the duration of each growth stage for different crops are available in the model's database. These data can be used in the absence of measured values. K_e is calculated according to FAO (Allen et al. 1998). K_{cb} and K_c are adjusted according to FAO (Allen et al. 1998) for wind speed and relative humidity if different from 2 m s^{-1} and 45%, respectively. The SALTMED model runs with a daily time step and uses K_{cb} and K_e. These parameter values are not universal, and their values differ according to climatic conditions and other factors.

2.2 *Plant Water Uptake in the Presence of Saline Water*

2.2.1 The Actual Water Uptake Rate

The formula adopted in the SALTMED model is that suggested by Cardon and Letey (1992), which determines the water uptake $S(d^{-1})$ as:

$$S(z,t) = \left[\frac{S_{\max}(t)}{1 + \left(\frac{a(t)h+\pi}{\pi_{50}(t)}\right)^3}\right]\lambda(z,t) \tag{3}$$

where $S_{\max}(t)$ is the maximum potential root water uptake at the time t; z is the vertical depth taken positive downward, $\lambda(z, t)$ is the depth- and time-dependent fraction of total root mass, L is the maximum rooting depth, h is the matric pressure head, π is the osmotic pressure head; π_{50} (t) is the time-dependent value of the osmotic pressure at which $S_{\max}(t)$ is reduced by 50%, and $a(t)$ is a weighing coefficient that accounts for the differential response of a crop to matric and solute pressure. The coefficient $a(t)$ equals $\pi_{50}(t)/h_{50}(t)$ where $h_{50}(t)$ is the matric pressure at which $S_{\max}(t)$ is reduced by 50%.

The maximum water uptake $S_{\max}$ (t) is calculated as:

$$S_{\max}(t) = ET_o(t) * K_{cb}(t) \tag{4}$$

The values of h_{50} and π_{50} can be obtained from experiments or from literature (Rhoades et al. 1992).

2.3 *The Relative Crop Yield, RY*

Due to the unique and strong relationship between water uptake and biomass production, and hence the final yield, the relative crop yield RY is estimated as the sum of the actual water uptake over the season divided by the sum of the potential water uptake (under no water and salinity stress conditions) as:

$$\mathrm{RY} = \frac{\sum S(x,z,t)}{\sum S_{\max}(x,z,t)} \tag{5}$$

where x, z are the horizontal and vertical co-ordinates of each grid cell that contain roots, respectively.

The actual yield, AY.

The actual yield, AY is simply obtainable by:

$$\mathrm{AY} = \mathrm{RY} * Y_{\max} \tag{6}$$

where $Y_{\max}$ is the maximum yield obtainable in a given region under optimum and stress-free conditions. This option assumes that salinity and water are the only stressors and all other factors are at optimum level. It is also used for quick answers when one needs to run several "what if" scenarios. The other option to obtain the actual yield is by calculating the daily biomass production and obtaining the actual yield from the harvest index times the total dry matter as given hereunder.

2.4 Crop Growth, Biomass Production, and Yield

The crop growth, biomass, dry matter production, and yield have been calculated based on radiation, photosynthetic efficiency, water uptake, air temperature, leaf nitrogen content, leaf area index, respiration losses, and the harvest index.

The approach used is very much based on the work of Eckersten and Jansson (1991).

$$\begin{aligned}&\text{The assimilation rate ``}A'' \text{ per unit of area}\\&= E * I * f(\mathrm{Temp}) * f(T) * f(\mathrm{Leaf} - N)\end{aligned} \tag{7}$$

where E is the photosynthetic efficiency (g dry matter MJ^{-1}), I is the radiation input: = Rs ($1 - e^{-k*\mathrm{LAI}}$), Rs is global radiation (MJ m^{-2} day^{-1}), k is extinction coefficient, and LAI is the leaf area index (m^2 m^{-2}). Rs is given in climate data, LAI is interpolated in SALTMED. Assimilation rate "A" per unit of area (g m^{-2} day^{-1}) = $E*$ $I*$ (stress factors related to temperature, transpiration, and leaf nitrogen content).

The transpiration stress factor is taken as a ratio of actual plant water uptake to the potential water uptake. The temperature stress is taken as deviation of the average temperature of a given day from the optimum temperature for the growth. The leaf nitrogen stress is taken as the deviation of the leaf nitrogen content of a given day from the optimum leaf nitrogen content.

2.4.1 Fixed and Variable Growth Stage Periods

There are two options for crop growth. The first option is for the crop to grow according to fixed sowing and harvest dates and each growth stage (initial, development, late) has a prefixed duration in days. The second option is to allow the crop to grow according to the accumulated heat units/degree days (sum of the daily difference between average air temperatures minus minimum temperature required for growth). Each growth stage is completed when a certain number of degree days has been reached. The sowing date and harvest date could, in this case, vary. This is important when studying the impact of climate change on sowing and harvest date as well as the length of the growing season.

2.4.2 Crop Rotation

The model can run with different rotations on different fields (up to 20 rotations). Each rotation could include a variety of different crops, including fallow.

2.5 Water and Solute Flow

The water flow in soils was described mathematically by the well-known Richard's equation.

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\psi + z)}{\partial z}\right] - S_w \tag{8}$$

where θ is volume wetness; t is the time; z is the depth; $K(\theta)$ is the hydraulic conductivity (a function of wetness); ψ is the matrix suction head; and S_w is the sink term representing extraction by plant roots. The movement of solute in the soil system, its rate and direction, depends greatly on the path of water movement, but it is also determined by diffusion and hydrodynamic dispersion. If the latter effects are negligible, solute flows by convection (Hillel 1977). The one-dimensional transient movement of a non-interacting solute in the soil can be expressed as:

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z}\left(D_a \frac{\partial c}{\partial z}\right) - \frac{\partial(qc)}{\partial z} - S_s \tag{9}$$

in which c is the concentration of the solute in the soil solution, q is the convective flux of the *solution*, D_a is a combined diffusion and dispersion coefficient, and S_s is a sink term for the solute representing root adsorption/uptake.

Under irrigation from a trickle line source, the water and solute transport can be viewed as two-dimensional flow (Fig. 1) and can be simulated by one of the following:

1. a "plane flow" model involving the Cartesian co-ordinates x and z. Plane flow takes place if one considers a set of trickle sources at equal distance and close enough to each other so that their wetting fronts overlap after a short time from the start of the irrigation.
2. a "cylindrical flow" model described by the cylindrical co-ordinates r and z.

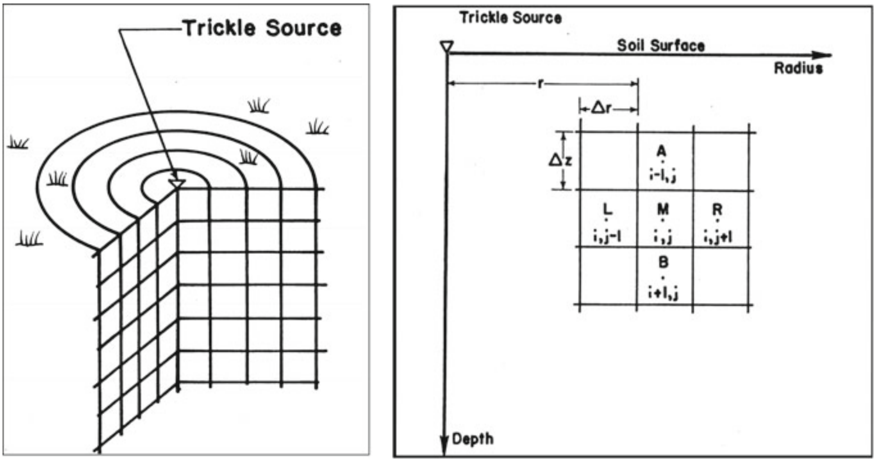


Fig. 1 Example of the flow domain under drip irrigation, two-dimensional flow

Cylindrical flow takes place if one considers the case of a single trickle nozzle, or a number of nozzles spaced far enough apart so that overlap of the wetting fronts of the adjacent sources does not take place. For a stable, isotropic, and homogeneous porous medium, the two-dimensional flow of water in the soil can be described according to Bresler (1975) as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial \psi}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\psi + z)}{\partial z}\right] \tag{10}$$

where x is the horizontal co-ordinate; z is the vertical co-ordinate (considered to be positive downward); $K(\theta)$ is the hydraulic conductivity of the soil. The two-dimension solute flow equation becomes:

$$\frac{\partial (C\theta)}{\partial t} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x} + D_{xz}\frac{\partial C}{\partial z} - q_x C\right) + \frac{\partial}{\partial z}\left(D_{zz}\frac{\partial C}{\partial z} + D_{zx}\frac{\partial C}{\partial x} - q_z C\right) \tag{11}$$

In the model, sprinkler, flood, and basin irrigation are described by one-dimensional flow equations (e.g., Eqs. 8 and 9). Furrow and trickle line sources are described by 2-dimensional equations (e.g., Eqs. 10 and 11). Trickle point source is described by cylindrical flow equations obtained by replacing x by the radius “r” and rearranging Eqs. (10) and (11) as given by Bresler (1975) and Fletcher Armstrong and Wilson (1983). The water and solute flow equations were solved numerically using a finite difference explicit scheme (Ragab et al. 1984).

2.5.1 Soil hydraulic parameters

Solving the water and solute transport equations requires two soil–water relations, namely the soil water content–water potential relation and the soil water potential–hydraulic conductivity relation. They were taken according to van Genuchten (1980) as:

$$\theta(h) = \theta_r + \left[(\theta_s - \theta_r)/\left(1 + |\alpha h|^n\right)^m\right] \tag{12}$$

$$K(h) = K_s K_r(h) = K_s \mathrm{Se}^{1/2}\left[1 - \left(1 - \mathrm{Se}^{1/m}\right)^m\right]^2 \tag{13}$$

where θ_r and θ_s denote the residual and the saturated moisture contents, respectively; K_s and K_r are saturated and relative hydraulic conductivity, respectively, α and n are shape parameters, $m = 1 - 1/n$ and S_e is effective saturation or normalized volumetric soil water content. α, n, and λ are empirical parameters.

2.6 *Drainage*

SALTMED has three options, free drainage at the bottom of the root zone (recharge) or subsurface drainage system open or tile system, and shallow groundwater with no drainage system. The drainage flow is based on Hooghoudt's drainage equation (Hooghoudt 1940) which gives a mathematical relation of the parameters involved in the subsurface drainage of flat land by a system of horizontal and parallel ditches or pipe drains without entrance resistance, placed at equal depth and subject to a steady recharge evenly distributed over the area. The most widely known form of Hooghoudt's equation was presented by Wesseling (1973). In a slightly modified form, it reads:

$$qL = (8\mathrm{Hm}/L)(\mathrm{Kb} \times \mathrm{De} + \mathrm{Ka} \times \mathrm{Ha}) \tag{14}$$

where q is the steady recharge of water percolating to the water table equal to the drain discharge (m/day or m/hr), L is the drain spacing (m), Hm is the height of the water table midway between drains, taken with respect to the center of the drain (m), Kb is the hydraulic conductivity of the soil below drain level (m/day or m/h), Ka is the hydraulic conductivity of the soil above drain level (m/day or m/h), De is Hooghoudt's equivalent depth to the impermeable layer below drain level, and Ha = Hm/2 is the average height of the water table above drain level.

The equivalent depth De depends on the depth D of the impermeable layer below the drains (Fig. 2) as follows:

$$\text{If } D < R: \quad \mathrm{De} = D \tag{15}$$

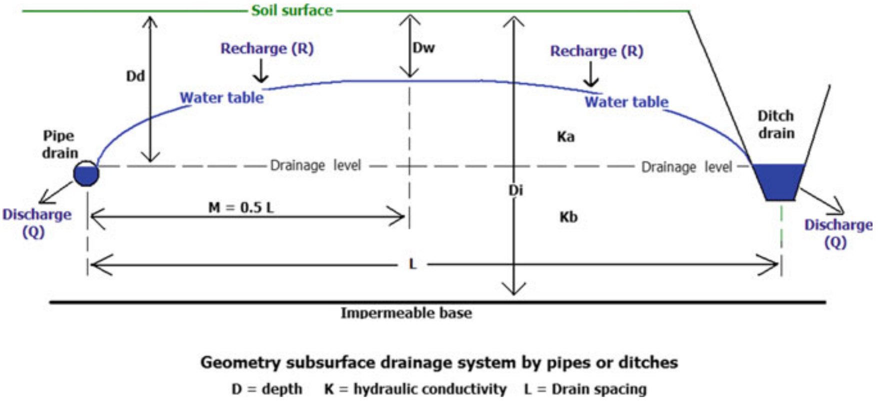


Fig. 2 Geometry of open and pipes drainage system

$$\text{If } R < D < L/4: \quad \mathrm{De} = D \times L/\{(L - D2) + 8D \times L \times \ln(D/R)\} \tag{16}$$

$$\text{If } D > L/4: \quad \mathrm{De} = L/8 \ln(L/R) \tag{17}$$

where R is the drain radius (m). For $L/8 < D < L/2$, Eqs. (16) and (17) give almost the same result. Equation 16 is the outcome of an analysis of Hooghoudt's theory as reported by Wesseling (1973). Equations 15 and 17 were given by Hooghoudt (1940).

If the drains are open ditches instead of buried pipes, the above equations are applicable with an equivalent radius calculated as $R = W/\pi$, where W is the wetted perimeter of the ditch. Further, if the coefficient 8 is changed to 6.4, the equations can be used for drainage with a falling water table (Oosterbaan, 1993). If drains are open ditches, the diameter needs to be calculated by the user as D = 2 W/π where W is the wetted perimeter of the ditch. $W z = B + 2\,h$ for rectangular, $W = b + 2h\sqrt{1 + z^2}$ for trapezoidal, and $W = 2h\sqrt{1 + z^2}$ for V shaped ditches. B is bottom breadth, h is height of water, and Z is the horizontal distance at which the water height drops by a single unit (side slope), $Z = 0.25$ for rock, 0.5 for hard compact pan, 1.25 for gravel, 1.5 for loam, 2 for loose sandy loam, 2.5 for wet sand, and 3 for light sand and wet clay.

2.7 Soil Nitrogen Dynamics and Nitrogen Uptake

This is very much based on SOIL N model of Johnsson et al. (1987). The following processes (Fig. 3) were implemented in SALTMED:

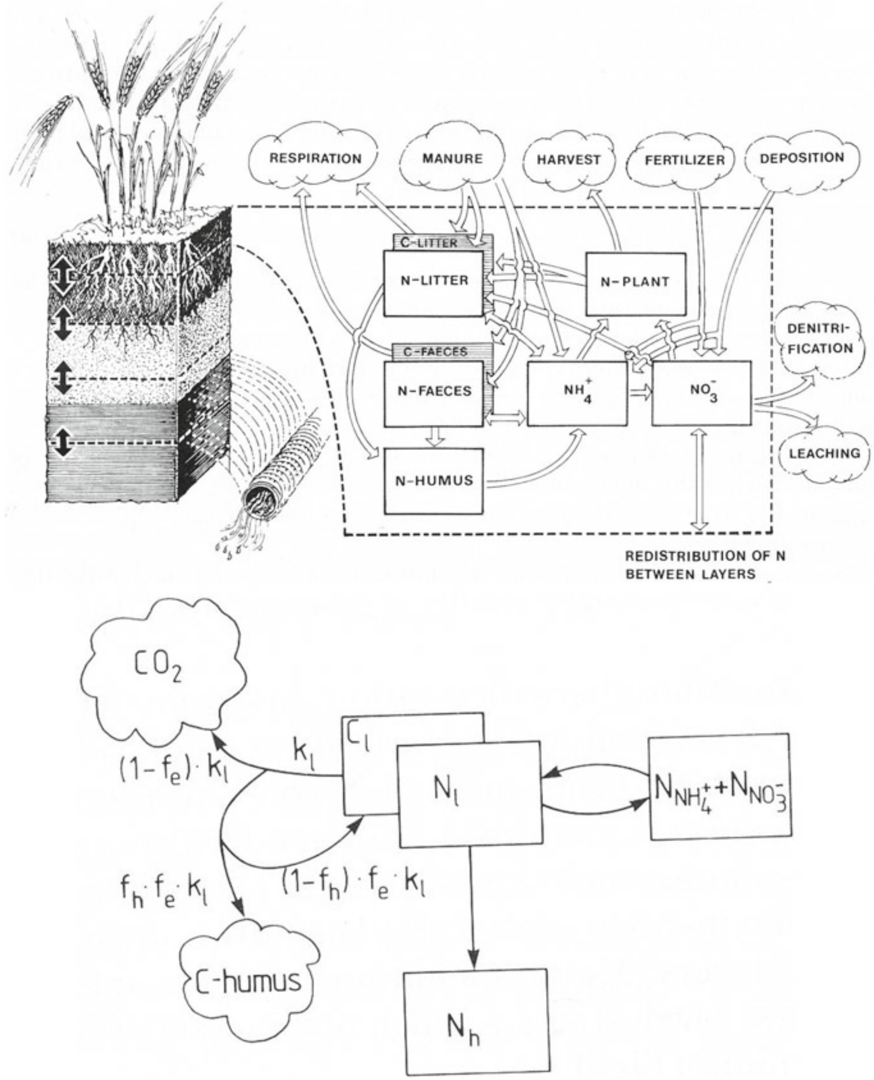


Fig. 3 Soil nitrogen cycle and processes according to Johnsson et al. (1987)

Mineralization
Immobilization
Nitrification
Denitrification
Leaching
Plant N Uptake

Nitrogen input included dry and wet deposition, incorporation of crop residues, manure application, chemical fertilizer application, and with irrigation water as fertigation.

Mineralization of humus, $N_h(z)$, is calculated as a first-order rate:

$$N_{h\rightarrow \mathrm{NH}_4^+}(z) = k_h e_t(z) e_m(z) N_h(z) \tag{18}$$

where k_h is the specific mineralization constant and $e_t(z)$ and $e_m(z)$ are response functions for soil temperature and moisture, respectively.

$N_{h\rightarrow \mathrm{NH}_4^+}$ is in g nitrogen m^{-2} day^{-1}, k_h is in day^{-1}, e_t and e_m are dimensionless, $N_h(z)$ is in g nitrogen m^{-2}.

Decomposition of soil litter carbon, $C_l(z)$ is a function of a specific rate constant (k_l), temperature, and moisture.

$$C_{l(d)}(z) = k_l e_t(z) e_m(z) C_l(z) \tag{19}$$

$C_{1(d)}(z)$ is expressed in g carbon m^{-2} day^{-1}; k_l in day^{-1}, e_t and e_m are dimensionless, and $C_l(z)$ is in g carbon m^{-2}.

The relative amounts of decomposition products formed:

$$C_{l\rightarrow \mathrm{CO}_2}(z) = (1 - f_e) C_{l(d)}(z) \tag{20}$$

$$C_{l\rightarrow h}(z) = f_e f_h C_{l(d)}(z) \tag{21}$$

and

$$C_{l\rightarrow l}(z) = f_e(1 - f_h) C_{l(d)}(z) \tag{22}$$

are governed by a synthesis efficiency constant (f_e) and a humification factor (f_h).

$C_{l\rightarrow \mathrm{CO}_2}$, $C_{l\rightarrow h}$ and $C_{l\rightarrow l}$ are expressed in g carbon m^{-2} day^{-1}, $C_{l(d)}$ is in g carbon m^{-2}, f_e and f_h are dimensionless.

From Eqs. (19), (21), and (22), net mineralization or immobilization of nitrogen in litter ($N_l(z)$) is then determined:

$$N_{l\rightarrow \mathrm{NH}_4}(z) = \left[\frac{N_l(z)}{N_l(z)} - \frac{f_e}{r_o}\right] C_{l(d)}(z) \tag{23}$$

where $N_{1\rightarrow \mathrm{NH}_4}$ is in g nitrogen m^{-2} day^{-1}, N_l is g nitrogen m^{-2}, C_l is g carbon m^{-2}, f_e and r_o (the C–N ratio of microorganisms and humified products) are dimensionless.

The transfer rate of ammonium to nitrate:

$$N_{\mathrm{NH}_4\rightarrow \mathrm{NO}_3}(z) = k_n e_t(z) e_m(z) \left[N_{\mathrm{NH}_4}(z) - \frac{N_{\mathrm{NO}_3}(z)}{\eta_q} \right] \tag{24}$$

depends on the potential rate (k_n) which is reduced as the nitrate–ammonium ratio (η_q) is approached.

$N_{\mathrm{NH_4 \to NO_3}}$ is expressed in g nitrogen m^{-2} day^{-1}, $N_{\mathrm{NH_4}}$ and $N_{\mathrm{NO_3}}$ are in g nitrogen m^{-2}, k_n is in day^{-1}, and η_q, e_t and e_m are dimensionless.

$$e_t(z) = Q_{10}^{\left[\frac{T(z)-t_0}{10}\right]} \tag{25}$$

where $T(z)$ is the soil temperature for the layer, t_o is the base temperature at which $e_t(z)$ equals 1 and Q_{10} is the factor change in rate with a 10-degree change in temperature.

$$e_m(z) = e_s + (1 - e_s)\left[\frac{\theta_s(z) - \theta(z)}{\theta_s(z) - \theta_{ho}(z)}\right]^m \quad \theta_s(z) \geq \theta(z) > \theta_{ho}(z) \tag{26a}$$

$$e_m(z) = 1 \quad \theta_{ho}(z) \geq \theta(z) \geq \theta_{lo}(z) \tag{26b}$$

$$e_m(z) = \left[\frac{\theta(z) - \theta_w(z)}{\theta_{lo}(z) - \theta_w(z)}\right]^m \tag{26c}$$

$$\theta_{lo}(z) > \theta(z) \geq \theta_w(z) \tag{26d}$$

where $\theta(z)$ is the saturated water content, $\theta_{ho}(z)$ and $\theta_{lo}(z)$ are the high and low water contents, respectively, for which the soil moisture factor is optimal, and $\theta_w(z)$ is the minimum water content for process activity. The coefficient e_s defines the relative effect of moisture when the soil is completely saturated, and m is an empirical constant. The two thresholds defining the optimal range are calculated as:

$$\theta_{lo}(z) = \theta_w(z) + \Delta\theta_1 \tag{27a}$$

$$\theta_{ho}(z) = \theta_s(z) - \Delta\theta_2 \tag{27b}$$

where $\Delta\theta_1$ is the volumetric range of water content where the response increases and $\Delta\theta_2$ is the corresponding range where the response decreases.

The water content is in m^3 m^{-3}, soil temperature is in °C, and e_t and e_m are dimensionless.

A logistic uptake curve is used to define the cumulative potential N demand during the growing season:

$$\int u(t)dt = \frac{u_a}{1 + \frac{u_a - u_b}{u_b} e^{-u_c t}} \tag{28}$$

where u_a is the potential annual N uptake, u_b and u_c are shape parameters, and t is days after the start of the growing season, u_a is expressed in g nitrogen m^{-2} season^{-1}.

Daily uptake of nitrate is then calculated from the relative root fraction in the layer ($f(z)$), the proportion of total mineral N as nitrate, and the derivative of the growth curve (u). u is obtained from Eq. (28) on daily basis expressed as gram nitrogen m^{-2} day^{-1}, $N_{\mathrm{NO}_3}(z)$ and $N_{\mathrm{NH}_4}(z)$ are in gram nitrogen m^{-2}.

$$N_{\mathrm{NO}_3\rightarrow p}(z) - \mathrm{MIN\ of}\quad f_r(z)\frac{N_{\mathrm{NO}_3}(z)}{N_{\mathrm{NO}_3}(z) + N_{\mathrm{NH}_4}(z)}u \tag{29a}$$

and

$$f_{ma}N_{\mathrm{NO}_3}(z) \tag{29b}$$

The denitrification rate is expressed as a power function which increases from a threshold ($\theta_d(z)$) and is maximum at saturation ($\theta_s(z)$), where d is an empirical constant.

$$e_{md}(z) = \left[\frac{\theta(z) - \theta_d(z)}{\theta_s(z) - \theta_d(z)}\right]^d \tag{30}$$

The denitrification rate for each layer depends on a potential denitrification rate ($k_d(z)$), the soil water/aeration status ($e_{\mathrm{md}}(z)$), and the same temperature factor ($e_t(z)$) used for the other biologically controlled processes.

$$N_{\mathrm{NO}_3\rightarrow}(z) = k_d(z)e_{md}(z)e_t(z)\left[\frac{\left[N_{\mathrm{NO}_3}(z)\right]}{\left[N_{\mathrm{NO}_3}(z)\right] + c_s}\right] \tag{31}$$

$N_{\mathrm{NO}_3\rightarrow}(z)$ and $k_d(z)$ are expressed in g nitrogen m^{-2} d^{-1}, $N_{\mathrm{NO}_3}(z)$, is in g nitrogen m^{-2}, C_s is in mg l^{-1}, e_t and e_{md} are dimensionless.

2.8 Calculating Soil Temperature from Air Temperature

The top soil layer is the most biologically active layer where most of the organic matter decomposition and mineralization takes place. The microbial activity is affected by the soil temperature of this layer. This temperature was found to be correlated with air temperature. The approach used here is to infer the soil temperature of the top layer (ploughing layer) from the air temperature based on the work of Kang et al. (2000) and Zheng et al. (1993).

For air temperature “A” and soil temperature “T”, the relation can be described as:

For $A_j > T_{j\text{-}1}$ (z):

$$T_j(z) = T_{j-1}(z) + \left[A_j - T_{j-1}(z)\right] * \mathrm{Exp}\left[-z(\pi/(k_s * p))^{0.5}\right] * \mathrm{Exp}\left[-k\left(\mathrm{LAI}_j + \mathrm{litter}_j\right)\right] \quad (32)$$

For $A_j \leq T_{j\text{-}1}$ (z):

$$T_j(z) = T_{j-1}(z) + \left[A_j - T_{j-1}(z)\right] * \mathrm{Exp}\left[-z\left((\pi/(k_s * p))^{0.5}\right)\right] * \mathrm{Exp}\left[-k\left(\mathrm{litter}_j\right)\right] \quad (33)$$

A_j is the average Air Temperature at day "j" in °C.

This is calculated from Tmin and Tmax given as input in climate data file.

$T_{j\text{-}1}$ (z) is Soil temperature at day "$_{j-1}$" previous day at depth "z" below soil surface, °C.

T_j (z) is Soil temperature at day "j" and depth "z" below soil surface, °C.

Exp $[-z\ ((\pi\ /\ (k_s * p))^{0.5}]$ is a damping ratio.

k_s is the thermal diffusivity as a function of soil water, air, and mineral content, $\mathrm{m}^2\ \mathrm{s}^{-1}$

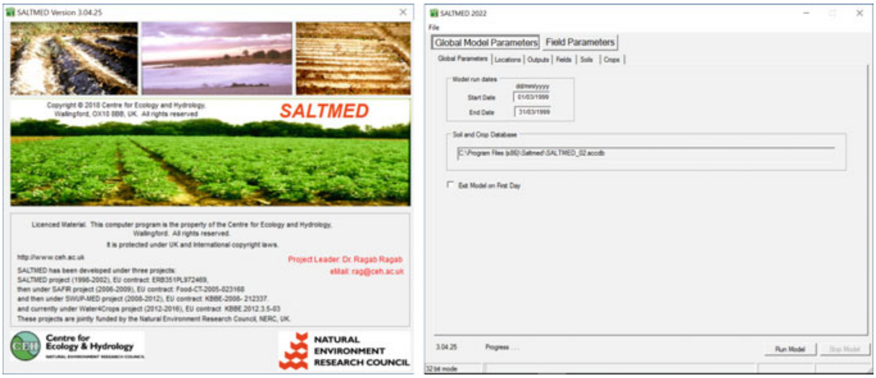
k_s = (thermal conductivity/(bulk density* specific heat capacity)).

P: is period of either diurnal or annual temperature variation, z is in meters.

LAI: is calculated already in the model on daily basis, Litter fraction is given as user input.

2.9 *Multiple and Simultaneous Model Application*

The SALTMED model runs with up to 20 fields, treatments, or rotations. This facility allows simultaneous runs of different actual systems of soil, crop, irrigation, and N-fertilizers and allows different "what if" scenarios as model applications in forecasting/prediction mode. Some of the main model tabs and an example of output are shown in Fig. 4 left side.



SALTMED Version 3.04.25

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http://www.ceh.ac.uk

Project Leader: Dr. Ragab Ragab
eMail: rag@ceh.ac.uk

SALTMED has been developed under three projects:
SALTMED project (1998-2002), EU contract: ERB351PL972469,
then under SAFIR project (2006-2009), EU contract: Food-CT-2005-023168
and then under SWUP-MED project (2008-2012), EU contract: KBBE-2008- 212337.
and currently under Water4Crops project (2012-2016), EU contract: KBBE.2012.3.5-03
These projects are jointly funded by the Natural Environment Research Council, NERC, UK.

SALTMED 2022

Model run dates
dd/mm/yyyy
Start Date 01/03/1999
End Date 31/03/1999

Soil and Crop Database
C:\Program Files (x86)\Saltmed\SALTMED_02.accdb

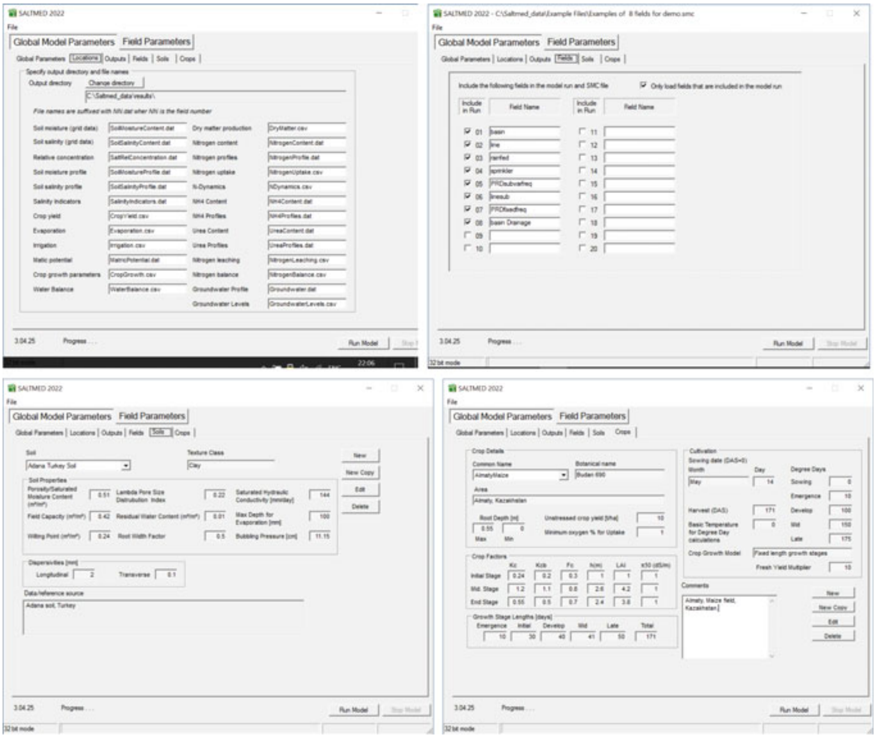
☐ Exit Model on First Day

3.04.25 Progress ...

32 bit mode

Fig. 4 SALTMED model opening frame (left) and global parameters tab (right)

The model has two tabs, global parameters tab, (Fig. 4 right side) where parameters are common to all field and not associated with any particular field and field parameters tab where parameters differ from one field to another. Under the global parameters (Fig. 5), the user can specify the fields or treatments up to 20 fields/treatments, decide on the name and location of the results folder where the model will be recording the results of each field, specify the soil properties of the soil of the study site, and specify the crop properties as shown in Fig. 5. Both soil and crop properties are saved into the input database and called within each field tab. Figure 6 shows some output presented on screen during the model run.



Specify output directory and file names

Output directory: C:\Saltmed_data\results\

File names are suffixed with NN.dat wher NN is the field number

Soil moisture (grid data)	SoilMoistureContent.dat	Dry matter production	DryMatter.csv
Soil salinity (grid data)	SoilSalinityContent.dat	Nitrogen content	NitrogenContent.dat
Relative concentration	SaltRelConcentration.dat	Nitrogen profiles	NitrogenProfile.dat
Soil moisture profile	SoilMoistureProfile.dat	Nitrogen uptake	NitrogenUptake.csv
Soil salinity profile	SoilSalinityProfile.dat	N-Dynamics	NDynamics.csv
Salinity indicators	SalinityIndicators.dat	NH4 Content	NH4Content.dat
Crop yield	CropYield.csv	NH4 Profiles	NH4Profiles.dat
Evaporation	Evaporation.csv	Urea Content	UreaContent.dat
Irrigation	Irrigation.csv	Urea Profiles	UreaProfiles.dat
Matic potential	MatricPotential.dat	Nitrogen leaching	NitrogenLeaching.csv
Crop growth parameters	CropGrowth.csv	Nitrogen balance	NitrogenBalance.csv
Water Balance	WaterBalance.csv	Groundwater Profile	Groundwater.dat
		Groundwater Levels	GroundwaterLevels.csv

Include the following fields in the model run and SMC file

☑ Only load fields that are included in the model run

Include in Run	Field Name	Include in Run	Field Name
☑ 01	basin	☐ 11	
☑ 02	line	☐ 12	
☑ 03	rainfed	☐ 13	
☑ 04	sprinkler	☐ 14	
☑ 05	PRDsubvarfreq	☐ 15	
☑ 06	linesub	☐ 16	
☑ 07	PRDfixedfreq	☐ 17	
☑ 08	basin Drainage	☐ 18	
☐ 09		☐ 19	
☐ 10		☐ 20	

Soil: Adana Turkey Soil

Texture Class: Clay

Soil Properties

Porosity/Saturated Moisture Content (m^3/m^3)	0.51	Lambda Pore Size Distrubution Index	0.22	Saturated Hydraulic Conductivity [mm/day]	144
Field Capacity (m^3/m^3)	0.42	Residual Water Content (m^3/m^3)	0.01	Max Depth for Evaporation [mm]	100
Wilting Point (m^3/m^3)	0.24	Root Width Factor	0.5	Bubbling Pressure [cm]	11.15

Dispersivities [mm]: Longitudinal 2, Transverse 0.1

Data/reference source: Adana soil, Turkey

Crop Details

Common Name: AlmatyMaize

Botanical name: Budan 690

Area: Almaty, Kazakhstan

Root Depth [m]: Max 0.55, Min 0

Unstressed crop yield [t/ha]: 10

Minimum oxygen % for Uptake: 1

Crop Factors

	Kc	Kcb	Fc	h(m)	LAI	ec50 (dS/m)
Initial Stage	0.24	0.2	0.3	1	1	1
Mid. Stage	1.2	1.1	0.8	2.6	4.2	1
End Stage	0.55	0.5	0.7	2.4	3.8	1

Growth Stage Lengths [days]

Emergence	Initial	Develop	Mid	Late	Total
10	30	40	41	50	171

Cultivation

Sowing date (DAS=0): Month May, Day 14

Harvest (DAS): 171

Basic Temperature for Degree Day calculations: 0

Degree Days: Sowing 0, Emergence 10, Develop 100, Mid 150, Late 175

Crop Growth Model: Fixed length growth stages

Fresh Yield Multiplier: 10

Comments: Almaty, Maize field, Kazakhstan

Fig. 5 Outputs tab (top left), Fields tab (top right), Soils tab (bottom left), and Crops tab (bottom right)

Example of Output:

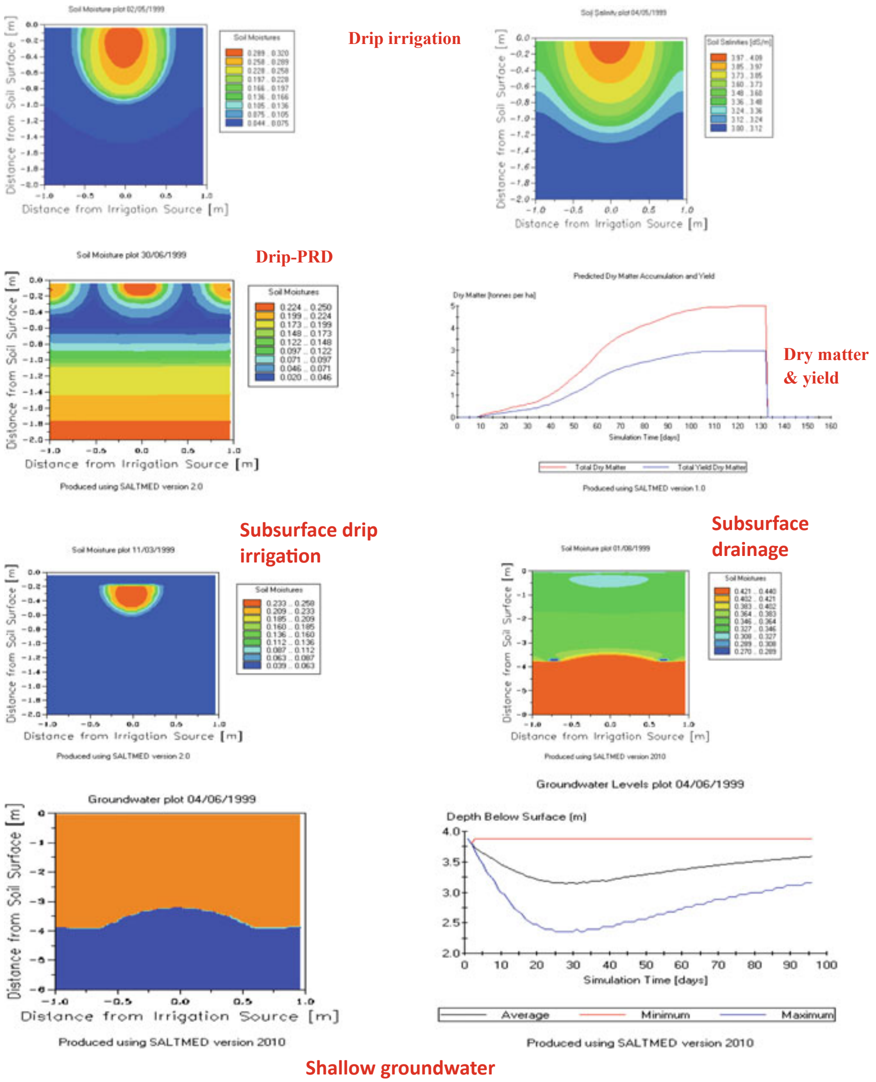
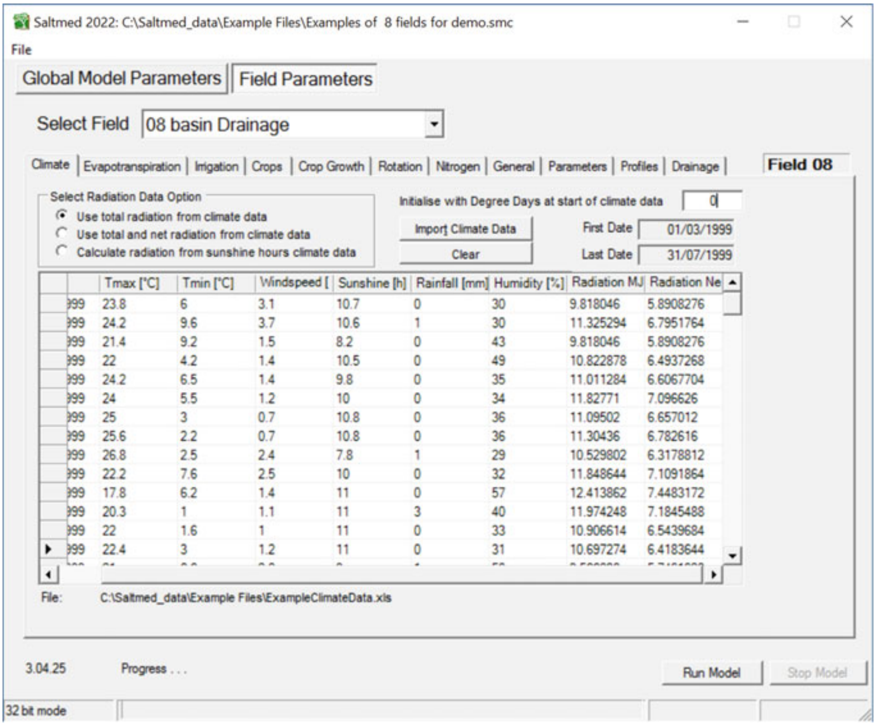


Fig. 6 Examples of output figures of SALTMED model

3 SALTMED Input Data Requirement

The data required depends on the selected application options and the interest of the user. The user does not need to provide all the information in the model tabs. For example, if no drainage system is present, the user does not need to fill in the data for the drainage tab. The model has more than one option for some applications, such as evapotranspiration, but the user does not need to provide data for all options and can just provide the necessary data and parameters for one evapotranspiration option. In the following sections, the model tabs will be shown and the data requirement for each tab will be highlighted. The model can run with up to 20 different fields or 20 treatments. Each field or treatment will require its own input, there is no input sharing among fields or treatments. The input data for the different model tabs will be discussed starting from left to right.

3.1 The Climate Data Tab



Saltmed 2022: C:\Saltmed_data\Example Files\Examples of 8 fields for demo.smc

Select Field: 08 basin Drainage

Field 08

Select Radiation Data Option
● Use total radiation from climate data
○ Use total and net radiation from climate data
○ Calculate radiation from sunshine hours climate data

Initialise with Degree Days at start of climate data: 0

First Date: 01/03/1999

Last Date: 31/07/1999

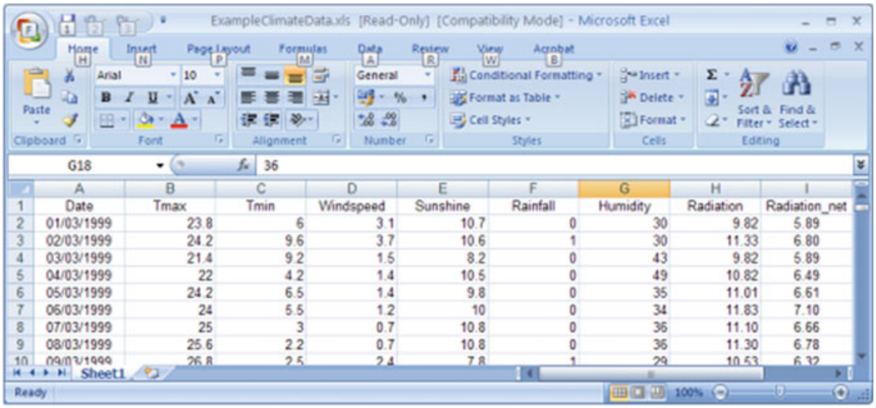
	Tmax [°C]	Tmin [°C]	Windspeed [	Sunshine [h]	Rainfall [mm]	Humidity [%]	Radiation MJ	Radiation Ne
99	23.8	6	3.1	10.7	0	30	9.818046	5.8908276
99	24.2	9.6	3.7	10.6	1	30	11.325294	6.7951764
99	21.4	9.2	1.5	8.2	0	43	9.818046	5.8908276
99	22	4.2	1.4	10.5	0	49	10.822878	6.4937268
99	24.2	6.5	1.4	9.8	0	35	11.011284	6.6067704
99	24	5.5	1.2	10	0	34	11.82771	7.096626
99	25	3	0.7	10.8	0	36	11.09502	6.657012
99	25.6	2.2	0.7	10.8	0	36	11.30436	6.782616
99	26.8	2.5	2.4	7.8	1	29	10.529802	6.3178812
99	22.2	7.6	2.5	10	0	32	11.848644	7.1091864
99	17.8	6.2	1.4	11	0	57	12.413862	7.4483172
99	20.3	1	1.1	11	3	40	11.974248	7.1845488
99	22	1.6	1	11	0	33	10.906614	6.5439684
99	22.4	3	1.2	11	0	31	10.697274	6.4183644

File: C:\Saltmed_data\Example Files\ExampleClimateData.xls

3.04.25 Progress . . .

As shown, the **daily data** required is:

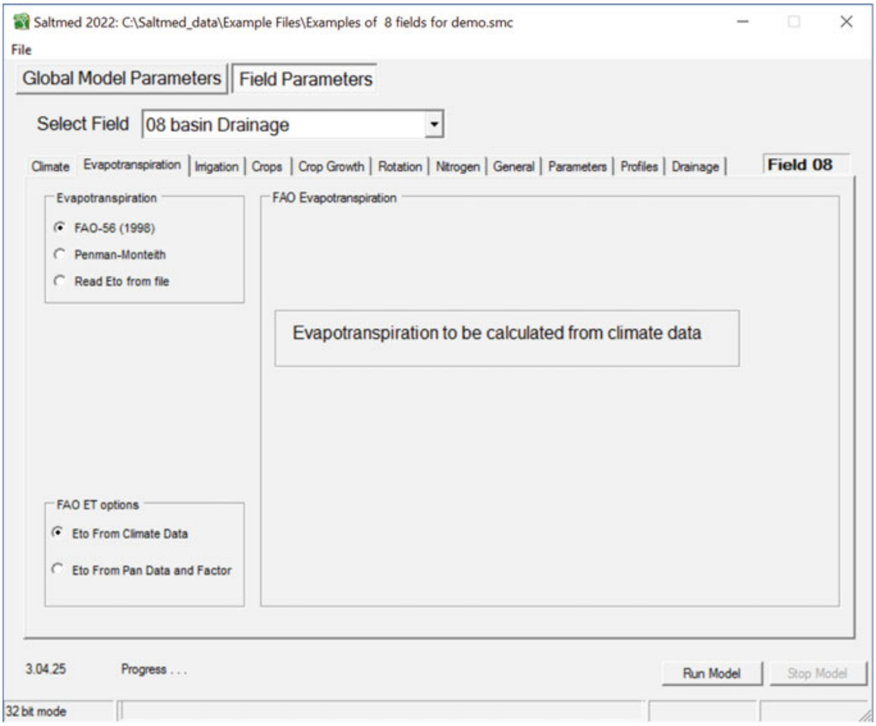
Maximum and minimum temperatures in °C
Wind speed in meters/seconds
Sunshine hours in hours (this is optional if radiation data is not available)
Rainfall in mm/day
Relative Humidity in %
Total solar radiation in MJ/m^2/day
Net radiation in MJ/m^2/day
The data are imported from excel file (*.xls or *.xlsx) or from tables of Access database.



	A	B	C	D	E	F	G	H	I
1	Date	Tmax	Tmin	Windspeed	Sunshine	Rainfall	Humidity	Radiation	Radiation_net
2	01/03/1999	23.8	6	3.1	10.7	0	30	9.82	5.89
3	02/03/1999	24.2	9.6	3.7	10.6	1	30	11.33	6.80
4	03/03/1999	21.4	9.2	1.5	8.2	0	43	9.82	5.89
5	04/03/1999	22	4.2	1.4	10.5	0	49	10.82	6.49
6	05/03/1999	24.2	6.5	1.4	9.8	0	35	11.01	6.61
7	06/03/1999	24	5.5	1.2	10	0	34	11.83	7.10
8	07/03/1999	25	3	0.7	10.8	0	36	11.10	6.66
9	08/03/1999	25.6	2.2	0.7	10.8	0	36	11.30	6.78
10	09/03/1999	26.8	2.5	2.4	7.8	1	29	10.53	6.32

3.2 *The Evapotranspiration Tab*

The evapotranspiration is calculated by different methods. The user needs to select only one.



Select Field: 08 basin Drainage

Field 08

Evapotranspiration
- ● FAO-56 (1998)
- ○ Penman-Monteith
- ○ Read Eto from file

FAO ET options
- ● Eto From Climate Data
- ○ Eto From Pan Data and Factor

FAO Evapotranspiration

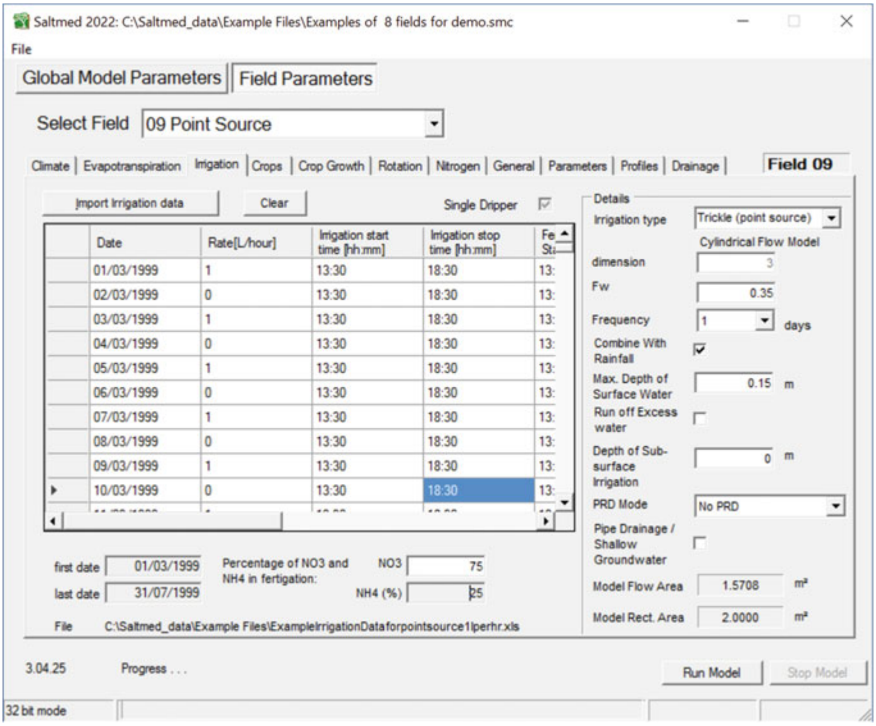
Evapotranspiration to be calculated from climate data

3.3 The Irrigation Tab

The data required are:

Irrigation rate (amount) in liter/hour, except for furrow and trickle line source in liter/meter of line or furrow length/hour.

1. Irrigation start time and stoppage time in the format of hours and minutes: hh:mm
2. Fertigation start and stoppage time (if fertigation is used): hh:mm
3. Water salinity in dS/m
4. Nitrogen in water in mg/l if fertigation is used. If ammonium nitrate is used, specify the % of ammonium to nitrate, as shown at the bottom of the tab.
5. Urea concentration in water in mg/l if urea is used in the fertigation.



Select Field: 09 Point Source

Single Dripper ☑

	Date	Rate[L/hour]	Irrigation start time [hh:mm]	Irrigation stop time [hh:mm]	Fe St
	01/03/1999	1	13:30	18:30	13:
	02/03/1999	0	13:30	18:30	13:
	03/03/1999	1	13:30	18:30	13:
	04/03/1999	0	13:30	18:30	13:
	05/03/1999	1	13:30	18:30	13:
	06/03/1999	0	13:30	18:30	13:
	07/03/1999	1	13:30	18:30	13:
	08/03/1999	0	13:30	18:30	13:
	09/03/1999	1	13:30	18:30	13:
▶	10/03/1999	0	13:30	18:30	13:

first date 01/03/1999

last date 31/07/1999

Percentage of NO3 and NH4 in fertigation: NO3 75

NH4 (%) 25

File C:\Saltmed_data\Example Files\ExampleIrrigationDataforpointsource1lperhr.xls

Details

Irrigation type: Trickle (point source)

Cylindrical Flow Model

dimension 3

Fw 0.35

Frequency 1 days

Combine With Rainfall ☑

Max. Depth of Surface Water 0.15 m

Run off Excess water ☐

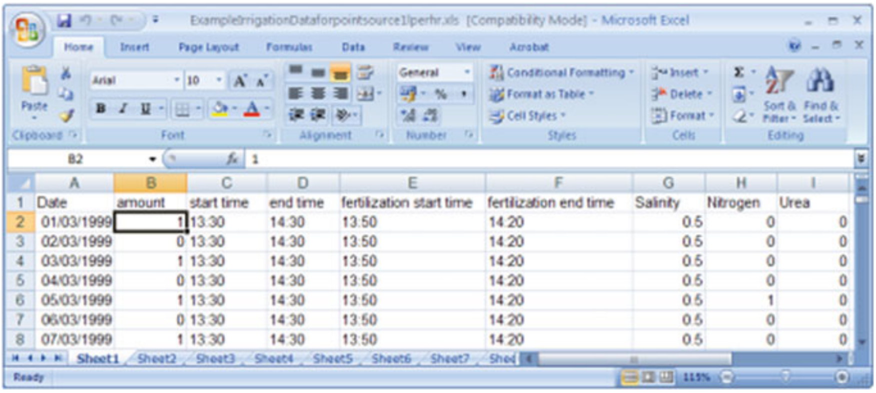
Depth of Sub-surface Irrigation 0 m

PRD Mode: No PRD

Pipe Drainage / Shallow Groundwater ☐

Model Flow Area 1.5708 m^2

Model Rect. Area 2.0000 m^2

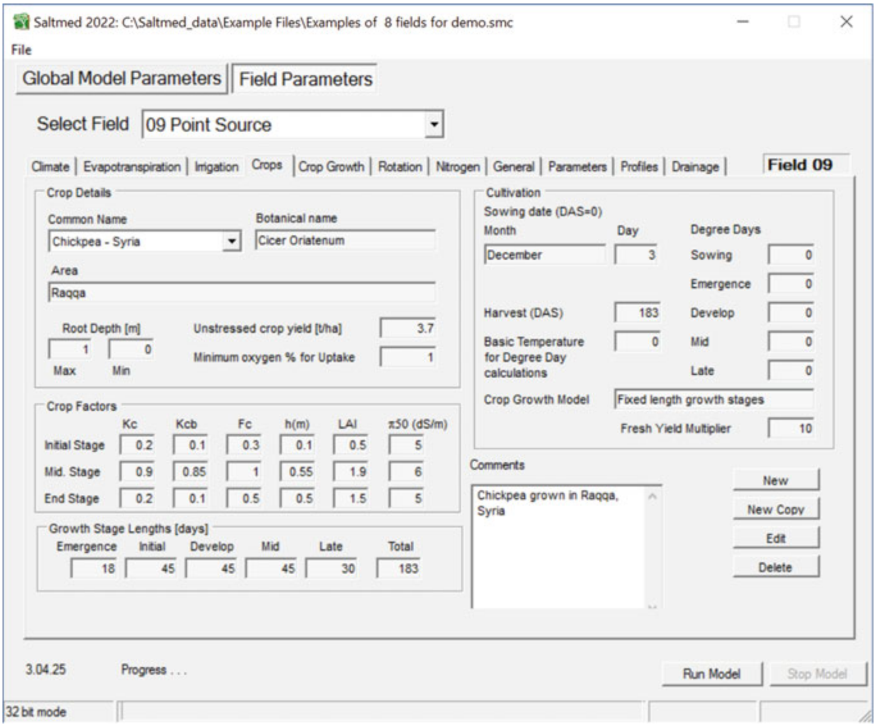


	A	B	C	D	E	F	G	H	I
1	Date	amount	start time	end time	fertilization start time	fertilization end time	Salinity	Nitrogen	Urea
2	01/03/1999	1	13:30	14:30	13:50	14:20	0.5	0	0
3	02/03/1999	0	13:30	14:30	13:50	14:20	0.5	0	0
4	03/03/1999	1	13:30	14:30	13:50	14:20	0.5	0	0
5	04/03/1999	0	13:30	14:30	13:50	14:20	0.5	0	0
6	05/03/1999	1	13:30	14:30	13:50	14:20	0.5	1	0
7	06/03/1999	0	13:30	14:30	13:50	14:20	0.5	0	0
8	07/03/1999	1	13:30	14:30	13:50	14:20	0.5	0	0

3.4 *Crop Parameters Tab*

The parameters required are:

1. Minimum and maximum rooting depth in meters
2. FAO-56 crop coefficients Kc, Kcb, fraction cover, Fc for initial, middle, and late growth stages. FAO-56 Irrigation and Drainage paper (Allen et al.1998) provides more information.
3. Crop height in meter, Leaf area index, LAI (total area of leaves in m^2/m^2 of soil area), and π_{50} (the osmotic pressure at which the water uptake is reduced to 50% of the maximum or potential water uptake) for each growth stage. This is an indicator of crop salinity tolerance. High values mean the crop is more tolerant to salinity; the crop salinity tolerance also varies according to the stage of growth.
4. Duration (days) of initial, development, mid, and late growth stages according to FAO-56 (Allen et al. 1998).
5. Sowing date, harvest date, days from sowing to emergency.
6. Minimum basic temperature for growth in °C.
7. Optional: In case the user is interested in using degree days/heat units for crop growth rather than fixed dates, the user will need to input the number of degree days/heat units required to reach each growth stage until harvest. This is useful for those interested in climate change impact on sowing and harvest dates, total biomass and yield, water balance component, nitrogen dynamics, and other relevant output of the model.



Select Field: 09 Point Source

Field 09

Crop Details

Common Name: Chickpea - Syria

Botanical name: Cicer Oriatenum

Area: Raqqa

Root Depth [m]: Max 1, Min 0

Unstressed crop yield [t/ha]: 3.7

Minimum oxygen % for Uptake: 1

Crop Factors

	Kc	Kcb	Fc	h(m)	LAI	π50 (dS/m)
Initial Stage	0.2	0.1	0.3	0.1	0.5	5
Mid. Stage	0.9	0.85	1	0.55	1.9	6
End Stage	0.2	0.1	0.5	0.5	1.5	5

Growth Stage Lengths [days]

Emergence	Initial	Develop	Mid	Late	Total
18	45	45	45	30	183

Cultivation

Sowing date (DAS=0): Month December, Day 3

Harvest (DAS): 183

Basic Temperature for Degree Day calculations: 0

Degree Days: Sowing 0, Emergence 0, Develop 0, Mid 0, Late 0

Crop Growth Model: Fixed length growth stages

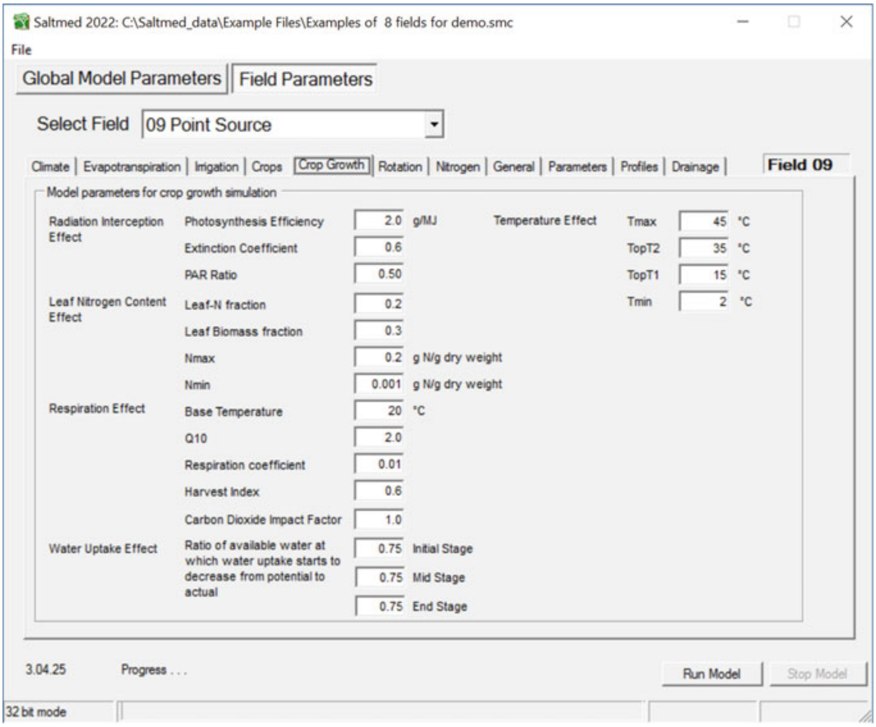
Fresh Yield Multiplier: 10

Comments: Chickpea grown in Raqqa, Syria

3.04.25 Progress . . .

3.5 Crop Growth Tab

The crop growth is calculated as a function of radiation, photosynthesis efficiency (gram dry matter/MJ radiation), stress factors related to water availability, temperature, nitrogen content of leaves, respiration losses (%), minimum, maximum, and optimum temperatures (°C) for growth. These parameters are obtainable by measurements or from literature or by calibration using the default values as starting values. Measured values are always preferred.



Select Field: 09 Point Source

Field 09

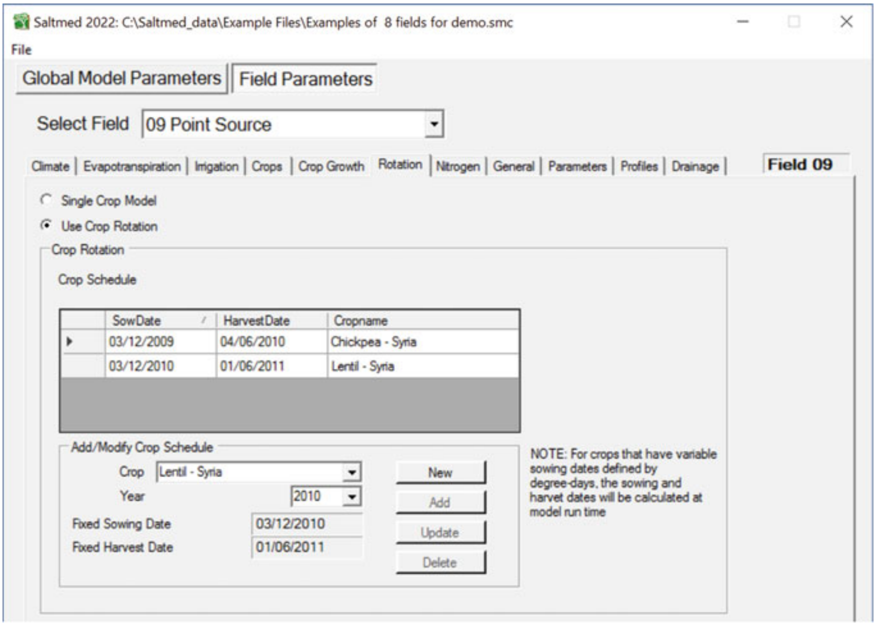
Model parameters for crop growth simulation

Radiation Interception Effect	Photosynthesis Efficiency	2.0	g/MJ
	Extinction Coefficient	0.6	
	PAR Ratio	0.50	
Leaf Nitrogen Content Effect	Leaf-N fraction	0.2	
	Leaf Biomass fraction	0.3	
	Nmax	0.2	g N/g dry weight
	Nmin	0.001	g N/g dry weight
Respiration Effect	Base Temperature	20	°C
	Q10	2.0	
	Respiration coefficient	0.01	
	Harvest Index	0.6	
	Carbon Dioxide Impact Factor	1.0	
Water Uptake Effect	Ratio of available water at which water uptake starts to decrease from potential to actual	0.75	Initial Stage
		0.75	Mid Stage
		0.75	End Stage

Temperature Effect		
Tmax	45	°C
TopT2	35	°C
TopT1	15	°C
Tmin	2	°C

a. Crop rotation tab

The user can select either single crop or select rotation from the dropdown menu. For rotation, the user needs to select the name of the crop, sowing date, and harvest date from the crop database. The crop parameters included in the rotation should have been stored in the database in advance using the crop tab editor under global parameters tab.



Select Field: 09 Point Source

Field 09

○ Single Crop Model

● Use Crop Rotation

Crop Rotation

Crop Schedule

SowDate	HarvestDate	Cropname
03/12/2009	04/06/2010	Chickpea - Syria
03/12/2010	01/06/2011	Lentil - Syria

Add/Modify Crop Schedule

Crop: Lentil - Syria

Year: 2010

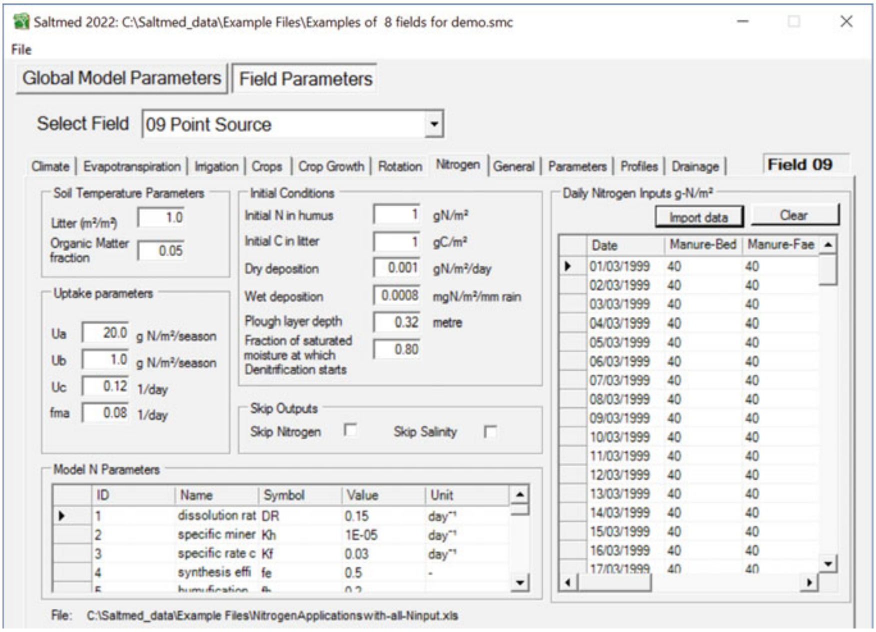
Fixed Sowing Date: 03/12/2010

Fixed Harvest Date: 01/06/2011

NOTE: For crops that have variable sowing dates defined by degree-days, the sowing and harvest dates will be calculated at model run time

b. Nitrogen tab

If nitrogen is added in dry form (organic or mineral), not with irrigation water (fertigation), the user needs to specify the amount of nitrogen fertilizer in gram N/m^2 of soil surface. The data should be given in an excel file that includes the date and amount given. The data should be organized using the format of the example file (see Figure below). If Fertigation is used, the user can tick the box of “skip Nitrogen” without a need to import a nitrogen file. In addition to daily nitrogen input, there are other parameters related to nitrogen uptake by plant, dry, and wet atmospheric deposition of nitrogen, initial nitrogen content of soil humus (gram nitrogen/m^2), and initial carbon content in soil litter (gram carbon/m2 of soil), litter distribution (m^2 litter/m^2 soil), and soil organic matter percent (% of soil mass). In addition, there are other parameters related to rate constants (rate of mineralization, rate of denitrification, etc.), C/N ratios, dissolution rates, etc., are saved in the input database and can be edited through Microsoft Access.



Select Field: 09 Point Source

Soil Temperature Parameters

Litter (m^2/m^2): 1.0

Organic Matter fraction: 0.05

Uptake parameters

Ua: 20.0 g N/m^2/season

Ub: 1.0 g N/m^2/season

Uc: 0.12 1/day

fma: 0.08 1/day

Initial Conditions

Initial N in humus: 1 gN/m^2

Initial C in litter: 1 gC/m^2

Dry deposition: 0.001 gN/m^2/day

Wet deposition: 0.0008 mgN/m^2/mm rain

Plough layer depth: 0.32 metre

Fraction of saturated moisture at which Denitrification starts: 0.80

Skip Outputs

Skip Nitrogen ☐ Skip Salinity ☐

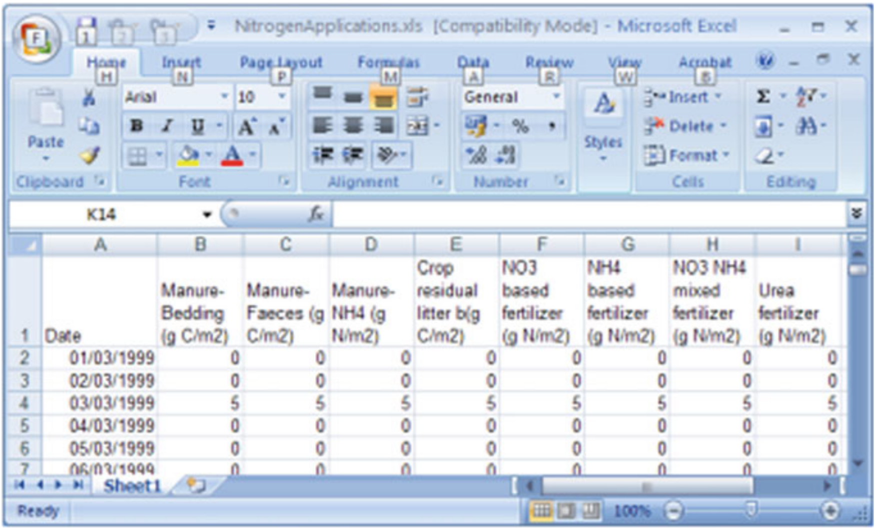
Model N Parameters

ID	Name	Symbol	Value	Unit
1	dissolution rat	DR	0.15	day^{-1}
2	specific miner	Kh	1E-05	day^{-1}
3	specific rate c	Kf	0.03	day^{-1}
4	synthesis effi	fe	0.5	-
5	humufication	fh	0.2	

Daily Nitrogen Inputs g-N/m²

Date	Manure-Bed	Manure-Fae
01/03/1999	40	40
02/03/1999	40	40
03/03/1999	40	40
04/03/1999	40	40
05/03/1999	40	40
06/03/1999	40	40
07/03/1999	40	40
08/03/1999	40	40
09/03/1999	40	40
10/03/1999	40	40
11/03/1999	40	40
12/03/1999	40	40
13/03/1999	40	40
14/03/1999	40	40
15/03/1999	40	40
16/03/1999	40	40
17/03/1999	40	40

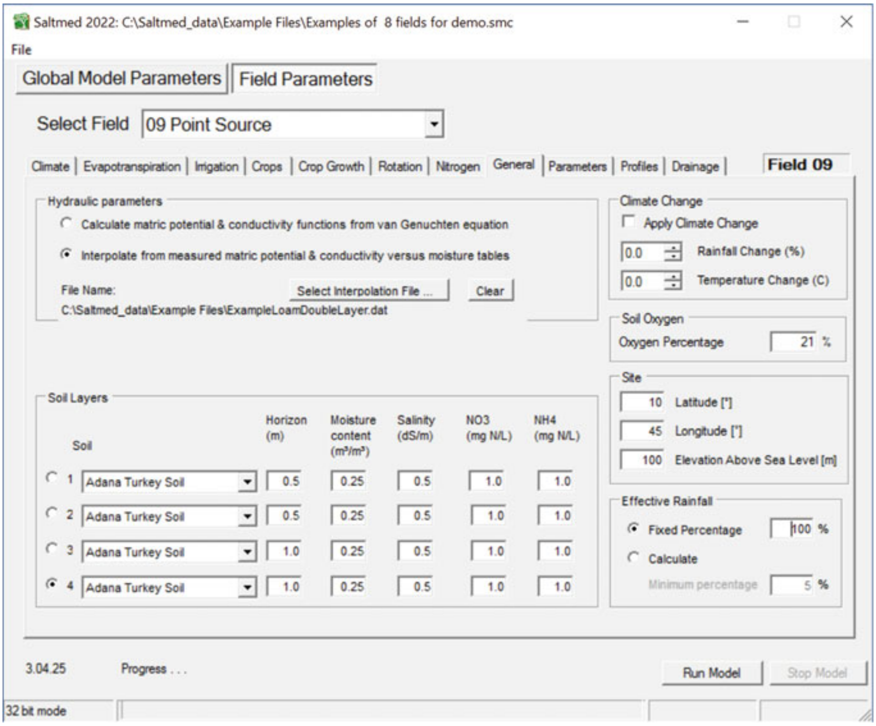
File: C:\Saltmed_data\Example Files\NitrogenApplicationswith-all-Ninput.xls



	A	B	C	D	E	F	G	H	I
1	Date	Manure-Bedding (g C/m2)	Manure-Faeces (g C/m2)	Manure-NH4 (g N/m2)	Crop residual litter b(g C/m2)	NO3 based fertilizer (g N/m2)	NH4 based fertilizer (g N/m2)	NO3 NH4 mixed fertilizer (g N/m2)	Urea fertilizer (g N/m2)
2	01/03/1999	0	0	0	0	0	0	0	0
3	02/03/1999	0	0	0	0	0	0	0	0
4	03/03/1999	5	5	5	5	5	5	5	5
5	04/03/1999	0	0	0	0	0	0	0	0
6	05/03/1999	0	0	0	0	0	0	0	0
7	06/03/1999	0	0	0	0	0	0	0	0

c. General tab

This tab allows the user to specify initial conditions (first day of model run) of soil moisture (m^3 water/m^3 soil), soil salinity (dS/m), soil Nitrate NO_3 (mg N/l), and soil NH_4 (mg N/l) for each soil layer, maximum 4 layers. The thickness of each layer should be given. On the same tab, there are two options to obtain the water retention curve and hydraulic conductivity curve. These two functions can either be calculated from other soil parameters given in the soil tab (under Global parameters tab) or from measured and tabulated pair values: soil moisture (m^3/m^3) versus water potential (m), and hydraulic conductivity (meter/second) versus soil moisture (m^3/m^3). Examples of these pair values are given in example files folder provided by the model.



Saltmed 2022: C:\Saltmed_data\Example Files\Examples of 8 fields for demo.smc

Select Field: 09 Point Source

Field 09

Hydraulic parameters

○ Calculate matric potential & conductivity functions from van Genuchten equation

● Interpolate from measured matric potential & conductivity versus moisture tables

File Name: C:\Saltmed_data\Example Files\ExampleLoamDoubleLayer.dat

Soil Layers

	Soil	Horizon (m)	Moisture content (m^3/m^3)	Salinity (dS/m)	NO3 (mg N/L)	NH4 (mg N/L)
○ 1	Adana Turkey Soil	0.5	0.25	0.5	1.0	1.0
○ 2	Adana Turkey Soil	0.5	0.25	0.5	1.0	1.0
○ 3	Adana Turkey Soil	1.0	0.25	0.5	1.0	1.0
● 4	Adana Turkey Soil	1.0	0.25	0.5	1.0	1.0

Climate Change

☐ Apply Climate Change

0.0 Rainfall Change (%)

0.0 Temperature Change (C)

Soil Oxygen

Oxygen Percentage 21 %

Site

10 Latitude [°]

45 Longitude [°]

100 Elevation Above Sea Level [m]

Effective Rainfall

● Fixed Percentage 100 %

○ Calculate

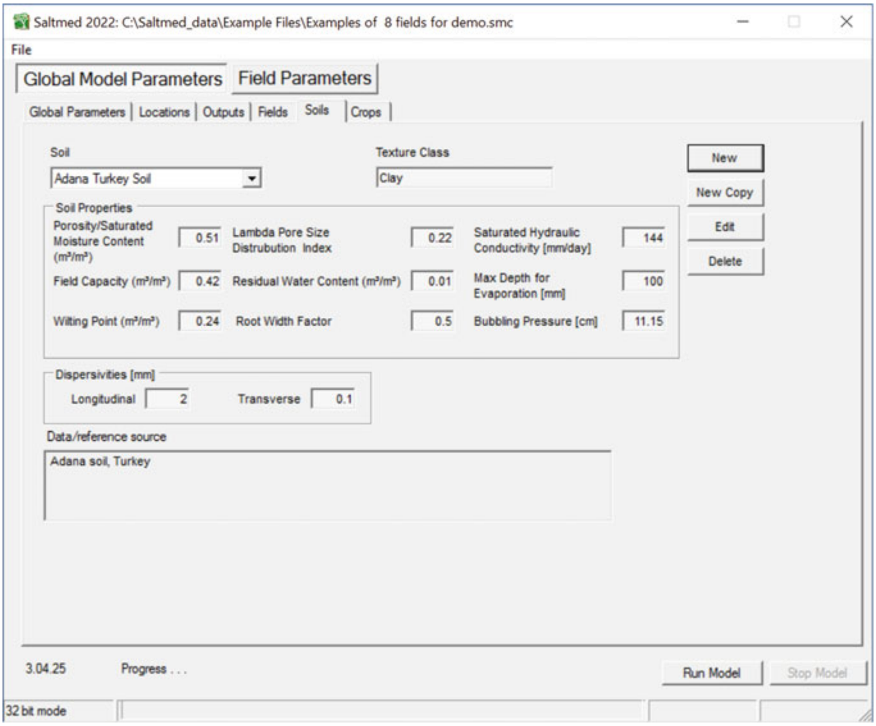
Minimum percentage 5 %

3.04.25 Progress . . .

32 bit mode

d. Soil parameters

An example of water retention and hydraulic conductivity measured values to be used in SALTMED is shown hereunder. First row is number of pair values (20), followed by volumetric soil moisture, m^3/m^3 (left) versus hydraulic conductivity, m/s (right), then another 20 values of soil moisture, m^3/m^3, versus water potential (m). This shown data is for a soil of single layer of loam. If more than one layer exists with different water retention and conductivity functions then using the same format, just add the other layers to the same file, one layer after the other (maximum 4 layers), see example files folder provided by the model.



Saltmed 2022: C:\Saltmed_data\Example Files\Examples of 8 fields for demo.smc

Soil: Adana Turkey Soil

Texture Class: Clay

Soil Properties

Porosity/Saturated Moisture Content (m^3/m^3): 0.51

Lambda Pore Size Distrubution Index: 0.22

Saturated Hydraulic Conductivity [mm/day]: 144

Field Capacity (m^3/m^3): 0.42

Residual Water Content (m^3/m^3): 0.01

Max Depth for Evaporation [mm]: 100

Wilting Point (m^3/m^3): 0.24

Root Width Factor: 0.5

Bubbling Pressure [cm]: 11.15

Dispersivities [mm]

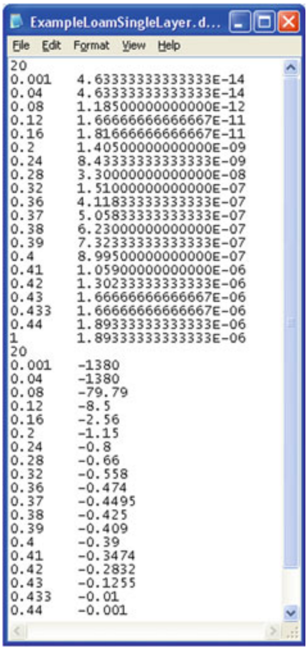
Longitudinal: 2

Transverse: 0.1

Data/reference source: Adana soil, Turkey

3.04.25 Progress . . .

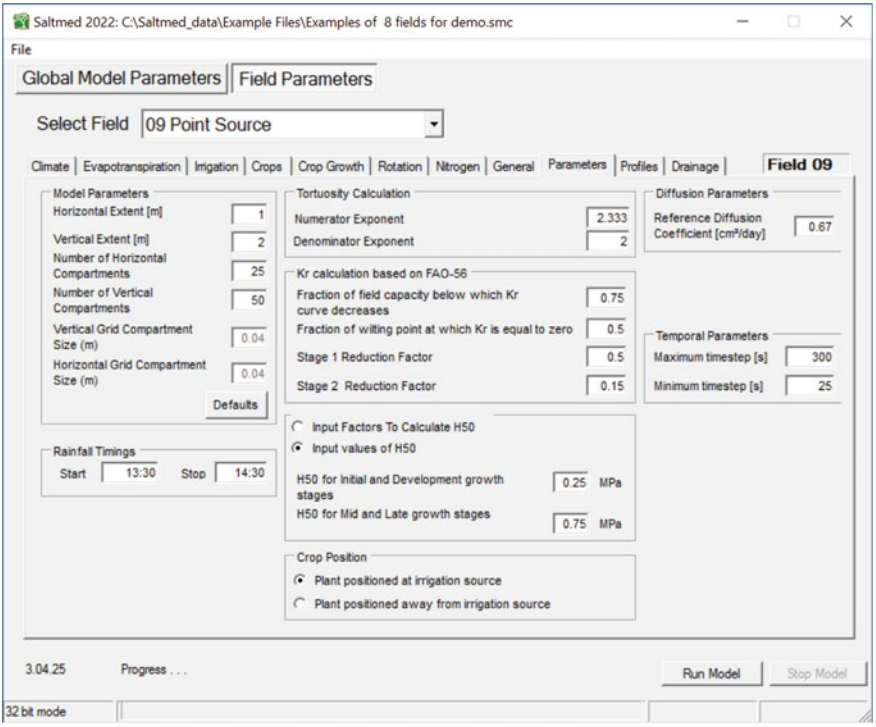
32 bit mode



```
20
0.001    4.63333333333333E-14
0.04     4.63333333333333E-14
0.08     1.18500000000000E-12
0.12     1.66666666666667E-11
0.16     1.81666666666667E-11
0.2      1.40500000000000E-09
0.24     8.43333333333333E-09
0.28     3.30000000000000E-08
0.32     1.51000000000000E-07
0.36     4.11833333333333E-07
0.37     5.05833333333333E-07
0.38     6.23000000000000E-07
0.39     7.32333333333333E-07
0.4      8.99500000000000E-07
0.41     1.05900000000000E-06
0.42     1.30233333333333E-06
0.43     1.66666666666667E-06
0.433    1.66666666666667E-06
0.44     1.89333333333333E-06
1        1.89333333333333E-06
20
0.001    -1380
0.04     -1380
0.08     -79.79
0.12     -8.5
0.16     -2.56
0.2      -1.15
0.24     -0.8
0.28     -0.66
0.32     -0.558
0.36     -0.474
0.37     -0.4495
0.38     -0.425
0.39     -0.409
0.4      -0.39
0.41     -0.3474
0.42     -0.2832
0.43     -0.1255
0.433    -0.01
0.44     -0.001
```

3.6 Parameters Tab

This tab includes a number of parameters. Depth and width of the model flow domain and size of each square in the flow domain. The model flow domain is divided into squares with default size of 4 cm by 4 cm. However, the size of the flow domain and size of the squares can be changed by the user. The model calculates the flows (water, solute, nitrogen) in each square of the domain. There are other parameters related to solute diffusivity, H_{50}, (the water potential at which the water uptake is reduced to 50% of the potential water uptake), parameters related to Kr which controls the bare soil evaporation as given in FAO-56 (Allen et al. 1998). Apart from the flow domain dimension, which is user input, the other parameters are default values but the user can change these values according to measurements or literature.



Select Field: 09 Point Source

Model Parameters
Horizontal Extent [m]: 1
Vertical Extent [m]: 2
Number of Horizontal Compartments: 25
Number of Vertical Compartments: 50
Vertical Grid Compartment Size (m): 0.04
Horizontal Grid Compartment Size (m): 0.04

Rainfall Timings
Start: 13:30
Stop: 14:30

Tortuosity Calculation
Numerator Exponent: 2.333
Denominator Exponent: 2

Kr calculation based on FAO-56
Fraction of field capacity below which Kr curve decreases: 0.75
Fraction of wilting point at which Kr is equal to zero: 0.5
Stage 1 Reduction Factor: 0.5
Stage 2 Reduction Factor: 0.15

○ Input Factors To Calculate H50
● Input values of H50
H50 for Initial and Development growth stages: 0.25 MPa
H50 for Mid and Late growth stages: 0.75 MPa

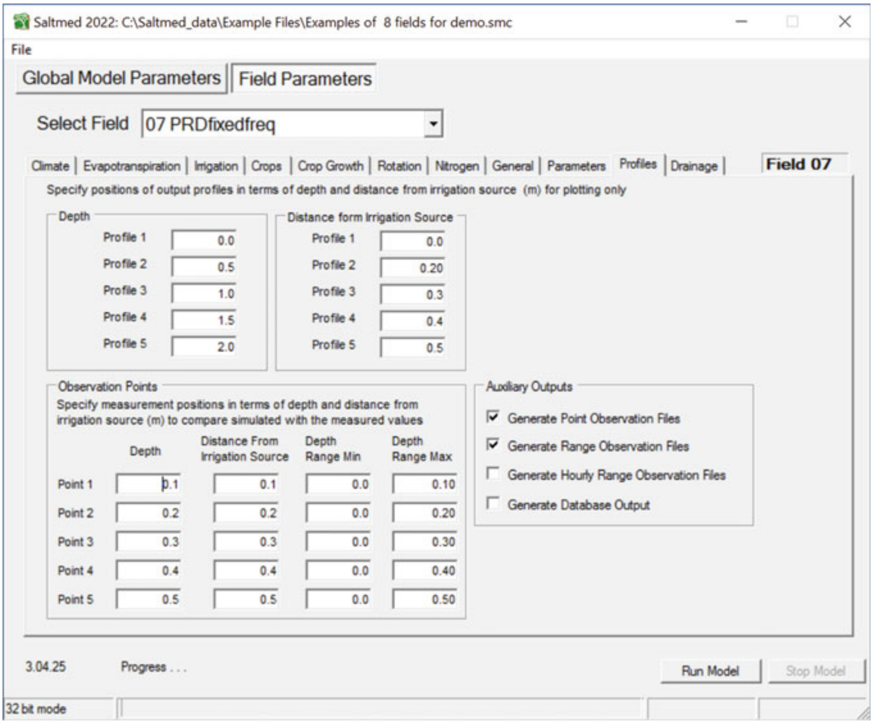
Crop Position
● Plant positioned at irrigation source
○ Plant positioned away from irrigation source

Diffusion Parameters
Reference Diffusion Coefficient [cm²/day]: 0.67

Temporal Parameters
Maximum timestep [s]: 300
Minimum timestep [s]: 25

3.7 Profiles Tab

This tab allows the user to specify what depth and how far from irrigation source, the soil moisture, soil salinity, and soil nitrogen profiles should be plotted in the figures that appear on the computer screen during the model run. In addition, the tab allows the user to select how the data should be recorded in the output file in order to compare measured values with simulated values. In such case, the user can request the simulated values to be recorded at the same depth and distance from the irrigation source exactly like the measured values so that, a comparison can be made in minutes using excel plotting facilities. The user can also request the same variables for certain layers (range values e.g., 0–30 cm, 40–60 cm depth). The user can also request to save the output in Access database if running huge data records (decades of years for climate change scenarios), these request options are shown in the figure below.



Select Field: 07 PRDfixedfreq

Specify positions of output profiles in terms of depth and distance from irrigation source (m) for plotting only

	Depth	Distance form Irrigation Source
Profile 1	0.0	0.0
Profile 2	0.5	0.20
Profile 3	1.0	0.3
Profile 4	1.5	0.4
Profile 5	2.0	0.5

Observation Points

Specify measurement positions in terms of depth and distance from irrigation source (m) to compare simulated with the measured values

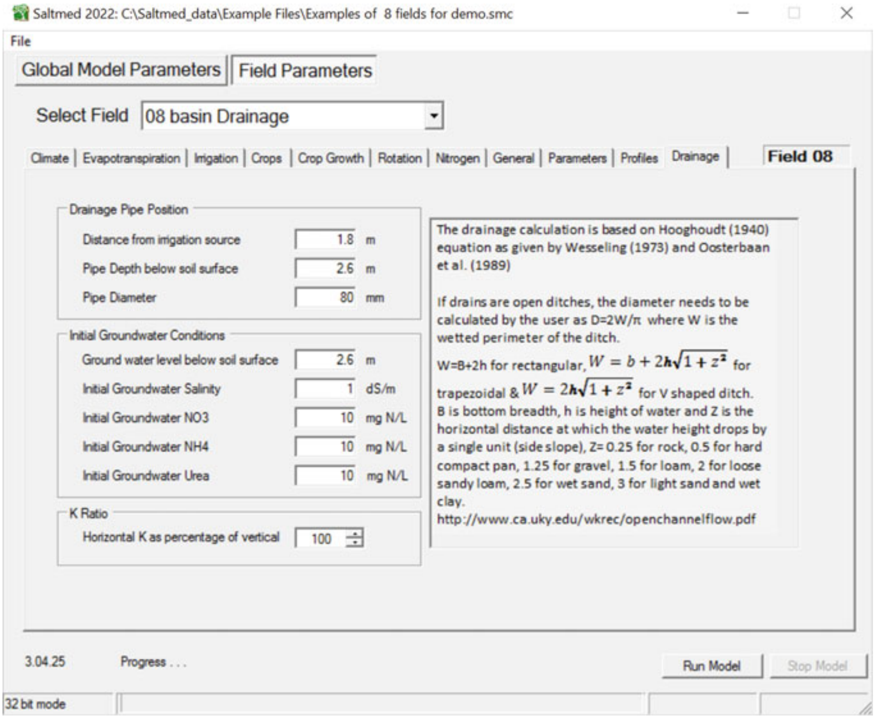
	Depth	Distance From Irrigation Source	Depth Range Min	Depth Range Max
Point 1	0.1	0.1	0.0	0.10
Point 2	0.2	0.2	0.0	0.20
Point 3	0.3	0.3	0.0	0.30
Point 4	0.4	0.4	0.0	0.40
Point 5	0.5	0.5	0.0	0.50

Auxiliary Outputs

☑ Generate Point Observation Files
☑ Generate Range Observation Files
☐ Generate Hourly Range Observation Files
☐ Generate Database Output

3.8 Drainage Tab

This tab can only be used in the case of presence of tile drains, open drains, or shallow groundwater. Parameters needed are depth of drains, their diameters, initial ground water salinity and nitrogen content, and ratio of horizontal hydraulic conductivity to the vertical conductivity (given in the soil tab).



Select Field: 08 basin Drainage

Drainage Pipe Position

Distance from irrigation source: 1.8 m
Pipe Depth below soil surface: 2.6 m
Pipe Diameter: 80 mm

Initial Groundwater Conditions

Ground water level below soil surface: 2.6 m
Initial Groundwater Salinity: 1 dS/m
Initial Groundwater NO3: 10 mg N/L
Initial Groundwater NH4: 10 mg N/L
Initial Groundwater Urea: 10 mg N/L

K Ratio

Horizontal K as percentage of vertical: 100

The drainage calculation is based on Hooghoudt (1940) equation as given by Wesseling (1973) and Oosterbaan et al. (1989)

If drains are open ditches, the diameter needs to be calculated by the user as D=2W/π where W is the wetted perimeter of the ditch.
W=B+2h for rectangular, $W = b + 2h\sqrt{1 + z^2}$ for trapezoidal & $W = 2h\sqrt{1 + z^2}$ for V shaped ditch.
B is bottom breadth, h is height of water and Z is the horizontal distance at which the water height drops by a single unit (side slope), Z= 0.25 for rock, 0.5 for hard compact pan, 1.25 for gravel, 1.5 for loam, 2 for loose sandy loam, 2.5 for wet sand, 3 for light sand and wet clay.
http://www.ca.uky.edu/wkrec/openchannelflow.pdf

3.8.1 Pipe Location and Dimensions

The model allows for a single pipe to be positioned within a field, at a specified distance from the irrigation source and depth below the surface (this pipe is mirrored to the other side of the irrigation source). The diameter of the pipe may also be defined.

3.8.2 Initial Groundwater Conditions

It is generally assumed that the soil below the drainage pipe is saturated, i.e., it is nominally the groundwater level. For the model to function correctly, the groundwater must not be allowed to act as recharge to the geology below the bottom soil layer since this could result in the soil moisture dropping below saturation, and flow into the pipes would be reduced or stopped. To prevent this situation, the bottom of the soil is assumed to be impermeable in the pipe drainage model, and this means that the main exit route for water leaving the model is via the pipe.

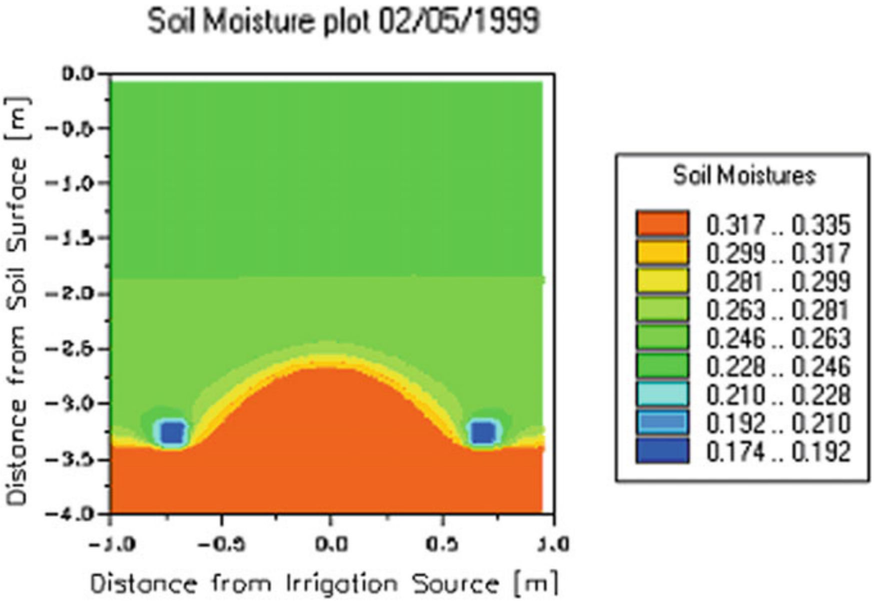
When a model runs with very dry soil it may take many weeks or months for irrigation to saturate the soil below the pipe and reach an equilibrium situation. To cut short this process, the model can be initialized with the groundwater below a specified depth. This means the model will start to function properly much more quickly.

The initial groundwater conditions also allow the specification of initial salinity, nitrogen, and urea.

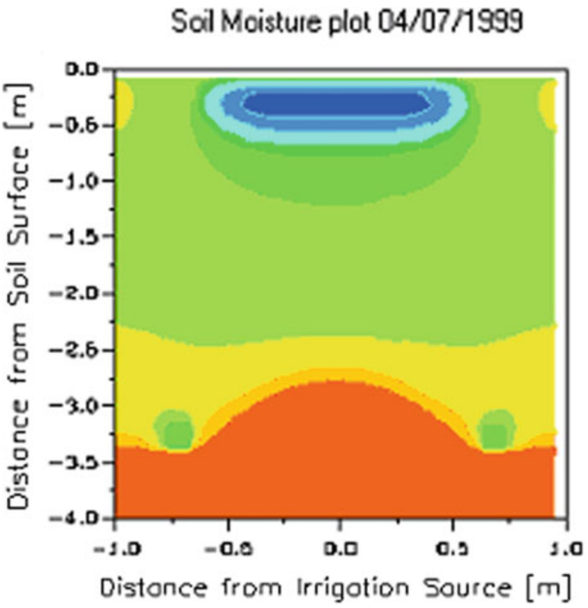
3.8.3 K Ratio

The conductivity of the soil layers may not be the same in the vertical and horizontal planes. The “K Ratio” field allows the horizontal conductivity to be defined as a percentage of the vertical conductivity. In absence of measurements or estimations, as a role of thump, the horizontal may be taken as one-third of the vertical conductivity.

A drainage model will normally be expected to exhibit a “dome” in soil moisture rising to approximately half the distance between the two drainage pipes that appear on the output graphs. A typical example is shown in the figure below:



The pipe locations can be clearly seen. In the example, we have not used a crop in order to simplify the output. Adding a crop into the model will tend to reduce the moisture values above the “dome”, as illustrated in the figure below:

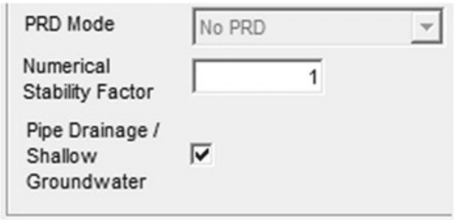


Obtaining this characteristic in a specific model usually requires some fine tuning and repeated running of the model changing one parameter at a time. Some hints to aid this tuning are as follows:

Behavior	Possible Cause	Parameter to change
"Dome" collapses to being low or even flat	Horizontal conductivity too high	Reduce "K Ratio" of horizontal conductivity to vertical conductivity
	Irrigation input too low	Increase irrigation via the input irrigation spreadsheets
	Pipe diameter too big	Reduce Pipe diameter
"Dome" rises too high and overpowers pipes	Horizontal conductivity too high	Increase "K Ratio" of horizontal conductivity to vertical conductivity
	Irrigation input too high	Reduce irrigation via the input irrigation spreadsheets
	Pipe diameter too small	Increase Pipe diameter

3.8.4 Enabling Pipe Drainage

For a model to use pipe drainage, it must be enabled via the "Irrigation" panel. Note that this option is only available for 2D and 3D models. This is a requirement in order to view proper moisture plots.



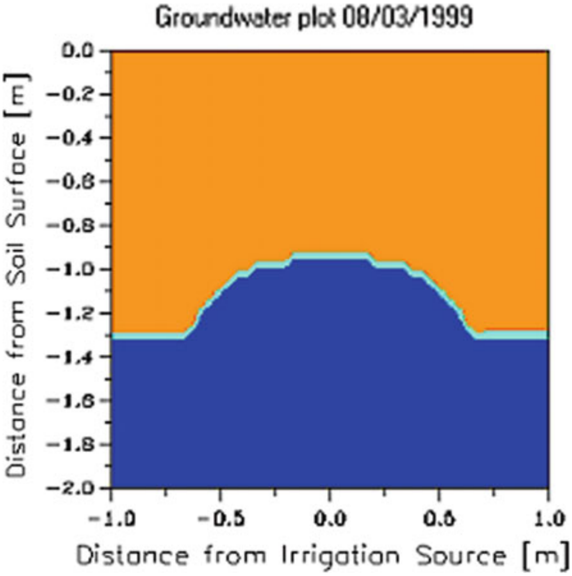
PRD Mode: No PRD

Numerical Stability Factor: 1

Pipe Drainage / Shallow Groundwater: ☑

3.8.5 Groundwater Output Plots

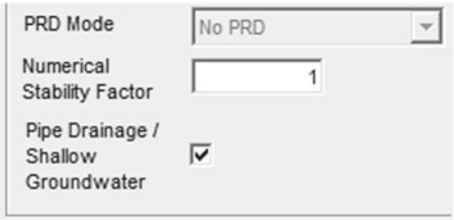
As an aid to setting up a pipe drainage model, an output “Groundwater” plot is provided. This does not show absolute moisture levels, but instead shows just which model cells are saturated. An example is shown in the figure below:



3.8.6 Shallow Groundwater System

In absence of a pipe drainage system and presence of shallow groundwater, it is possible to simulate a shallow groundwater model using features provided for drainage systems. The method is as follows:

- Set the irrigation tab to use Pipe Drainage/Shallow Groundwater.



PRD Mode: No PRD

Numerical Stability Factor: 1

Pipe Drainage / Shallow Groundwater: ☑

This has the effect of making the bottom of the model impermeable and allows groundwater to build up.

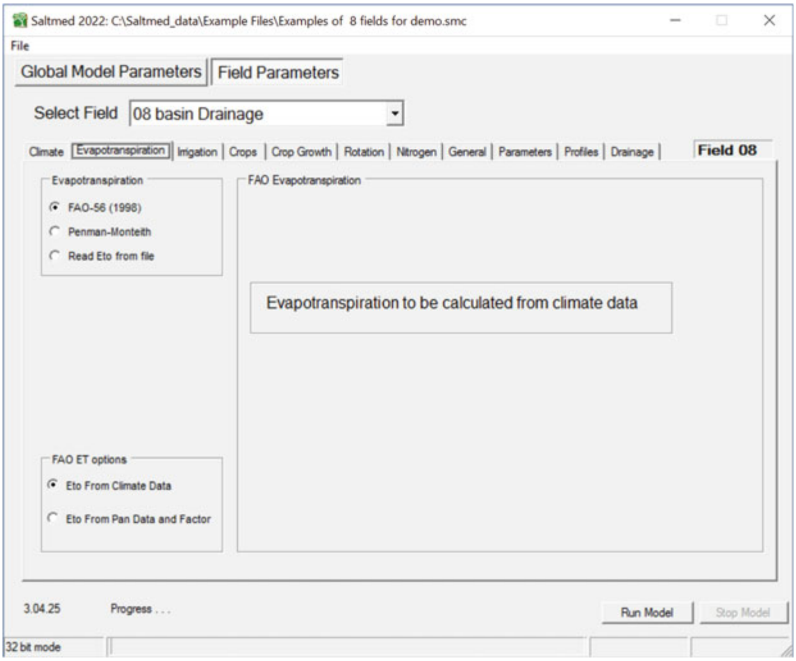
- Set the diameter of the drainage pipe to zero.
  This means that no water can exit the model via the pipe, and groundwater will rise up and past the pipe location, simulating groundwater.

3.8.7 Limitations to the Shallow Groundwater Option

When using the shallow groundwater option, it is possible for the groundwater to rise and saturate the entire soil profile. If this happens, the model will show increased surface runoff (sometimes known as groundwater flooding), since water cannot infiltrate other than to replace evaporation and/or transpiration. Careful control of irrigation input values may be needed to get a model that maintains a groundwater level that is below the surface.

3.9 Evapotranspiration, ET, Tab Options

1. Option 1. Calculates the ET using climate data according to the FAO modified Equation of Penman–Monteith (assumed stomata conductance of 70 m/s).



Select Field: 08 basin Drainage

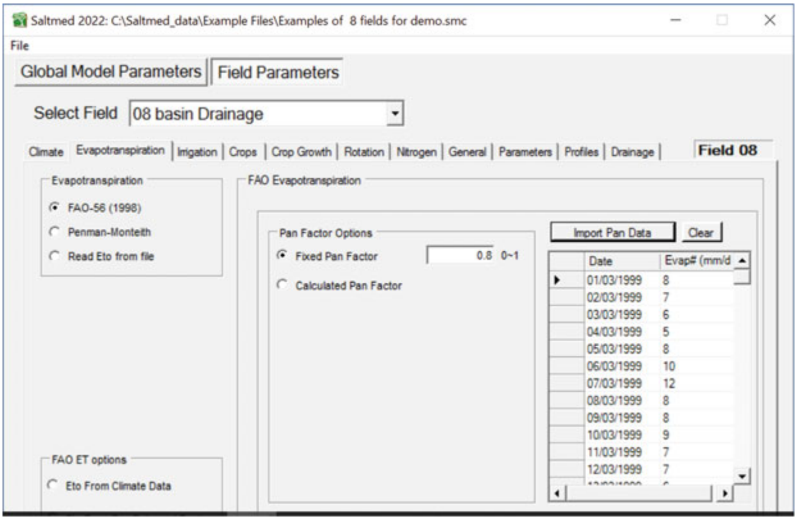
Evapotranspiration
● FAO-56 (1998)
○ Penman-Monteith
○ Read Eto from file

FAO ET options
● Eto From Climate Data
○ Eto From Pan Data and Factor

FAO Evapotranspiration

Evapotranspiration to be calculated from climate data

2. Option 2 calculates the ET from Class A pan, an excel file containing daily evaporation in mm/day is needed. Class A pan factor can be specified by the user or calculated using FAO formula, see FAO-Irrigation and Drainage Paper No. 56 (Allen et al. 1998) for more information.



Select Field: 08 basin Drainage

Evapotranspiration
● FAO-56 (1998)
○ Penman-Monteith
○ Read Eto from file

FAO ET options
○ Eto From Climate Data

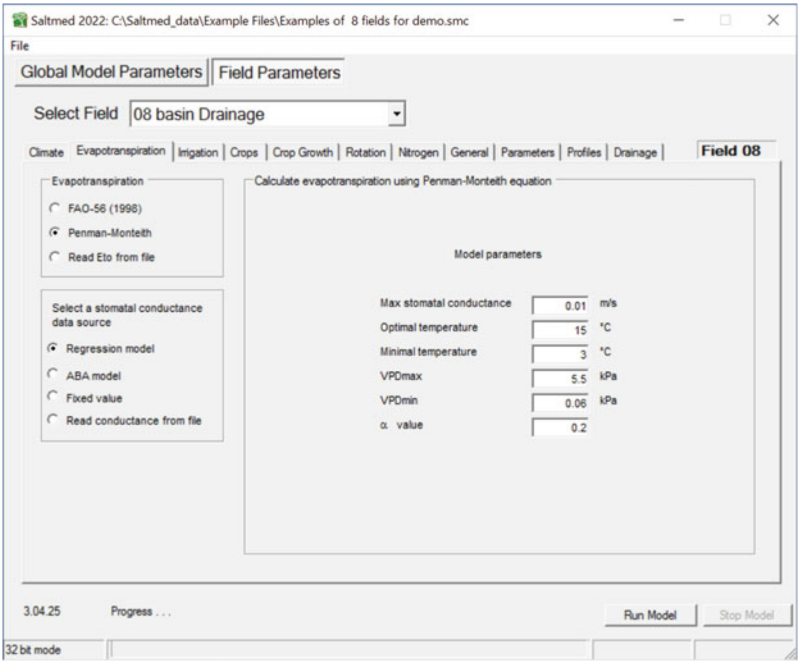
FAO Evapotranspiration

Pan Factor Options
● Fixed Pan Factor 0.8 0~1
○ Calculated Pan Factor

Date	Evap# (mm/d
01/03/1999	8
02/03/1999	7
03/03/1999	6
04/03/1999	5
05/03/1999	8
06/03/1999	10
07/03/1999	12
08/03/1999	8
09/03/1999	8
10/03/1999	9
11/03/1999	7
12/03/1999	7

3. Option 3 is to calculate ET from the **original** Penman–Monteith equation, with 4 options to calculate the stomata conductance. This conductance is needed in calculating ET using the original Penman–Monteith equation. The four options are:

   1. Calculating stomata conductance from environmental parameters, using a regression model (Jarvis 1976; Körner 1994) and some fitting parameters as shown in the dialogue box below.



Select Field: 08 basin Drainage

Evapotranspiration
- ○ FAO-56 (1998)
- ● Penman-Monteith
- ○ Read Eto from file

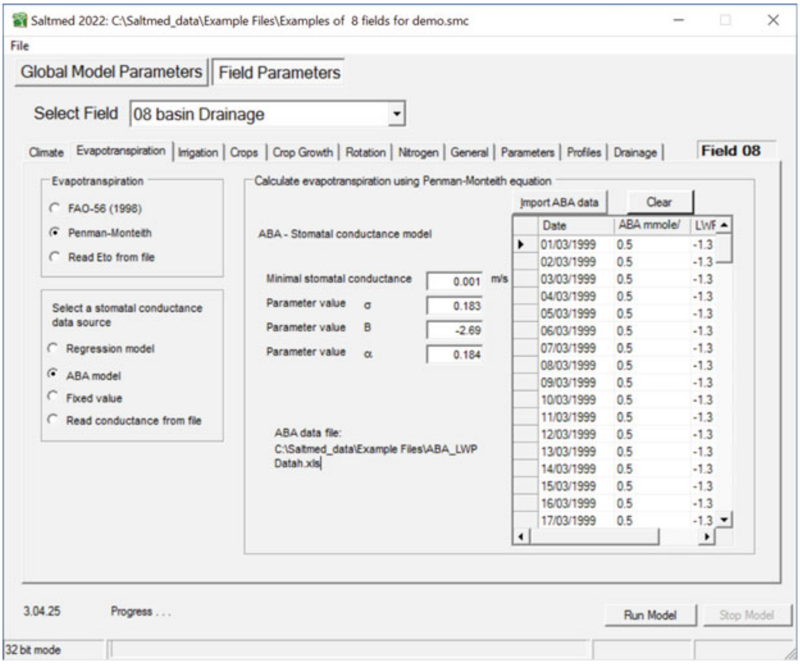
Select a stomatal conductance data source
- ● Regression model
- ○ ABA model
- ○ Fixed value
- ○ Read conductance from file

Calculate evapotranspiration using Penman-Monteith equation

Model parameters

Max stomatal conductance	0.01	m/s
Optimal temperature	15	°C
Minimal temperature	3	°C
VPDmax	5.5	kPa
VPDmin	0.06	kPa
α value	0.2	

   2. Calculating stomata conductance from daily values of Abscisic Acid (ABA) concentration in mmole m^{-3} and leaf water potential in MPa according to Tardieu et al. (1993). Data are provided as excel file (see example in the example files folder). Other fitting parameter values as suggested by the authors are given as default values in the dialogue box below.



Saltmed 2022: C:\Saltmed_data\Example Files\Examples of 8 fields for demo.smc

Select Field: 08 basin Drainage

Field 08

Evapotranspiration
○ FAO-56 (1998)
● Penman-Monteith
○ Read Eto from file

Select a stomatal conductance data source
○ Regression model
● ABA model
○ Fixed value
○ Read conductance from file

Calculate evapotranspiration using Penman-Monteith equation

ABA - Stomatal conductance model

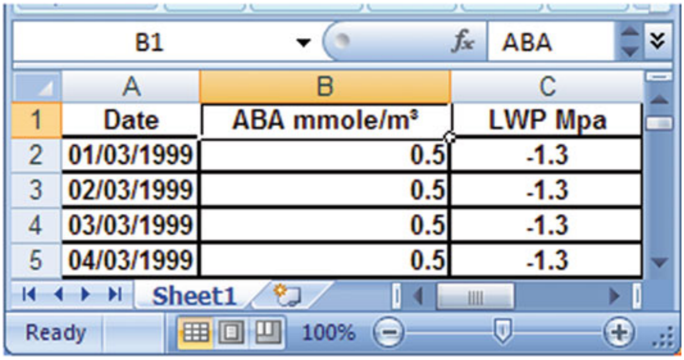
Minimal stomatal conductance: 0.001 m/s
Parameter value σ: 0.183
Parameter value B: -2.69
Parameter value α: 0.184

ABA data file:
C:\Saltmed_data\Example Files\ABA_LWP Datah.xls

Date	ABA mmole/	LWF
01/03/1999	0.5	-1.3
02/03/1999	0.5	-1.3
03/03/1999	0.5	-1.3
04/03/1999	0.5	-1.3
05/03/1999	0.5	-1.3
06/03/1999	0.5	-1.3
07/03/1999	0.5	-1.3
08/03/1999	0.5	-1.3
09/03/1999	0.5	-1.3
10/03/1999	0.5	-1.3
11/03/1999	0.5	-1.3
12/03/1999	0.5	-1.3
13/03/1999	0.5	-1.3
14/03/1999	0.5	-1.3
15/03/1999	0.5	-1.3
16/03/1999	0.5	-1.3
17/03/1999	0.5	-1.3

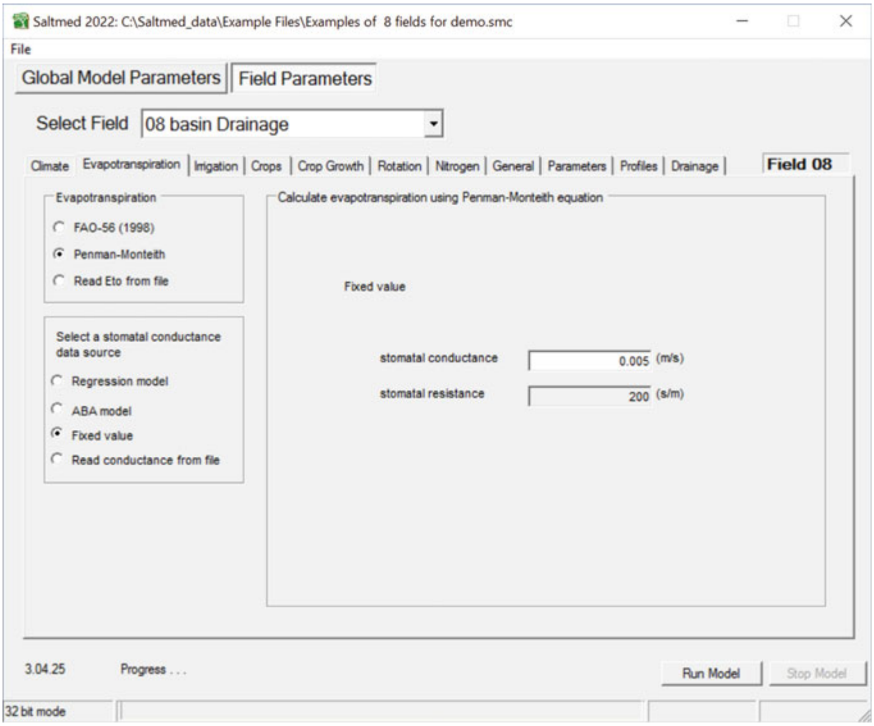
3.04.25 Progress . . .

32 bit mode



	A	B	C
1	Date	ABA mmole/m³	LWP Mpa
2	01/03/1999	0.5	-1.3
3	02/03/1999	0.5	-1.3
4	03/03/1999	0.5	-1.3
5	04/03/1999	0.5	-1.3

3. Using measured or estimated seasonal average stomata conductance value as in the dialoguebox below.



Select Field: 08 basin Drainage

Evapotranspiration
○ FAO-56 (1998)
● Penman-Monteith
○ Read Eto from file

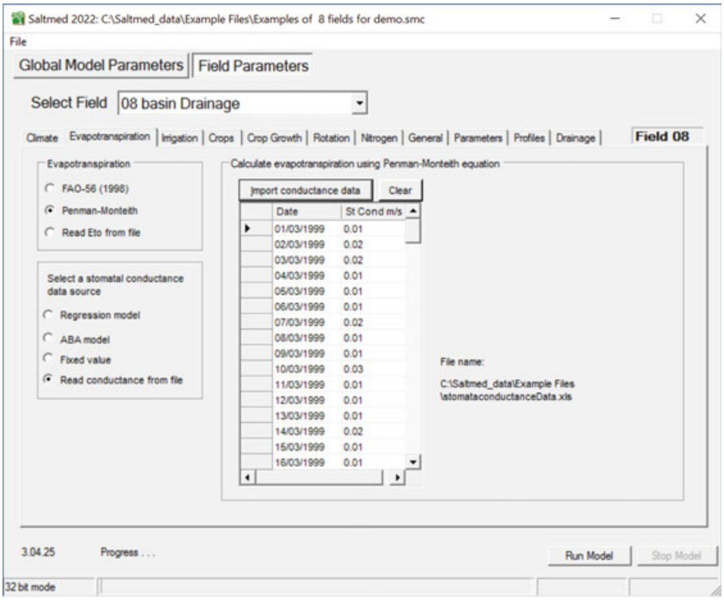
Select a stomatal conductance data source
○ Regression model
○ ABA model
● Fixed value
○ Read conductance from file

Calculate evapotranspiration using Penman-Monteith equation

Fixed value

stomatal conductance 0.005 (m/s)
stomatal resistance 200 (s/m)

4. Use daily measured values of stomata conductance. Data are provided in meter/second in an excel file, see example in the example files folder provided by the model.



Select Field: 08 basin Drainage

Field 08

Evapotranspiration
○ FAO-56 (1998)
● Penman-Monteith
○ Read Eto from file

Select a stomatal conductance data source
○ Regression model
○ ABA model
○ Fixed value
● Read conductance from file

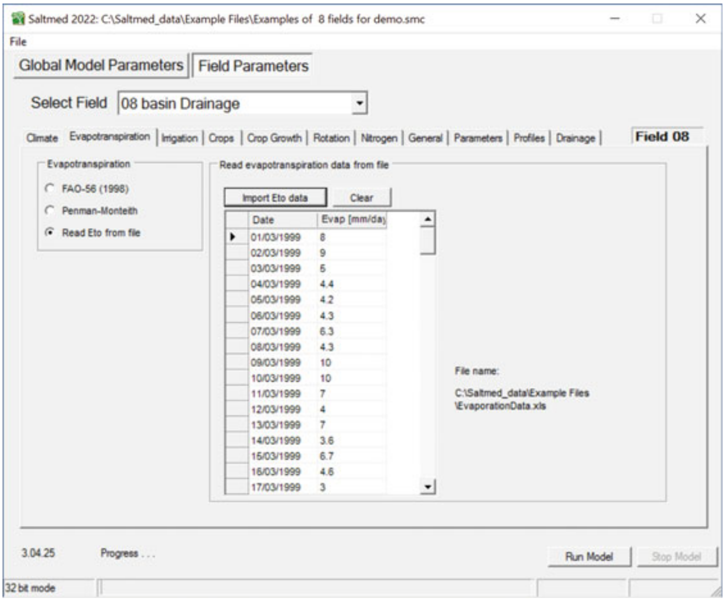
Calculate evapotranspiration using Penman-Monteith equation

Date	St Cond m/s
01/03/1999	0.01
02/03/1999	0.02
03/03/1999	0.02
04/03/1999	0.01
05/03/1999	0.01
06/03/1999	0.01
07/03/1999	0.02
08/03/1999	0.01
09/03/1999	0.01
10/03/1999	0.03
11/03/1999	0.01
12/03/1999	0.01
13/03/1999	0.01
14/03/1999	0.02
15/03/1999	0.01
16/03/1999	0.01

File name:
C:\Saltmed_data\Example Files
\stomataconductanceData.xls

3.04.25 Progress . . .

4. Option 4: Use readily calculated or measured Reference ET in mm/day given as an excel file. This allows the user to use own measured values or calculated values by other methods or equations different from those used in SALTMED, see example in the example files folder provided by the model.



Select Field: 08 basin Drainage

Field 08

Evapotranspiration
○ FAO-56 (1998)
○ Penman-Monteith
● Read Eto from file

Read evapotranspiration data from file

Date	Evap [mm/day
01/03/1999	8
02/03/1999	9
03/03/1999	5
04/03/1999	4.4
05/03/1999	4.2
06/03/1999	4.3
07/03/1999	6.3
08/03/1999	4.3
09/03/1999	10
10/03/1999	10
11/03/1999	7
12/03/1999	4
13/03/1999	7
14/03/1999	3.6
15/03/1999	6.7
16/03/1999	4.6
17/03/1999	3

File name:
C:\Saltmed_data\Example Files
\EvaporationData.xls

3.04.25 Progress . . .

4 "Goodness of Fit" Indicators

The SALTMED model performance was evaluated by quantitative (statistical) and qualitative (graphical) methods. In the graphical approach, the measured and simulated values of soil moisture were plotted against time. The response of the model can, therefore, be visually quantified. The statistical approach involved the use of the "goodness of fit" test proposed by Loague and Green (1991) to compare observed data with results predicted by the model. The "goodness of fit" indicators are the root mean square error (RMSE), coefficient of determination (R^2), and coefficient of residual mass (CRM).

The RMSE values show by how much the simulations under or overestimate the measurements:

$$\mathrm{RMSE} = \sqrt{\sum (y_o - y_s)^2 / N} \tag{34}$$

where

- y_s = predicted value
- y_o = observed value
- N = total number of observations

The R^2 statistics demonstrate the ratio between the scatter of simulated values and the average value of measurements:

$$R^2 = \left\{ \frac{1}{N} \quad \frac{\sum \left(y_o - y_o^-\right)\left(y_s - y_s^-\right)}{\sigma y_o - \sigma y_s} \right\} \tag{35}$$

where

- y_o^- = averaged observed value
- y_s^- = averaged simulated value
- σy_o = observed data standard deviation
- σy_s = simulated data standard deviation

The coefficient of residual mass (CRM) is defined by:

$$CRM = \frac{\left(\sum y_0 - \sum y_s\right)}{\sum y_0} \tag{36}$$

The CRM is a measure of the tendency of the model to overestimate or underestimate the measurements. Positive values for CRM indicate that the model underestimates the measurements and negative values for CRM indicate a tendency to overestimate. For a perfect fit between observed and simulated data, values of RMSE, CRM, R^2, should be equal 0.0, 0.0, and 1.0, respectively. All the analyses were made using excel (Microsoft Inc.)

5 SALTMED Applications

The model has been tested against a number of field experiments in different countries such as: tomato and potato under drip irrigation in Syria, Egypt, Crete, Serbia, and Italy (Ragab et al. 2005b and 2015; Afzal et al. 2016), in Iran, sugar cane under sprinkler irrigation (Golabi et al. 2009), in Greece, cotton under drip irrigation (Kalfountzos et al. 2009), in Denmark, quinoa irrigated with saline water (Razzaghi et al. 2011), in Morocco, quinoa, sweetcorn, and chickpea under drip irrigation (Hirich et al. 2012), in Brazil, vegetable crops (Montenegro et al. 2010), in Italy, quinoa and amaranth using saline water (Pulvento et al. 2013, 2015b), in Portugal, rainfed and irrigated chickpea (Silva et al. 2013), in Morocco, quinoa under deficit drip irrigation (Fghire et al. 2015), in Turkey, sweet pepper in green houses using saline water (Rameshwaran et al. 2015, 2016b), in Syria, legumes (lentil, chickpea, and faba bean) using saline water (Arslan et al. 2016; Rameshwaran et al. 2016a), in Turkey, quinoa using fresh and saline water (Kaya and Yazar 2016), and in Egypt, potato using gated pipes furrow irrigation (El-Shafie et al. 2017).

The abovementioned studies illustrated the capability and reliability of the SALTMED model in simulating the field observed yield and dry matter, soil moisture, and salinity concentration of the root zone. In addition, the model was also able to derive an important relation commonly known as the salinity-yield response function (Arslan et al. 2016; Rameshwaran et al. 2015, 2016a, b). SALTMED was also used to study the possible impact of climate change on yield, dry matter, crop water requirements, harvest and sowing dates, and length of the growing season of amaranth and corn crops in Italy and Morocco (Pulvento et al. 2015a; Hirich et al. 2016). The model has been intensively used in Egypt on a variety of field crops (Abdelraouf and Ragab 2017, 2018a, b, c; Abdelraouf et al. 2020; Dewedar et al. 2021; Marwa et al. 2020; El-Shafie et al. 2017), in Pakistan (Chauhdary et al. 2019, 2020), in Iran (Basiri et al. 2020; Dastranj et al. 2018), in Portugal (Silva et al. 2013, 2017), and in Morocco (Hirich et al. 2012, 2016, 2020; Filali et al. 2017; Fghire et al. 2015).

The model has also been used to derive some parameters that are not easy to measure (e.g., Leaf Area Index, LAI, Salinity tolerance index π_{50}, etc.) More details about the applications are published in a Special Issue of Journal of Irrigation and Drainage (Ragab 2020).

6 Some Issues Related to Salinity Measurements, Modeling, and Irrigation

6.1 The Field Versus Laboratory Measured Salinity

The ECe measured in the laboratory using saturated paste extract does not represent the salinityof the field. Salinity of the field is associated with a concurrent soil moisture. Both salinity and soil moisture should be measured at the same time and at the same depth Models produced soil salinity are associated with a twin value of soil moisture. Model users often make mistakes by comparing the soil salinity of the model with the laboratory salinitymeasured from the saturated paste extract. Keep in mind that plants grow between the wilting soil moisture content and close to saturated soil moisture content. In that range, salinity goes from low at saturation to high at wilting point.

6.2 Issues Related to Measurements

Variability due to heterogeneity: how representative the point measurements are for an area of various vegetation and soil types. Difficulties in measuring some parameters especially in semi and arid regions (e.g., infiltration, hydraulic conductivity, deep percolation below the root zone, etc.). The instruments technology did not advance as much as the modeling e.g., point versus area measurements.

6.3 Issues Related to the Irrigation Systems for Saline Water Application

Drip irrigation especially the subsurface is best suited. Subsurface keeps higher soil moisture in the root zone, reducing salt concentration of the root zone, and improving water uptake and yield.

Sprinkler can cause salt accumulation on the canopy and leaf burn in sensitive crops, low nozzles close to the ground would be better. Furrow: planting location is important. However, surface irrigation in general is not recommended.

6.4 Issues Related to Management Strategies for Water of Different Salinities

Different waters are blended/mixed in the supply network or altering good and poor quality according to the availability or switching according to the critical stage of the growth. Using the fresh water at the sensitive growth stage (early development stage) and using the saline water at the growth tolerant stage is recommended more than irrigating always with mixed water (fresh + saline).

6.5 Issues Related to Leaching Requirement

When? Only when salt concentration exceeds plant tolerance limit.

How? By unavoidable irrigation inefficiency, occasional rain, apply fresh water seasonally (recommended), apply fresh water after each irrigation (not recommended unless there is a great risk for the crop if no leaching is considered).

6.6 Issues Related to Modeling

Representation of the physical processes at field scale. Most of the models are based on point scale equations. Most models struggle with accounting for heterogeneity in soil and plant cover. Difficulties in calibration of models especially due to data adequacy/gaps, scale mismatch between model output and measurements. Most of the model results do not come with uncertainty bounds.

6.7 Uncertainty in Modeling

Model uncertainty stems from the assumptions, processes descriptions, mechanisms, mathematical formulation, and the numerical scheme. In nature, all processes operate simultaneously while in model they don't (they follow an order of execution). If evaporation is calculated after infiltration, expect recharge and soil moisture to be different if the order of calculation was reversed. Linearity exists in some model processes but not in nature where nothing is linear.

6.8 Using the Field Scale Models for Salinity Management

Agricultural water management models are already in use and able to predict soil salinity at a certain soil moisture content over the time (e.g., SALTMED model Ragab 2002, 2015; Ragab 2020). Salinization is a slow process and models are useful for long-term predictions. These models once validated, they can be used to predict soil salinity and yield, long-term impact of using saline water on yield and soil productivity, accurate estimation of the leaching requirement, establishing more dynamic yield-salinity response function that accounts for soil and irrigation water salinity combined.

6.9 *Non-Conventional Way to Use the Models*

Using the model to predict missing parameters and difficult-to-measure parameters (i.e., π_{50}, Kcb, Kc, Photosynthesis efficiency, etc.), using the model to predict climate change impact (CO_2, radiation, rainfall, temperature, etc.), using the model for experimental design such as the best crop rotation, tillage level, fertilizer management, and scheduling, using the model to estimate the crop water requirement and time to irrigate (scheduling), and using the model to design a program for data collection**.**

7 Tips for Saline Water Management

1. Using saline water requires a suitable irrigation system. Low nozzle sprayers/sprinklers below the canopy, close to the ground, and subsurface drip irrigation are suitable. However, Nano-Drip subsurface irrigation using Ultra Low Drip irrigation systems (flow 0.1 to 0.3 l/h) would be a good option and saves 30% of irrigation water.
2. Leaching should only be considered when the salt concentration exceeds the plant tolerance limit. Leaching can be carried out by unavoidable irrigation inefficiency, occasional rain, and seasonal application of fresh water. Excessive or routine leaching after each irrigation is not recommended as leaching can also leach nutrients, wastes water, and adds extra salt if the leaching water is saline.
3. When two sources of water, e.g., fresh and saline water, are available alternating use of the fresh water at the beginning of the growth season, as the young crop is sensitive to salinity, followed by irrigating with the saline water at later stage, when the crop less sensitive, is a better management than irrigating with the mix of the two water resources for the whole season.
4. Calibrated and validated models (e.g., SALTMED) can be used as good management tools to predict the long-term salinity impact on soil, plant, groundwater, and leaching requirement without the need to conduct field experiments. They can also be used in a non-conventional way to predict missing parameters and difficult-to-measure parameters (i.e., π_{50}, Kcb, Kc, photosynthesis efficiency, etc.), to predict climate change impact (CO_2, radiation, rainfall, temperature, etc.), produce an experimental design such as the best crop rotation, tillage level, fertilizer management, and scheduling, estimate the crop water requirement and time to irrigate (scheduling), and using the model to design a program for data collection.
5. Using the actual evapotranspiration, ET, measured or calculated from equations based on validation against measurements is recommended above the commonly used equations (e.g., Modified Penman–Monteith) as they produce potential ET representing the atmospheric demand not the crop demand for water by using only meteorological data with no plant representation in the equation. The potential ET is higher than the actual ET and will lead to excessive unnecessary waste of

water. Accurate estimation of irrigation water requirement is important because irrigating with excessive saline water means, adding more salts, leaching nutrients and fertilizers, decreasing soil and groundwater qualities, decreasing water productivity and water use efficiency, and irrigating less area.

6. Land management is important when using saline water for irrigation. Land preparation is important to ensure uniform distribution of irrigation water, infiltration, and better salinity control. Subsoiling, chiseling, and ploughing break up compaction and improve water infiltration and leaching. Special treatments such as deep ploughing, adding and mixing sand with the soil layer, and addition of organic matter, gypsum, or green manure improve soil permeability. Conservative tillage, zero or minimum tillage has advantages as it reduces soil evaporation, increases water availability, reduces surface salinity, increases organic matter, reduces soil erosion, increases nutrient availability, reduces agrochemical use, labor, and machinery.
7. The spatial variability and soil heterogeneity make area-based measurements more representative. In situ continuous measurements of both soil moisture and salinity at the same time is more accurate than laboratory methods. The salinity relation with yield or other crop parameters is better described using scaled relations e.g., relative yield vs salinity rather than absolute yield vs salinity.

8 SALTMED Model Software and Document Availability

SALTMED model (Ragab 2019) can be downloaded from the following links.
http://icid-ciid.org/inner_page/41.
https://www.ceh.ac.uk/services/saltmed#download.
https://drive.google.com/file/d/1GHoL0daZYPRb4zn2H4M_oPl_3vlOUKpg/view.

An online course is available at: https://www.youtube.com/watch?v=JRMeUFzuBYU.

"SALTMED Publications in Irrigation and Drainage. Virtual Issues First published: 20 May.

2020 Last updated: 20 May 2020. Wiley online Library". https://onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1531-0361.saltmed-publications.

ICID webinar on Use of saline water, 1 July 2020. http://icid-ciid.org/inner_page/131.

Presentation at the Second International Laayoune Forum on Biosaline Agriculture, 14–16 June 2022. https://icid-ciid.org/icid_data_web/LAFOBA2022_ppts.pdf.

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No. Food-CT-2005-023168 and Water 4 crops "Integrating bio-treated wastewater with enhanced water use efficiency to support the Green Economy in EU and India" Grant agreement No. 11933. THEME [KBBE.2012.3.5-03] EU KBBE 2012.3.5-03.

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Part VII
Use of Desalination Technology to Produce Non-saline Water for Irrigation

Chapter 16
Desalination for Agriculture: Is It Affordable?

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Abstract Desalination is becoming increasingly important as a solution to the Middle East and North Africa (MENA) region's water problem. Many water-stressed countries in MENA are increasing their water supplies with desalination to meet the needs of the continuous growth of population and industrial, tourism, and agriculture developments. Agriculture in particular is starting to benefit from desalination technologies in some regions suffering from seawater intrusion and water and soil salinization. However, desalination presents some constraints in terms of cost, energy consumption, and brine management. In addition, solar energy is the most abundant form of renewable energy and most of the MENA countries have the potential to exploit this energy form for developing solar-driven desalination processes. Thus, membrane operations driven with renewable energy can make desalination more sustainable and environment friendly. In particular, Reverse Osmosis (RO) desalination technology coupled with solar energy will supply freshwater at a competitive price and reduce the usual greenhouse impacts associated with grid electricity demand for desalination. Could desalination for agriculture become sustainable if we use renewable energies and find the right approaches to deal with the brine? This is what we try to respond to in this review.

Keywords Desalination · Agriculture · Brackish water · Brine · Reverse osmosis · Solar energy

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1 Introduction

Many countries in the MENA region are suffering from an acute water scarcity, and are increasing their water supplies with desalination to meet the needs of continuous growth of population and industrial, tourism, and agriculture developments. It is no longer possible to consider desalinated water as a limited resource. More than 100 Mm^3 of desalinated water is produced per day as of 2018, representing about 1% of total world needs. The largest share of desalinated water is produced by Saudi Arabia, which is about one-fifth of the world's total, followed by the United States, the United Arab Emirates (UAE), China, Spain, and Kuwait. Since the Gulf States (GCC) use almost all of their limited groundwater resources for agricultural purposes, these countries depend heavily on desalination to provide water to their citizens and industries. In order to make seawater and brackish water drinkable, governments and companies spend up to $14 billion per year (Stanley et al. 2019).

Desalination in the MENA region is a solution to water shortage that allows the production of reasonable amounts of freshwater to meet the rapidly increasing water demand. In the GCC countries, the principal sector of use of desalinated water is the domestic (municipal) sector in which there is no other option than desalinated water, some cities in the GCC depending entirely on desalinated water, such as Muscat, Doha, or Dubai. Desalination capacity in the MENA region is shown in Fig. 1. Almost three-quarters of the desalinated water produced is destined for domestic use while most of the rest is distributed for industrial use, followed by tourism, the military, agriculture, and power plants.

Desalination plants together with irrigation systems using well-treated wastewater are considered suitable alternatives for climate change adaptation, which can replace the lack of natural water availability. But it is not limited to that, we can also consider raising awareness of water shortage to make it easier to adopt non-conventional techniques such as seawater desalination and water reuse, together with efficiency improvements of infrastructure and reduction of consumption. Furthermore, there is a need to invest in infrastructure that ensures sustainable and equitable water distribution as well as efficient water use. Desalination facilities using properly treated wastewater and caring for environmental impacts can become a useful option for some case studies located in the coastal regions (Cabrera et al. 2019). For example, in Spain, in order to face climate change and its impacts on water resources, adaptation measures consist of the increase in the capacity of desalination, principally in the southern regions of the country where there is intensive agricultural activity and acute water shortage. Adaptation measures, on the other hand, may hinder mitigation, e.g., seawater desalination or ground water pumping for both consumption and irrigation requires energy, eventually generated from fossil fuels. Increased water consumption due to the climate change is resulting in more severe droughts that can trigger forest fires or wetland destruction, resulting in a loss of stored carbon. On the other hand, it can increase water demand, leading to a negative feedback effect of worsening drought. On the other hand, better water management can improve farming

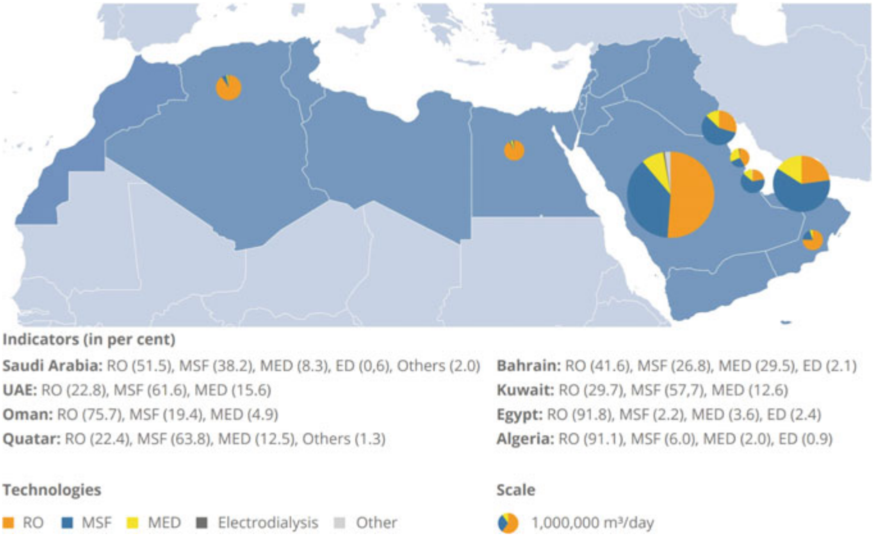


Fig. 1 MENA Desalination Capacities and the Technology Used (*RO* Reverse osmosis, *MSF* Multi-stage flash distillation, *MED* Multi-Effect Desalination, *ED* Electrodialysis) (*Source* Desal Data/GWI)

practices, contribute to carbon storage through reforestation, preserve wetlands, and minimize heat spells (UNECE 2015).

An important number of peer-reviewed papers has been published in the last few years addressing desalination in agriculture (Al Jabri et al. 2019; Bales et al. 2019; Burn et al. 2015; Hipólito-Valencia et al. 2021). It is worth noting that there are no papers that address the issues faced by the farmers—how to earn money using desalination and how to make the whole effort environmentally sustainable (Barron et al. 2015). Moreover, the scientific community recognized that desalination in agriculture would only be suitable for high-value crops (El Kharraz 2020). On the other hand, several papers discuss the feasibility of desalination in agriculture in different parts of the world (Chaibi 2000; Al Ansari 2013; El Zarroug et al. 2020). There is even a more practical approach of using desalinated water for greenhouses, described by El Zarroug et al. (2020). Technology has also enabled planning software for desalination in agriculture which was developed by Multsch et al. (2017). Some case studies of desalinated water use in agriculture are addressed in other papers (Muanda et al. 2021; Daghari et al. 2020a; McCool et al. 2010). Economic and policy issues were addressed, for example, by Welle et al. (2017).

Membrane technologies that are suitable for agricultural water production are described by several authors (Kumar et al. 2018; Nayar 2020; Raveh and Ben-Gal 2018; Zarzo et al. 2013), who looked at the possibility of agricultural drainage water for reuse employing Reverse Osmosis (RO) technology.

Desalination is still a good technical solution to enhance the availability of freshwater in coastal areas with scarce water resources and in zones where saline groundwater, drainage water, and treated wastewater are present. Farmers cultivating greenhouses and hydroponic crops are starting to use RO to desalinate and purify their water for irrigation for greenhouse use, as reverse osmosis-produced water tends to be less polluted with bacteria and nematodes, which also helps in controlling plant diseases. A number of small reverse osmosis plants have been built in many rural areas of MENA countries where there is no solution for water supply.

2 Desalination for Agriculture

Increasing groundwater salinity is one of the key challenges facing coastal agricultural areas in the MENA region, with falling water tables caused by seawater intrusion and overexploitation of aquifers. This situation has led farmers from many countries to use desalinated brackish water to provide water for their crops. It is obvious that when the supply of water in such a water-poor region is concerned, there is a necessity to make adaptations in operations to prepare for a changing climate, reduce the human footprint by reducing greenhouse gas emissions and provide more renewable energy. Actually, we need to adapt to reduced rainfall by using alternative sources of water, including desalination and recycled water, and by conducting controlled fires to protect water supply basins from bushfires (Smith et al. 2020). Brackish water desalination is currently the most widely used for agriculture in some MENA countries, as it requires less energy and therefore results in lower greenhouse gas (GHG) emissions than seawater desalination. It can also be used with recycled water recharge of groundwater aquifers (Barraque et al. 2017). In addition, for a semi-arid country like Tunisia, 99% of mobilizable water is now mobilized (Detay and Bersillon 1996), therefore the water supply choice of dam construction is no longer an alternative option.

Under this heading, we will show experiences that have proven that desalination plants can power an irrigation system for sustainable agricultural production.

Table 1 shows desalination use in agriculture in some countries around the world.

Table 1 Desalination use in agriculture worldwide according to Zarzo et al. (2013)

Countries	Use %
Spain	22
Italy	1.5
United States	1.3
Kuwait	13
Saudi Arabia	0.5
Qatar	0.1
Bahrain	0.4

The Agadir desalination project in Morocco is part of the Spanish operator Abengoa's strategic plan to address water supply challenges in the regions of the world most affected by water scarcity. Additionally, it will be the region's greatest capacity desalination plant. A total of $92 million in financing has been arranged with a consortium of local banks led by Bank of Africa, thus allowing for a higher integration and involvement with the local financial and commercial sector. Furthermore, this desalination project is considered as the first project that the National Power and Drinking Water Office (ONEE) has developed through a Public–Private Partnership (PPP) system, which puts Abengoa at the forefront of this particular model in Morocco. The project is estimated at 0.41 billion dollars in its two components (potable water and farm water) and eventually aims to secure the water supply of the Agadir region as well as provide water for high-value-added irrigated crops in the Chtouka area. In its entirety, the project includes the construction of a desalination plant with a total capacity of 275,000 m^3/d, making it the largest of its kind designed for drinking water and irrigation. According to the contract, it is possible to expand the production capacity up to 450,000 m^3/d. One of the main advantages of this project is the potential of being operated by wind power to respond to the domestic water demand, as well as the irrigation water needs in the Agadir region. The project will contribute to the protection of the regional aquifers and the prevention of their overexploitation, as well as developing the agricultural and tourism sectors, which are the two main economic drivers of the region. In the GCC countries, Kuwait uses 13% of its desalination capacity for irrigation. Saudi Arabia is only using 0.5% of its desalination capacity for irrigation, while Bahrain and Qatar are using 0.4% and 0.1%, respectively. In Oman, for example, an increasing number of farmers in the coastal region of Al-Batinah are using small-scale desalination plants to produce water for irrigation due to the increased level of soil and water salinization. Desalination technology is still a costly choice for agriculture, which presents a number of environmental challenges such as energy needs, water quality, and disposal means of rejected brine that, in several cases, ends up contaminating groundwater and increasing its salinity. However, desalination remains an advantageous solution for sustainable agriculture if used within well-defined constraints. Desalination is still an excellent option for increasing the availability of drinking water in coastal regions with limited water supplies and in regions where brackish water such as saline groundwater, drainage water, and treated wastewater are available. Greenhouse and hydroponic farmers are starting to use reverse osmosis for desalination and purification of greenhouse irrigation water. The water produced by reverse osmosis tends to be lower in bacteria and nematodes, which also contributes to control plant diseases. In rural areas where there are no other options for water supply, small RO plants have been installed. More and more Omani farmers are switching from surface water channels to RO desalinated brackish groundwater sources. Spain presents a significant case study on the use of desalinated water for agriculture. More than 300 treatment plants are located in Spain, which represents about 40% of the total plants in the MENA region. Agriculture uses about 22.4% of all desalinated water. The majority of these plants are processing brackish water (only 10% of the total desalinated water for agriculture comes from seawater) and are located in coastal areas or away from the sea at a maximum distance of 60 km (GWI 2018). Small and medium-sized brackish water desalination facilities, with a capacity of less than 1,000 m^3/d, are popular in Spain because they can more easily adapt to the needs of individual farmers and to the existing hydraulic structure. Desalinated water is not used exclusively for irrigation. In order to reduce the cost of desalination, farmers in Spain mix desalinated water with surface water and poor quality groundwater. Desalination plants are owned by farmers, and their farming is practiced within their organized societies in order to compete with local and international markets. The use of desalination for agriculture is governed by a specific institutional framework created by the Spanish government. They can also increase net returns through well-defined marketing strategies. In contrast, small-scale desalination units are used by farmers in Oman to support low-yielding field crops (see Fig. 2). The majority of inland desalination facilities (80%) in Oman are RO type with limited capacities (less than 10,000 m^3/d). More than 50% desalinate inland or brackish water (TDS 3,000 mg/l $\leq$ 20,000 mg/l) (GWI 2018).

There are a number of Omani farmers who produce “classical” crops such as cucumbers and tomatoes in greenhouses. These low-income field crops indicate that they are not market-oriented and most farms are intended to maintain existing farming practices, among other goals. Once securing a new source of freshwater, farmers added more facilities on their farms; principally residential buildings (small resorts

Fig. 2 A desalination system in one of the Omani farms (Al-Batinah region) including the RO system and the evaporation pond to treat the brine

and/or swimming pools) or livestock-raising facilities (Al Jabri et al. 2019). In 2020, there were more than 1,000 small desalination plants in Omani farms. In general, they are small plants of 10–50 m^3/day capacity to treat a salinity of up to 10,000 mg/l, and they are used to irrigate low value crops (7.8–15,600 USD/unit). The energy source is in general the normal power grid; while the brine disposal is the main constraint, and the farmers either use evaporation ponds, abandoned wells, or injection wells which are unfortunately associated with the risk of contaminating groundwaters. The amounts and quality of produced water are of international standards, while the rejected brine is about 50–60% of the water intake. Without electricity subsidy, the cost of desalination from small desalination plants in Oman is around 0.65 USD/m^3, which is 63% higher than the cost paid by farmers in Spain (0.40 USD/m^3). In addition, farmers in Oman pay more for the water "bill" because the water needs for the surveyed crops are much higher than in Spain (22,000 vs. 5,600 m^3/ha/year). While all Spanish farmers are mixing desalinated water with other low-quality water sources, about 78% of Omani farmers surveyed are using purely desalinated water to irrigate crops with low-income-value (Al Jabri et al. 2019). These factors make the use of desalinated water in agriculture in Oman considerably less profitable than in Spain. Furthermore, in Spain, medium-sized central desalination plants with high recovery rates are used compared to the small units with low recovery rates used in Oman. The cost of desalination is significantly reduced by the "economy of scale" and high recovery rates. Based on the economic analysis, the desalination cost ranges between USD 0.46–1.32/m^3 with an average of USD 0.55/m^3 depending on unit size (Al Jabri et al. 2019). To make the approach sustainable it should allow only for controlled environment agriculture and only for high-value crops; and it is a must to have brine management facilities and promote the use of renewable energy. In addition, farmers must invest in desalination only for cash crops that have a high return, and they need to target water use efficiencies based on global experiences. In this regard, a research project was funded by the Omani Ministry of Agriculture and Fisheries and carried out by researchers from Sultan Qaboos University (SQU) and the Middle East Desalination Research Center (MEDRC) with the aim to deploy a pilot solar desalination unit for agriculture (see Fig. 3). This kind of project is extremely important for farmers to show them how solar desalination units operate and how the brine should be managed, in the case of this project, an evaporation pond has been built.

In the framework of the aforementioned project, three field experiments have been set up: an open field, a shaded field, and a hydroponic field. The objective was to assess desalinated water use efficiency, crop productivity, the economic feasibility of desalinated water for irrigation, and also show the impact of desalinated water on soil properties. Mixing desalinated water with low-quality groundwater and following certain irrigation deficit schemes to irrigate high-value crops are two options to minimize the cost of desalination for agriculture. In Spain, the cost of brackish water desalination for agriculture is reduced by the use of pricing schemes for energy. There are six pricing schemes in Spain that vary based on the time of the day, week, and year. Desalination plants are operating during the periods of low demand that correspond to the lowest price scheme. In addition, mixing desalinated water with other water

Fig. 3 A pilot photovoltaics (PV)-RO unit installed at the Middle East Desalination Research Center (1.3 m^3/h). Project carried out by researchers from SQU and MEDRC

sources, such as surface water and low-quality groundwater, results in reducing the costs in Spain. The Gulf countries have no energy pricing schemes, which makes the cost fixed. Moreover, in Oman, energy is subsidized by the government and farmers pay only 30% of the original (total) cost (Zekri et al. 2014). On the other hand, using seawater desalination to irrigate profitable crops like tomatoes, berries, or other vegetable crops could be a sensible solution to continue producing horticultural products and saving water, therefore, water–food nexus is to be considered to balance between economic profitability and the need to save water.

In the Souss Massa region in Morocco, for example, the pumping cost is around USD 0.3/m^3, while the average desalination cost is USD 0.5/m^3, with small change depending on desalination technology (Hirich et al. 2016). To meet the irrigation water needs of the Souss Massa region, half of the Agadir desalination plant's capacity will be used. However, it is about seawater desalination and not brackish water. In some regions of Tunisia, desalination of brackish water is also used to improve the water quality for irrigation, as is the case in Mahdia. As shown in Fig. 4 the authorities set up a pilot project for a desalination unit for agriculture in Mahdia in 2016. Supported by EU funding, the project aimed to reduce salinity from 5.8 g/l to 0.2 g/l. The USD 5 M project is equipped with a 600 m^3 water reservoir and is used by 60 farmers to irrigate greenhouse crops. This project can irrigate three times more land volume than traditional drip methods.

The evaluation of the appropriateness of desalination for agriculture must be done based on the net economic returns of agricultural products together with the environmental costs. Therefore, the technology's feasibility for agriculture in Oman should

Fig. 4 Desalination unit for agriculture in Mahdia (Tunisia)

be explored through such concerns. Farmers were recommended to set up common central desalination plants to provide water for agriculture according to the hydrological characteristics of groundwater aquifers for reducing both energy consumption and operation and maintenance (OM) costs and to make the management of return water optimal. The plants would be designed, built, and operated through cooperation between farmers and the private sector. The recommendations also included the advice to start introducing industries based on the highly saline wastewater from desalination plants as this is critical to minimize environmental impacts and safe disposal of the brine, as well as to achieve economic benefits. Among the recommendations was also the preparation of a public database available to scientists and decision-makers which includes all information concerning the number of agricultural desalination units, with their capacities, sites, produced agricultural products, their production efficiency, and disposal of the brine (OWS 2018).

3 Challenges of Desalination in Agriculture

There are several challenges facing desalination in agriculture. The main one is brine disposal. Production of brine varies, and brine quality depends on how much freshwater is produced from the intake water. On other hand, prolonged use of brackish water for agricultural irrigation may deteriorate the soil structure, which can affect the permeability and water retention performance of the soil and reduce crop growth and production. In addition, desalination for agriculture requires extra cost to remove boron [B] and the total dissolved solids [TDS]. It depends on each country, but in general the recommended standards for irrigation are B < 0.5 mg/l, TDS < 450 mg/l, and Cl < 105 mg/l. Boron, in neutral and acidic environments, passes through the RO filters with a concentration of about 2 mg/l. Therefore, it may be required to perform additional filtration, which means an extra cost would be added.

Desalination removes important ions that maintain the structure of soil and serve as nutrients, e.g., Ca^{2+}, Mg^{2+}, and $SO_4{}^{2-}$, therefore this is challenging, and the produced water may need to be remineralized to be able to use it in irrigation. There are also economic challenges. In fact, small units produce water at higher cost (economy of scale). Based on the desired quality of desalinated water, the running cost of chemicals and membranes is relatively low, in addition to the costs of desalination can be controlled with the optimization of the seasonal crop water requirements. Furthermore, the salinity level of brackish water (about 10,000 mg/l) is much lower than that of seawater, which means that the cost of desalinating brackish water will be lower than that of seawater. Despite this development, the costs of desalinated water are still too high to fully use this resource in irrigated farming, except for intensive horticulture for high-value cash crops, such as vegetables and flowers (mainly in greenhouses), cultivated in coastal regions.

Desalination costs can be reduced by using more efficient irrigation systems and intensifying agriculture of high-value crops. The decreasing cost of desalination technologies is due mainly to the advancement of filtration technologies, better energy recovery devices, in particular in RO systems, which can recover up to 92% of the energy, which leads to a greatly reduced cost. Moreover, in arid regions like the Middle East and North Africa where direct normal irradiance (DNI) is high, a new generation of thermal power plants called Concentrating Solar Power (CSP) is seen as a promising technology for water desalination (Abouaziza et al. 2021). CSP technologies use mirrors to concentrate light energy from the sun and convert it into heat to create high temperature steam to drive a turbine that creates electrical energy for the RO or this heat can be used as thermal energy to desalinate feed water in Multi-Stage Flash (MSF) and Multi-Effect Distillation (Elimelech and Phillip 2011). Thanks to the CSP stations, there will not be a phase change. The thermal energy supplied will be used directly by the thermal desalination stations, which increases the desalination efficiency. According to Fichtner (2011), desalination using CSP technology will be the second source of water supply in the medium climate change scenario for the MENA region after surface water extractions with values of 79.5 billion m^3 and 165.7 billion m^3 per year respectively by 2040. The reduction of greenhouse gas emissions from fossil fuel combustion will be a major factor in the development of solar desalination.

A vast study was undertaken in Tunisia on the feasibility of desalination of water for irrigation for an irrigated coastal zone. This study included several aspects. According to Daghari et al. (2021), when all crop water needs are to be met with desalinated water, the net income is negative for currently cultivated crops, except for strawberry. Daghari et al. inform us that desalination can only be recommended for crops with low water requirements and high added value by having a very lucrative income which would limit, notwithstanding its existing applications, its competitiveness for future applications.

Desalination for agriculture has several benefits, in particular:

- It allows a tailored quality for irrigation water,
- It ensures a continuous supply,
- It enables agriculture products of consistent quality,
- It allows increasing production compared to other water sources,
- It allows that water attains a higher resale price due to quality and supply assurance, and
- It allows the recovery of saline soils by irrigation with higher water quality.

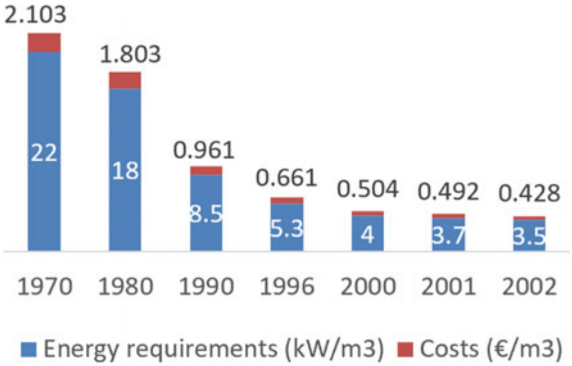
In Morocco, one of the biggest desalination plants is currently being constructed in the coastal city of Agadir, it is called Douira seawater desalination plant (Table 2). It is the first Public–Private Partnership (PPP) project under construction, the desalinated water produced would be dedicated jointly to the supply of drinking water and irrigation. It started operating in 2021 (IDA 2018). This project has a budget of USD 271, 4 million, and a treatment capacity of around 75 million cubic meters of desalinated water per year. In addition, the plant is expected to produce nearly 275,000 cubic meters of desalinated water daily before reaching its maximum capacity of 450,000 cubic meters per day. It will be accompanied by reservoirs for storing drinking water and at least five pumping stations, 22 km of pipelines, and about 490 km of distribution network. At least 150,000 m^3/d of water is dedicated to freshwater needs and will be transported daily to greater Agadir, including the city and the territory, while the remaining 125,000 m^3 per day will be used to supply an irrigation system in the Chtouka plain (area of 13,000 ha) (El Kharraz 2020). The process of desalinating water by RO is quite energy-intensive. In order to reduce the plant's electricity consumption, it was decided to install a pressure exchanger system, which is derived from high-pressure filtration, which allows energy to be recovered. The system has a very positive impact on the cost of energy, which is estimated to reduce by about 43% per cubic meter produced (Shaffer et al. 2012). The Moroccan National Office for Electricity and Potable Water (ONEE) expected to devote additional investments of USD 66 million for the construction of 44 km of pipelines, a 35,000 m^3 drinking water tank, the installation of 3 high voltage power lines over 55 km from the Tiznit source plant which is already connected to the Noor Ouarzazate solar complex, and the construction of two pumping stations and two loading tanks (El Kharraz 2020).

In Spain, desalination for agriculture has been considered as an option since the early' 70s. 22% of the desalination capacity is used for producing irrigation water

Table 2 Specifications taken from the Chtouka Ait Baha project (El Kharraz 2020)

Desalination technology	RO
Daily water production (m^3/d)	275,000
Annual availability rate (%)	95
Amortization (years)	20

Fig. 5 Desalination cost in Spain in the period (1970–2002) (GWI 2018)



(Zarzo et al. 2013). The first seawater reverse osmosis (SWRO) plant for irrigation was built in 1987 with a capacity of 6,900 m^3/day. The first large desalination plant in the Canary Islands was built in 1990 with a capacity of 36,000 m^3/day, and recently was expanded to the current capacity of 80,000 m^3/day. Spain adopted desalination not for agriculture only but also for touristic purposes with the use of water to sustain golf courses. Costs have been decreasing considerably over the last 50 years (see Fig. 5).

- 1995–2000: >200 desalination plants were installed at the coastal zone with a capacity of 36,000 m^3/day and capacities of 100–5,000 in the Spanish islands.
- In 2001, the Spanish government built the biggest desalination SWRO plant in Spain, at that time with a capacity of 120,000 m^3/day for agriculture
- In 2004, the Spanish government started the AGUA desalination program with a capacity of 63,000,000 m^3/year with part of the production used for irrigation. Most units were built with the government's approval and subsidies.

In Tunisia, desalination for agriculture has been considered as an option to irrigate lettuce. Work has been undertaken to determine the best way to plan irrigation when saline and desalinated water are used. El Zarroug et al. (2020a) and Daghari et al. (2020b) used different doses of freshwater and saline irrigation: T (Treatment) 80 (fresh)-20 (saline), T50 (fresh)-50 (saline), and T1d-1d where irrigation is done one day with fresh and the next day with saline water. The effect on crop growth and on soil salinity was measured for three different electrical conductivities (EC) (1.56, 4.68, and 7.81 dS/m). For irrigation with an EC of 1.56 dS/m, the T50-50 treatments gave the best performance. For EC 4.68 and 7.81 dS/m, a decrease in crop height was observed for all treatments. Also, for soil salinity at the end of the lettuce growing cycle, T50-50 was the best treatment that has given the best results across the board. The more the interval of irrigation with desalinated and saline water is reduced, the more the agricultural yield increases, and the salinity of the soil remains low.

In Australia, Sun drop Farms own 20 ha of greenhouses to produce over 15,000 tons of high-value crops all year round. They use solar thermal energy for desalination of seawater for irrigation, produce energy for operation, and to heat and cool down the crops during the various seasons. They pump seawater and brines over about 5,000 m (Lyra et al. 2016).

4 Discussion

Reverse osmosis is widely used to treat water in industrial and agricultural applications. It effectively removes salts from seawater, brackish, or wastewater. Reverse osmosis produces a clean stream of high purity water, as well as a smaller stream of waste, referred to as concentrate or brine. The brine is a very concentrated solution of various salts and contaminants separated from the water by the reverse osmosis membranes. Brine requires proper disposal, which often requires permits or other regulatory compliance actions. There are many brine disposal methods available, which all have different environmental and capital costs. In countries, such as UAE, Oman, and Saudi Arabia, the most frequent disposal methods in inland areas are evaporation ponds and land application. The MENA region is known to be the largest producer of desalinated water in the world, producing half of the region's water capacity. Many new plants are planned in the coming years to meet the increasing demand. A number of factors are to be considered when it comes to deciding on the best option such as the volume or quantity of brine, quality of brine, location and availability of the receiving site, regulations, costs, and public acceptance. As far as the brine is concerned, another option is to reuse the brine, e.g., for fish culture (Red snapper, tilapia, black bream, Mullet, Barramundi, and brine shrimp), agriculture (salt-tolerant crops), algae production or biosaline agriculture, minerals recovery, and solar ponds. Evaporation ponds are especially suitable to dispose of rejected brine from inland desalination plants in arid and semi-arid areas, due to the abundance of solar energy. In irrigation projects facing a soil salinity problem due to a shallow saline groundwater table, evaporation ponds are also in use. Saline water tables are lowered by pumping or tile draining and the drainage water is stored in evaporation ponds. While evaporation ponds have long been used for salt production in many parts of the world, the disposal of concentrate from desalination plants in inland areas using evaporation ponds is of much significance both economically and environmentally. Guidelines are needed for the design, construction, maintenance, and operation of evaporation ponds for rejected brine disposal in an economical and environmentally sensitive manner.

A simple calculation shows that the best way to manage brine using evaporation ponds is to reduce brine production by increasing the recovery rate (Table 3). This will reduce the size of the ponds. Such an approach will be most feasible for small farms in Oman. Of course, trying to increase the recovery rate will require larger input of energy. The example in Table 3 shows that for a small desalination plant, an increase of recovery rate from 50 to 90% will reduce the pond size from 3,000 to 600 m^2 (80% reduction). An economic analysis coupled with government regulations can motivate the farmers to adopt such an approach. A cooperative approach with farmers

Table 3 Evaporation ponds set up and characteristics

Recovery rate %	Product water m^3/day	Brine m^3/day	Brine m^3/yr	Evaporation rate m/yr	Area needed m^2	Brine quality ppm	Total salt tons	Salt depth cm/yr	Cost of pond USD	Comment
50	20	20	6,000	2	3,000	10,000	60	1	30,000	Will operate for a long time
90	36	4	1,200	2	600	50,000	60	5	6,000	Requires better RO systems, More Energy Cost

grouping together and constructing evaporation ponds to be used by many farmers paying nominal fees should also be considered. Another possibility that needs to be investigated is to construct a network of pipes to collect the brine from various farms and ultimately dispose it in the nearby sea.

Evaporation ponds have several uses. Salt evaporation ponds produce salt from seawater. They are also used to dispose of brine from desalination plants. Mines use ponds to separate ore from water. Evaporation ponds at contaminated sites remove the water from hazardous waste, which greatly reduces its weight and volume and allows the waste to be more easily transported, treated, and stored. It is important to understand that evaporation is not the same as condensation although evaporation in an enclosed environment can subsequently lead to the condition of condensation as evaporated moisture is “condensed” out of the air and is reverted to a liquid stage. Evaporation ponds can also be used to evaporate the precipitation that falls on a contaminated site. The contaminants that the water picks up on the ground are left behind after it evaporates. This prevents the contamination from spreading further down the watershed. Evaporation ponds are used to prevent pesticides, fertilizers, and salts from agricultural wastewater from contaminating the water bodies they would flow into. In California, selenium in agricultural wastewater has been especially problematic, causing birth defects in waterfowl (Hundley 1992). Other innovative and non-traditional ways to use brine in industrial processes with the dual beneficial objective to significantly reduce its volume and to mitigate the adverse effects of some contaminants, such as CO_2, need to be investigated. That said, there are economic opportunities to use brine in aquaculture, to generate electricity, to irrigate salt-tolerant species, and by recovering the salt and metals contained in brine—including lithium, sodium chloride, gypsum, calcium, magnesium, potassium, and bromine. With better technology, many metals and salts in desalination plant effluent could be mined. These include magnesium, sodium, lithium, calcium, bromine, boron, potassium, strontium, rubidium, and uranium, all used by industry, in products, and agriculture. The required technologies are not yet well developed, and recovery of these resources is, at present, economically uncompetitive. The use of saline drainage water offers potential social, commercial, and environmental gains. Rejected brine has been used for aquaculture, showing a 300% increase in fish biomass. Brine has also been successfully used to cultivate the dietary supplement Spirulina (filamentous cyanobacteria rich in minerals and vitamins), which is a biomass of cyanobacteria that can be consumed, and to irrigate forage shrubs and crops, although the latter use can cause progressive land salinization. The Wider adoption of membrane technologies, especially in the MENA region, looks like the best way to reduce chemical-laden brine, because adopting membrane technologies for pretreatment reduces the use of chemicals. Almost all new plants planned in the region will use RO technology, a trend likely to continue as budget-minded Gulf governments reduce subsidies on fossil fuels. These cuts, by making thermal plants less competitive, are the main reason membrane technologies are finally taking off in the Gulf countries. The imperative to make seawater drinkable shows no sign of easing. Given current consumption rates, the UAE’s largest emirate could run out of its groundwater natural supplies “within a couple of decades,” the Abu Dhabi Environment Agency (EAD) said in a 2017 report. Rising demand for limited water resources is spurring new ideas for food production and as such increase interest in desalination of saline water. In Dubai, the International Center for Biosaline Agriculture (ICBA) recycles brine to irrigate salt-tolerant plants and plants such as salicornia, which can either be consumed or used for biofuel (Lyra et al. 2016). The research institute also breeds food crops like quinoa that flourish in saline desert soils.

Desalination is the most used solution to address water shortage especially for potable water applications. It is the only feasible option to provide substantial amounts of water beyond the hydrological cycle (Suwaileh et al. 2019). It offers the potential to cover the deficit in freshwater demand for agriculture and might be the only feasible means for water scarce countries and regions. In a semi-arid country like Tunisia, mixing good-quality water with poor quality groundwater is common practice. In the coastal region of Dyair-Al-Hujjej in Cap Bon, the number of abandoned wells increased from 1268 to 3200 between 1980 and 2005, due to the increase in the salinity of the water following overexploitation and seawater intrusion (Daghari and Gharbi 2014). An EC greater than 28 dS/m has been measured in some wells (Kumar et al. 2018). Several farms have been deserted because of this salinization. In order to safeguard this irrigated area, the Tunisian government carried out an expensive transfer of surface freshwater from another watershed over 100 km away, via the Medjerda-Cap Bon canal. The farmers used the mixture of surface freshwater and saline water from the aquifer to increase the potential of the irrigation water. They inject this surface water with an EC of less than 1.4 dS/m into wells to be mixed with saline water from the aquifer. Thanks to this transfer of water from the dams, farmers were able to extend the array of crops they can grow by introducing strawberry cultivation, which considerably increased their income. Desalination of water for irrigation water supply can be a bonus for many irrigated areas in semi-arid and arid regions.

5 Conclusion

Desalination for agriculture is an attractive option as a source of irrigation water. In fact, desalination units are simple to operate and can be automated to handle seasonal variations in demand. The high initial cost can be compensated for by adopting more water saving techniques in conjunction with crop selection e.g., hydroponics with high-value crops. On the other hand, social impact is “positive” because farms are not abandoned. That said, more research is needed with regard to the means of disposal of rejected water and ion-specific issues. Desalination for agriculture can be made economically and environmentally sustainable under certain conditions even for small units. Moreover, focus should not only be on using technology but also on reducing the demand through water conservation practices in agriculture. Finally, there is a great prospect of using renewable energy in controlled environment agriculture. The coupling of solar energy with desalination technologies is seen as having the potential to offer a sustainable route for increasing the supplies of desalinated water. However, the success in implementing solar desalination technologies at a commercial scale depends on the improvements to convert solar energy into electrical and/or thermal energies economically as desalination processes need these types of energies. Current research provides little room for large scale application of solar desalination, but it can be used by farmers for small or medium scale applications in remote locations where there is no grid electricity. Under such conditions, conventional systems' water cost rises up to 1.5 $/m^3. Decentralized solar powered water desalination systems offer independence and help to avoid having to cope with price rises from the utility or water companies.

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Chapter 17
The Technological Challenges of Desalination for Irrigation in Morocco

Mahmoud Hafsi and Mohamed Taky

Abstract Agriculture, with an average of 70% of the volume of freshwater consumed globally, is particularly under pressure to improve water management and explore the options available to match supply and demand. The Moroccan economy being highly dependent on agriculture (19% of the country's gross domestic product, GDP) is particularly affected by drought, which is becoming a frequent event. To deal with this situation of water scarcity, Morocco has adopted a new water management strategy based on the desalination of seawater and brackish water for all uses, including irrigation. It should be noted that most of the desalination systems developed over the world are based on reverse osmosis technology. However, many challenges currently limit the possibilities for accelerating the use of desalination in agriculture. These challenges are financial, institutional, societal, and technological.

On the technological level, in addition to the excessive energy consumption of desalination techniques, other constraints appear when using desalination for irrigation, in particular: (i) the quality of desalinated water characterized by the lack of nutrients (ii) the fate of brine discharges, which can lead to serious environmental risks. To overcome these constraints, particularly in the context of the desalination of brackish water, it would be relevant to consider other desalination technologies, mainly Electrolysis and Nanofiltration which, for a certain salinity, have advantages over reverse osmosis in terms of reduction of brine discharges and in terms of the quality of the water produced.

Keywords Salinity · Reverse Osmosis · Electrodialyse · Nanofiltration · Brine discharge

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1 Introduction

By 2050, based on current consumption patterns and agricultural practices, it is projected that there will not be enough water available for current arable lands to produce enough food to feed the 9.5 billion people on the planet at that time. Population growth, coupled with climate change, also causes the availability of freshwater resources around the world to vary dramatically over space and time (Barbosa et al. 2015; HTF Market Intelligence Consulting 2017), leading to increased reliance on groundwater abstraction. Total global water demand is dominated by agricultural use (70%) followed by industrial use (21%) and domestic use (9%).

It is expected that water availability over the world, and in particular in the Middle East and North Africa (MENA) region, will decrease due to climate change. Total renewable water resources will be significantly reduced due to the fluctuations in precipitation and evapotranspiration. When considering the data for the whole MENA region, the total renewable water resources will decrease by about 12% a year (Awaad et al. 2020).

Furthermore, it is expected by 2050 that irrigation water requirements will increase by about 15% over present requirements, if global warming will cause wet weather. Conversely, if the climate becomes drier, irrigation requirements are expected to increase by about 33%. Overall, water requirements are estimated to increase by approximately 24% over the current requirements (Awaad et al. 2020).

Agriculture, with an average of 70% of the volume of freshwater consumed worldwide, is particularly under pressure to improve water management and explore available options to match supply and demand. As Morocco is heavily dependent on agriculture, which represents 19% of the country's GPD (Hirich et al. 2015; Addison et al. 2012), it is particularly affected by drought, which became a frequent event. The optimization of water resources management is an unavoidable option to maintain and to develop agriculture.

To deal with mismatch between availability and demand for freshwater, particularly for agriculture, the desalination of seawater, brackish water, or water reuse are the unique options to increase water supply beyond what is available in the hydrological cycle, and to satisfy the demand.

This new concern is clearly addressed in the Moroccan National Drinking Water Supply and Irrigation program (2020–2027) (http://81.192.10.228>ressources en eau), recently launched in order to secure water supply to guarantee economic and social development. In this program, it is planned, among other actions, to build three new seawater desalination plants, to increase water resources for drinking water supply, livestock, and irrigation.

Desalination is thus increasingly becoming relevant for agriculture. Global trends around food consumption and water usage are also leading to the adoption of more efficient and high-yielding forms of agriculture, such as greenhouse-based production and hydroponics. These high-yielding agriculture sectors are also early adopters of desalination technologies, with greenhouse and hydroponic growers around the world beginning to use RO to treat their water.

This paper aims to present the development of desalination technologies in Morocco, first to meet drinking and industrial water needs until its adoption to meet agricultural needs. The paper will analyze technological choices and the operating constraints of the desalination systems adopted.

In the field of desalination, the technological choice is mainly based on the cost of the water produced, also expressed in specific energy consumption. The fate of brine discharges has only very recently been the subject of very limited reflection. This aspect is particularly important and limiting in the case of the demineralization of brackish water (BW). This paper aims to highlight the importance of managing brine discharge, notably by reducing its volume.

2 Overview on Desalination in the World

Desalination technology is developing very fast and becoming a critical component for ensuring water resources sustainability worldwide. The capacity of the plants and quality of the raw water used are important for the cost of the freshwater produced. A steady increase in desalinated water production capacity has been recorded since the sixties of the last century and has accelerated, very markedly, since the 2000s, (Jones et al. 2019). A growth of 6.8% has been registered during the last decade. According to the Global Water Intelligence review, the capacity of desalination plants worldwide reached almost 116 million m^3/d in 2021, with more than 21,000 desalination plants, installed in 150 countries. 61% of the world's installed desalination capacity corresponds to seawater (SW) and 30% to BW (www.desaldata.com; Feria-Díaz et al. 2021).

Many indicators showed that the trend toward the generalization of the use of desalination in the world will be confirmed in the future. UNESCO (World Water Day 2020, 2020) estimates that around 2.2 billion people in the world live without access to freshwater and up to 5.7 billion people could live in 2050 in areas where water will be rare for at least one month a year. It is estimated that the global desalination market will grow at a rate of 9% in the coming years and that 74% of this growth will come from Europe, the Middle East, and Africa (Gaoet al. 2017).

The world's population dependence on desalinated SW is expected to increase from 7.5% of the world's population in 2015 to 18% in 2050. In addition, over the past six years, the world's total water desalination capacity, including desalination of BW and SW, has increased steadily with an annual rate of around 9%. Similarly, global desalinated SW production capacity is expected to double by 2040 (Hanasaki et al. 2016; Russo and Kurtzman 2019).

In Morocco, desalination has been adopted for drinking water production and for industrial uses, mainly mining, since 1976 in the south of the country, and then has been widely developed throughout the country. The graphs in Fig. 1 show a slow, but steady, growth in the desalination for drinking water during the 1990s and 2000s. From 2013, this increase was illustrated by higher number and desalination

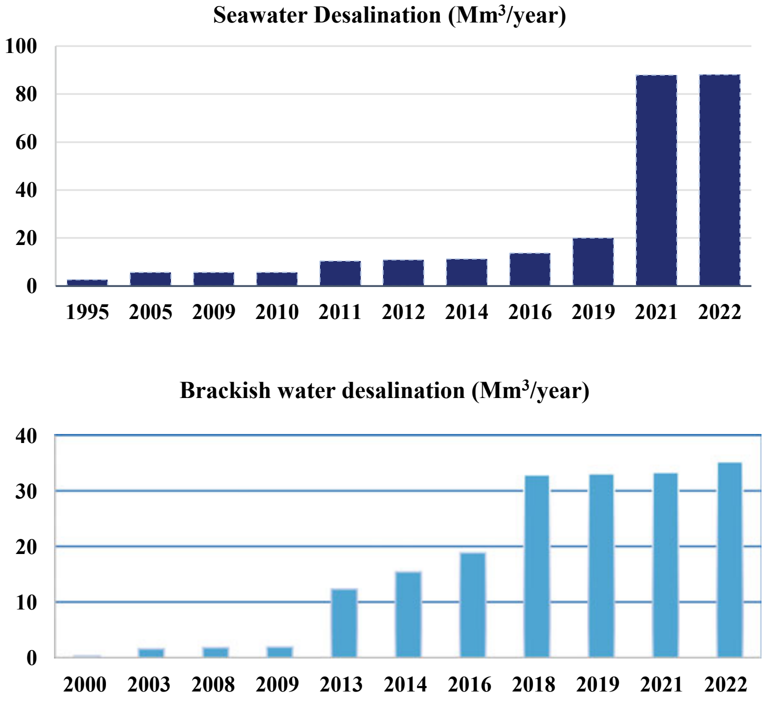

Fig. 1 Evolution of desalination capacities (sea & brackish water) for drinking water uses in Morocco

plants capacities. Globally, three phases of development characterize the adoption of desalination, to meet the water needs for socio-economic development in Morocco:

1. **Phase 1**: Started in 1976, in the southern provinces, with small desalination plants. Initially, three technologies were tested: reverse osmosis (RO), electrodialysis (ED), and the mechanical steam compressor. Two types of water had been desalinated: SW and BW. This "learning" phase enabled Morocco to acquire knowledge in the field of desalination. RO was then adopted as "the most appropriate technology for water production in Morocco," particularly in view of its energy consumption.
2. **Phase 2**: Since 1995, desalination by RO, has become widespread in the central and northern provinces. Faced with a drought that has become frequent, desalination has become the only alternative to meet drinking and industrial water needs.
3. **Phase 3**: Since 2020, Morocco has implemented the new strategy based on the use of desalination technology, mainly RO, to meet agricultural needs.

3 Principles of Main Desalination Technologies

Desalination is a process that is used to recover pure water from SW or BW. There are two main streams of water that desalination produces, the freshwater and a more concentrated stream (brine). The two major types of technologies that are used around the world for desalination can be broadly classified as either thermal or membrane-based processes (Table 1). Both technologies need energy to operate and produce freshwater.

3.1 Thermal Desalination Processes

Thermal desalination is a process whereby saline water is heated to produce water vapor and collecting the condense vapor (distillate) to produce pure water. The main thermal desalination processes used over the world include multi-stage flash desalination (MSF) (Fig. 2), multiple-effect distillation (MED) (Fig. 3), and vapor compression (VC).

MSF and MED are the most widespread technologies. In these processes, condensed steam is used to supply latent heat that is required to vaporize the water. Due to their outstanding high energy demands, this process is basically used for the SW desalination process, and they are able to produce high purity water suitable for industrial process applications. Thermal process unit capacities are, in general, higher compared to membrane process. In general, thermal desalination plants are located near “heating production plants”, which supply the distillation system with residual heat.

Thermal processes have the advantage of producing water with low TDS (less than 50 mg/l for MSF and less than 10 mg/l for MED). They also do not require

Table 1 Desalination technologies and processes

Thermal Technology	Membrane Technology
Multi-Stage Flash Distillation (MSF)	Electrodialysis (ED)
Multi-Effect Distillation (MED)	Electrodialysis reversal (EDR)
Vapor Compression Distillation (VCD)	Reverse Osmosis (RO) Nanofiltration (NF)

N.B:
ED and EDR are based on the same structure and operating principle. EDR was developed to reduce the impact of fouling on ED system performance. In the case of the EDR, during operation, the direction of the electric current is reversed according to a predefined frequency.
Nanofiltration (NF), has been introduced recently as desalination technology in some desalination plants.

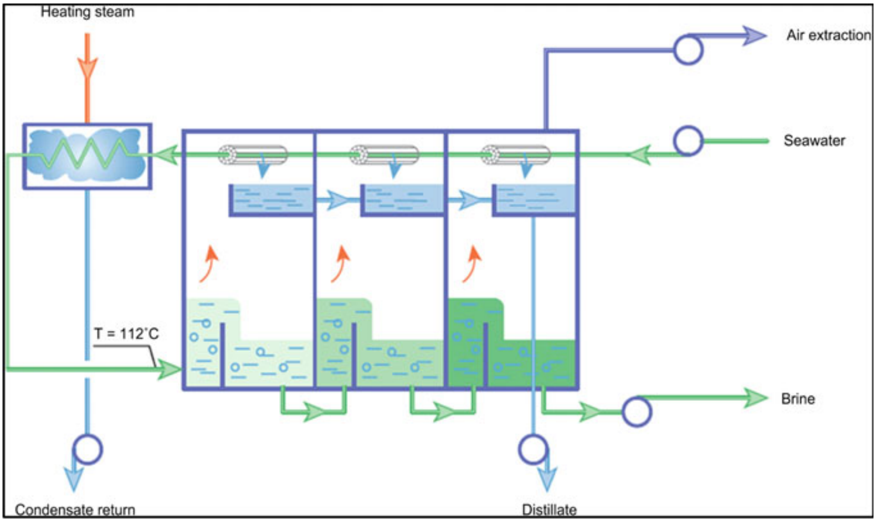

Fig. 2 Schematic diagram of multi-stage

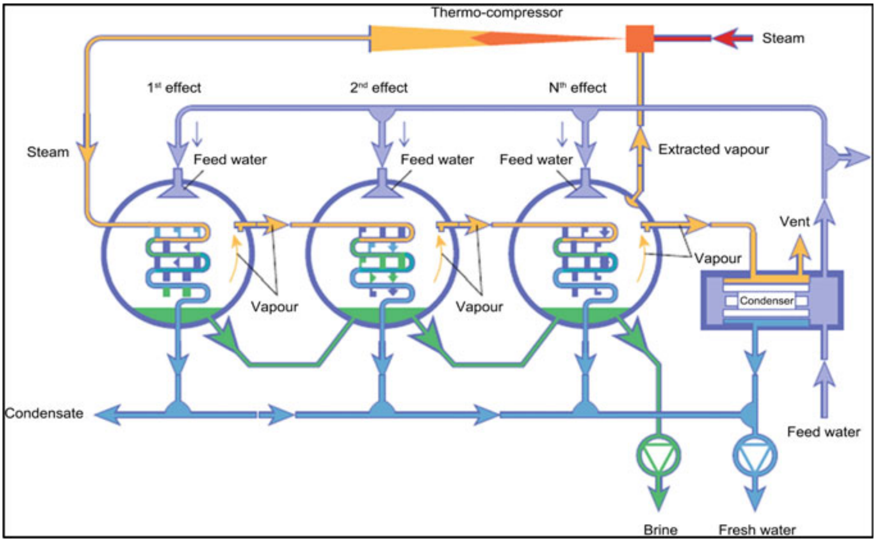

Fig. 3 Schematic diagram of multi-effect

extensive pretreatment and are independent of the TDS of the feed water. The main disadvantages are the high Capex, high Opex, and high energy requirement. The total electricity consumption (in kWh/m^3) is in the range of 14–21 for MED and 19.5–27 for MSF (Soliman et al. 2021).

3.2 Membrane-Based Desalination Processes

The analysis that will be presented in this part concerns the desalination of BW. For SW it's definitely accepted that RO is the best desalination technology. Membrane-based desalination technologies which could be suggested for BW desalination can be subdivided into three broad categories: (ED/EDR), RO, and NF.

3.2.1 Electrodialysis (ED)/Electrodialysis Reversal (EDR)

ED or EDR is an electrochemical charge-driven separation process where dissolved ions are separated through ion permeable membranes under the influence of an electrical potential gradient. Ion exchange membranes (IEM), manufactured from ion exchange polymers, have the ability to selectively transport ions with a positive or negative charge and reject ions of the opposite charge. An electrical potential is used to move salts through a membrane, leaving freshwater behind as product water. The ED desalination process has generally been used for BW desalination.

Figure 4 shows the principle of the ED process. In a saline solution, the dissolved ions such as sodium (Na^+) and chloride (Cl^-) travel to the opposite electrodes passing respectively through cation exchange membrane (CEM) and anion exchange membrane (AEM). Cation exchange membrane and anion exchange membrane are basically alternately positioned. As ED occurs, the saline feed solution is demineralized, this is the dilute compartment. The solutions on either side of the feed compartment, separated by a cation exchange membrane and an anion exchange membrane, become concentrated. The current supply electrodes, dedicated to ensure the imposition of the electric potential difference, are placed at the ends of the stack of membranes.

EDR unit operates according to the same principle as ED, except that both the product and concentrate channels are identical in construction. EDR is implemented by reversing electrodes at the same time as the inversion of the hydraulic circuits: cathode becomes anode and dilute becomes concentrated and the concentrated becomes dilute. The reversal process is useful in breaking up and flushing out scales, slimes, and other deposits in the cells before they build up allowing to drastically reduce the consequences of concentration polarization and fouling (Oyoh 2016).

3.2.2 Reverse Osmosis (RO)

Reverse Osmosis is the process by which an applied pressure, greater than the osmotic pressure, is exerted on the compartment that once contained the high-concentration solution (Fig. 5). This pressure forces water to pass through the membrane in the direction reverse to that of osmosis. Water now moves from the compartment with the high-concentration solution to that with the low concentration solution. In this

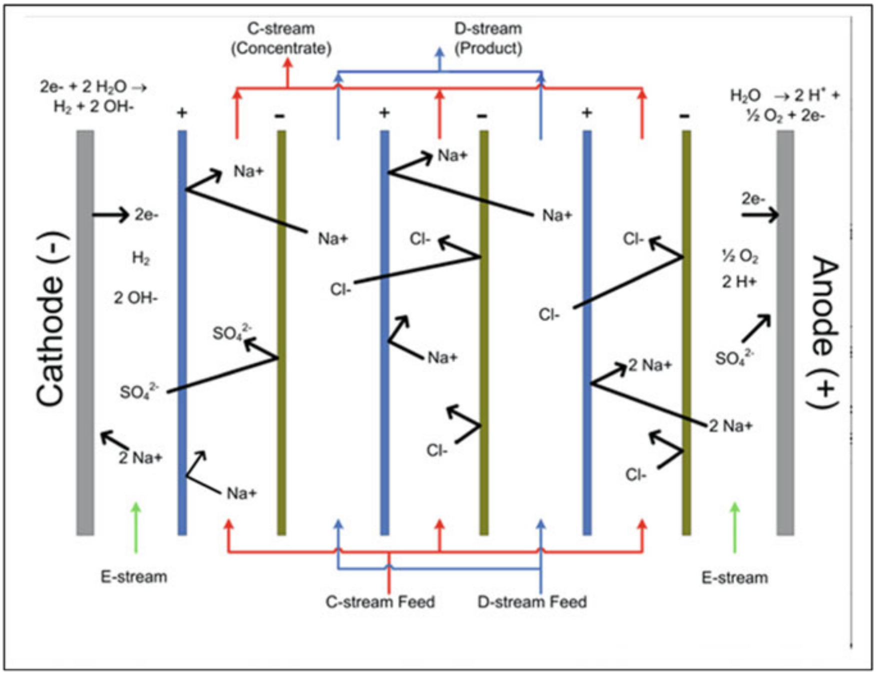

Fig. 4 Schematic diagram of electrodialysis

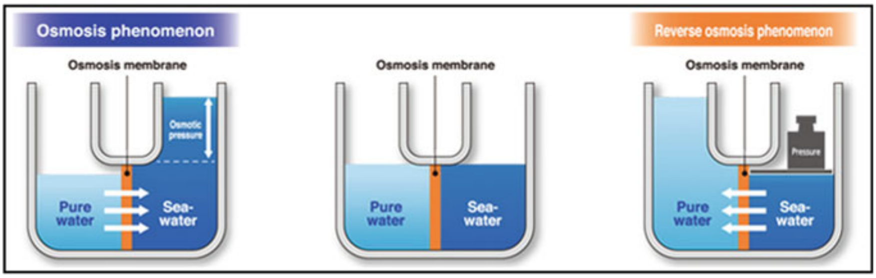

Fig. 5 Schematic diagram of osmosis and reverse osmosis phenomenon

manner, relatively pure water passes through membrane into the one compartment while dissolved solids are retained in the other compartment. Hence, the water in the one compartment is purified or “demineralized,” and the solids in the other compartment are concentrated or dewatered.

Some membranes will reject up to 99% of all dissolved solids and commonly have molecular weight cutoffs in the range of 100–300 Dalton (Da) for organic chemicals. Increased pressure increases the rate of permeation; however, fouling would also increase.

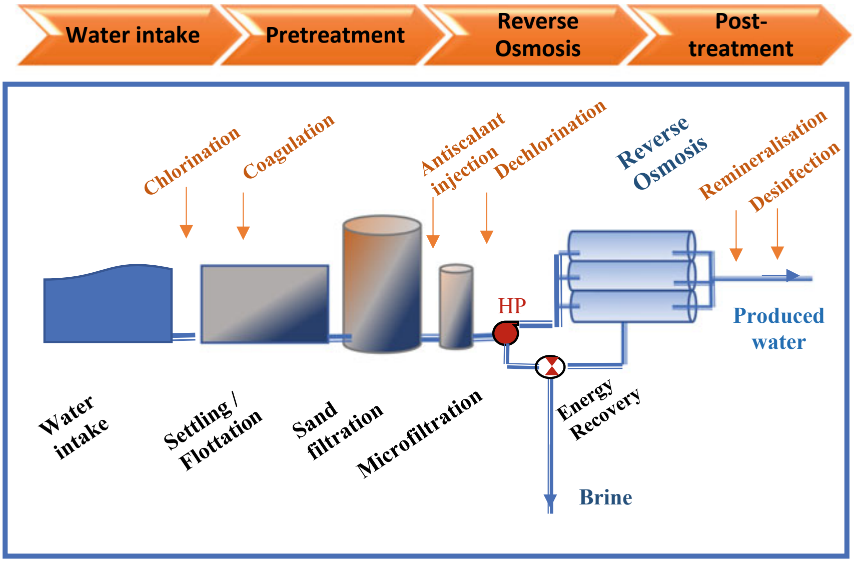

Fig. 6 Schematic of classical reverse osmosis seawater desalination plant

RO is the large technology widely used for seawater desalination. RO process (Fig. 6) requires much lower energy than thermal processes, however the total dissolved salt (TDS) of the product water is a little bit higher than the distillation case. In general, the TDS of desalinated water, using RO, is less than 500 mg/l (for simple pass mode), in classical two steps configuration.

The performance of RO is related to the salinity and the quality of the feed water and therefore depends strongly on the pretreatment.

The challenging problems of RO are mineral are biological fouling. Four types of fouling which all lead to the decline of flux of desalinated water, increase of the transmembrane pressure, and the specific energy consumption (SEC):

- Organic fouling, provoked by the accumulation of the retained natural organic matter (NOM).
- Scaling, due to scale deposit by exceeding the solubility of several salts: e.g., $CaCO_3$ and $CaSO_4$.
- Colloidal fouling: due to formation of a layer on membrane surface: e.g., Aluminum, Silicate minerals, silicates, iron, oxides/hydroxides.
- Biofouling: formation of biofilm due to bacteria, algae, fungi, and Extracellular polymer substance (EPS).

The SEC depends on several factors, mainly on plant capacity, feed water quality, and pretreatment steps.

3.2.3 Nanofiltration

Based on the same principle as RO, NF is capable of removing many relatively larger organic compounds above approximately 300 Dalton (Da) and rejecting many divalent salts; monovalent ion removal can be in the range of 50–90%. NF operates at lower pressure than RO.

The size of pores in NF membranes (nominally $\sim$ 1 nm) is such that even small uncharged solutes are highly rejected while the surface electrostatic properties allow monovalent ions to be reasonably well transmitted with multivalent ions mostly retained. These characteristics make NF membranes extremely useful in the fractionation and selective removal of solutes from complex process streams. Permeability of NF membrane is higher than RO, and the operating pressures in NF are much lower than in RO.

Even if NF has proven its efficiency in water softening and in removing some molecules like pesticide, fluoride, organic molecules, etc., in the surface water treatment, its introduction in the desalination field is very limited.

As shown by Fig. 7, two application principles exist, based on dead end filtration and tangential filtration. The tangential filtration is more adapted to reduce the membrane fouling, hence it is more used than dead end filtration.

The oldest reference known (Cyna et al. 2002) of using NF in a drinking water system is the Méry-Sur-Oise case, since 1994. In SW desalination field, very recently, in Umm Lujj desalination plant, in Saudi Arabia, NF has been tested as pretreatment system of RO. The obtained results are very promising.

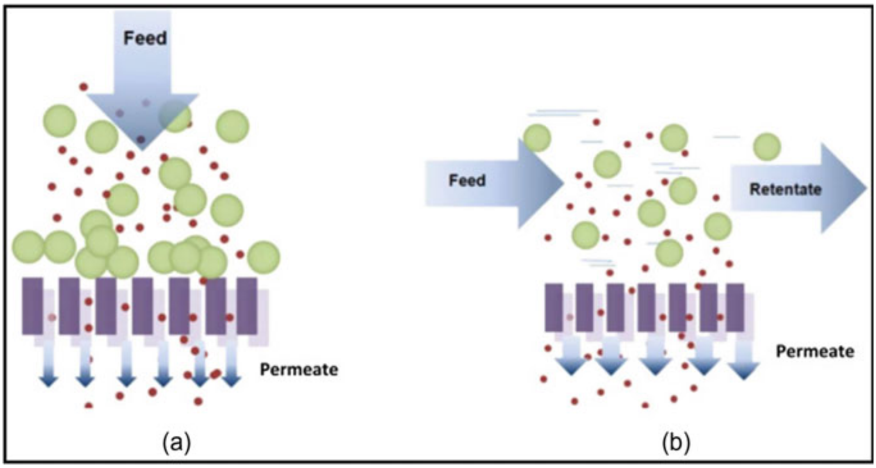

Fig. 7 Schematic principle of nanofiltration (a) Dead end filtration (b) Tangential filtration

3.3 Comparison of NF, RO, and ED

NF and RO are two pressure-driven membrane processes closely related in that both share the same composite membrane structure and are generally used to reduce the salinity in the solution. However, NF membranes use both size and charge of the ion to remove it from solution whereas RO membranes rely only on "solution-diffusion" transport to affect a separation.

NF membranes have pore sizes ranging from approximately 0.001 to 0.01 microns, and therefore the rejection of ions in solution by an NF membrane is lower than that of an RO membrane, thus NF technology is commonly used to "soften" drinking water or to remove specific particles. However, in contrast to RO, the use of NF in desalination (SW and BW) worldwide is very limited. Indeed, the RO, due to its high separation quality performances is largely used for desalination.

The membranes used for ED are totally different from RO and NF membranes. It's important to underline that RO and ED membranes do not have physical pores, and that ED membranes are polymeric membranes charged with fixed ionic groups.

Unlike the operating principles of RO and NF, where water passes through the membranes and salts are more or less retained, in the ED process the operating principle is based on extracting the salts through an alternating set of selective ion exchange membranes (CEM and AEM), under electric potential gradient, the salt is then being driven, toward the electrodes, by electricity. The IEM used in ED and EDR, are exclusively organic, more resistant to chlorine oxidation and to fouling, and are significantly thicker than RO membranes. Figure 8 shows the driving forces involved in each technology.

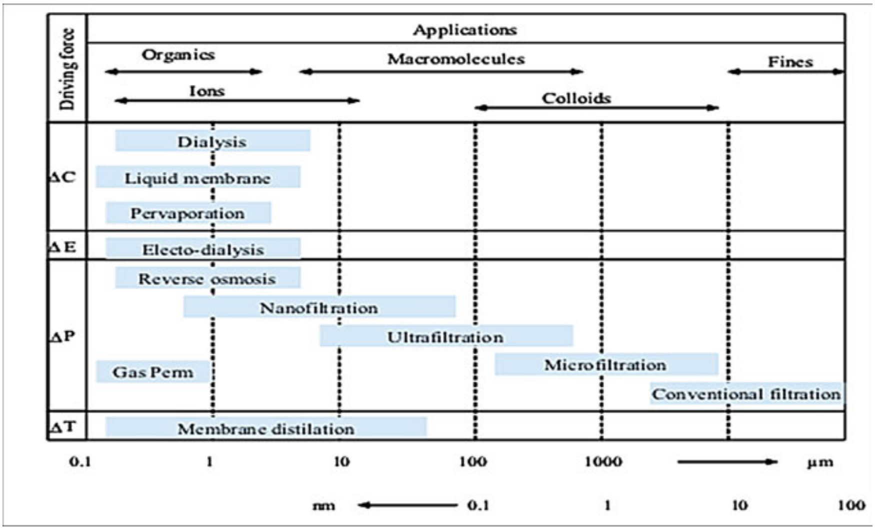

Fig. 8 Illustration of the driving forces involved in each technology, NF, RO, and ED

Typically, ED membrane separation is found to be cost competitive for feed water for TDS lower than 3000 mg/l. This applicability threshold, however, is a function of the unit cost of electricity and may vary from project to project (Voutchkov 2013). In fact, the energy requirement is to be proportional to the salinity to remove. The performance of ED is, however, limited by the exchange capacity of membranes.

The TDS removal efficiency of ED desalination systems is not affected by non-ionized compounds or compounds with a weak ion charge (i.e., solids particles, organics, and microorganisms). Therefore, ED desalination processes are not affected by water turbidity and the membranes are less sensitive to biofouling and scaling than RO membranes.

Electrodialysis technology offers the possibility of selective desalination, and therefore some of the nutrients present in the feed water will remain in the desalinated water. ED desalination only partially removes nutrients from the source water.

This option gives an advantage for ED over RO for the use of desalinated water in agriculture, since water desalinated by RO will be completely free of nutrients, whereas water from ED will contain nutrients.

Table 2 shows the rejection of ions exhibited by NF and RO membranes. Most of the elements existing in water are rejected by the distillation system and by RO membranes. In the case of NF rejection is more selective, divalent ions are more rejected than monovalent ions (Table 3).

As already mentioned, the main difference between ED, NF, and RO is the fact that RO is non-selective technology. All ions are rejected with a very high ratio. The selectivity of ED and NF gives an opportunity for specific treatment dedicated to remove specific components.

However, the specific energy consumption is much lower for RO compared to ED for high salinities. For low salinities, the specific energy consumptions of the two technologies could be equal or less for ED and NF compared to RO, as shown in Tables 4 and 5.

Table 2 Rejection of ions by NF and RO membranes, published by membrane manufacturer (Elazhar F.)

	Nanofiltration rejection (%)	Reverse osmosis rejection (%)
TDS	61–98	90–99
Hardness	76–95	61.99
Calcium	74–99	95–99
Magnesium	74–989	94–98
Sodium	33–55	92–98
Chloride	79–98	92–98
Sulfate	94–99	96–99
Bicarbonate	45–96	85–95
Fluoride	45–98	92–95
Nitrate	39–96	92–98

Table 3 Tan Tan brackish water simulation with membrane suppliers' softwares (Dach H.)

Membrane Type	Flux (l/m2-hr)	Specific Energy (kWh/m^3)	Permeate TDS (mg/l)	Permeate Cl$^-$ (mg/l)	Permeate Na + (mg/l)	Permeate SO$_4^{2-}$ (mg/l)	Permeate Ca^{2+} (mg/l)	Permeate Mg^{2+} (mg/l)
Reverse osmosis								
BW-30-400 Dow Filmtec	24.2	0.76	56.4	14.1	8.3	2.5	1.7	0.8
BW-30-LE-440 Dow Filmtec	22.0	0.56	153.1	32.0	18.7	5.6	3.9	1.7
ESPA-2 Hydranautics	24.2	0.60	48.3	20.7	14.6	2.2	1.4	0.6
ESPA-1 Hydranautics	24.2	0.52	158.3	51.5	45.1	7.8	4.3	1.8
ESPA-4 Hydranautics	24.2	0.46	203.3	66.5	57.9	10.1	5.6	2.4
ESPA-3 Hydranautics	24.2	0.48	381.8	128.0	108.8	5.9	3.1	1.3
BLN Saehan	24.4	0.50	72.7	32.4	15.9	6.9	3.6	1.5
BLR Saehan	24.4	0.55	38.8	17.3	8.5	3.7	1.9	0.8
BLF Saehan	24.4	0.45	122.1	54.4	26.6	11.7	6.1	2.6
Nanofiltration								
NF-90-400 Dow Filmtec	24.2	0.44	259.4	138.0	78.0	10.3	10.5	4.6
ESNA-LF Hydranautics	24.2	0.45	710.5	371.4	224.7	26.7	22.6	9.6
NE-90 Saehan	24.3	0.39	423.6	221.2	108.2	5.9	3.1	1.3

Table 4 **Reverse osmosis membranes** (BW30, REBLF) andnanofiltration (NF90) performances in Tan Tan desalination plant at a recovery rate of 70% and a permeate flux of 26 $l\cdot h^{-1}\cdot m^{-2}$ (Dach H.)

Membrane	Permeability ($l\cdot h^{-1}\cdot m^{-2}\cdot bar$)	Working pressure (bar)	Permeate TDS (mg/l)	SEC kWh/m^3
NF90	6.4	9.2	490	0.44
REBLF	5.1	10	260	0.48
BW30	2.4	19	165	0.93

Table 5 Cost of Nitrate removal of groundwater by reverse osmosis, nanofiltration, and electrodialysis: performances and cost comparison (Belhamidi S.)

Process	Capex (€)	Opex (€/m^3)	SEC (€/m^3)
ED	116,356	10,472.04	0.0361
NF	98,344	8,850.96	0.0247
RO	141,781.8	12,760.362	0.0247

The last aspect should be looked at to compare these three technologies for their recovery rate. Table 6 shows that RO has the lowest recovery rate compared to ED and NF. Which implies more brine production by RO compared to other technologies.

This brine, highly concentrated in salt, should be well managed in order to avoid negative environmental impacts.

Table 6 Comparison of recovery ratio of different membrane desalination technologies

Technology	Recovery rate	Advantages	Disadvantages
RO	< 70–75	**W**ide use for municipal and industrial uses **A**dapted of a wide range of water TDS	Membrane fouling and durability Limited recovery rate
ED	< 95	**L**ess susceptibility to scale formation. High salt removal **A**daptable for specific ions remove	Limited to low TDS
NF	80–85	**L**ow operating pressures; **H**igh rejection of divalent ions; wide integration capacity as pretreatment for other desalination technologies	High salt passage Low ability to reject boron

4 Desalination for Agricultural Purposes

The highest proportion of desalinated water use in agriculture occurs in Spain, where the current installed capacity is 1.4 million m^3/d and 22% is used in agriculture for growing high value crops, such as vegetables, fruits, including tomatoes and peppers, and vineyards. In Kuwait, where the current installed capacity exceeds 1 million m^3/d, 13% is used for agriculture but in Saudi Arabia, the world's leading producer of desalinated water; only 0.5% of its desalination capacity is used for agricultural purposes. Other countries that use desalinated water for food production are Italy (desalination capacity 64,700 m^3/d–1.5% for agriculture), Bahrain (620,000 m^3/d–0.4%), Qatar (0.1%), the United States (1.3%) (Suwaileh et al. 2020) estimated at 548,000 m^3/d, representing 40% of the national freshwater irrigation consumption (Russo and Kurtzman 2019).

The assessment of the suitability of a desalination technology for agriculture is based on the net economic returns of agricultural products as well as the environmental costs. Burnet al. (2015) and Salem et al. (2019) provided a detailed analysis of desalination technologies available for agriculture, including RO, NF, ED, EDR, and MSF. The choice of technology depends on the quality of the feed water and the desired quality of the produced water, the investment costs, the operating and maintenance costs, the energy costs, and the net yields expected from agricultural products. Considering the energy efficiency and the quantities of water produced-Burn et al. (2015) identified RO technology as the most appropriate technology for agriculture. This conclusion is questionable since it did not take into account the environmental impact of the discharge of SWRO brines, which are much larger, in volume, compared to those of NF and ED.

Morocco, with the application of the new strategy for water resources management, has taken a big step in the use of desalination in agriculture. Thus, several projects have been set up or are underway: The SWRO desalination plant of Agadir, with a production capacity of 400,000 m^3/d, 50% of which is intended for agriculture, the SWRO desalination plant of Dakhla (scheduled for 2024) powered by wind energy with 90,000 m^3/d of production capacity and the SWRO desalination plant of Casablanca (scheduled for 2027) with a capacity of 825,000 m^3/d, of which around 10% will be used for agriculture. Many other brackish desalination plants are also under construction or planned across the country.

It is important to highlight that all desalination projects dedicated to irrigation, both from seawater and brackish water, completed or in progress in Morocco, have opted for RO technology.

Box 1. Key figures Agadir desalination plant

The overall cost of Agadir desalination plant project is 4.41 billion dirhams (1 dirham = 0,094 US$) including 2.35 billion dirhams for its irrigation component and 2.06 billion dirhams for its drinking water component. This mutualized seawater desalination plant will use osmosis technology.

Its initial production capacity (Phase 1) is 275,000 m^3/d of which 150,000 m^3/d will be used to meet the drinking water needs of the city of Agadir and 125,000 m^3/d are allocated to meet to the irrigation water needs of an area of 15,000 ha.

In a second phase, the desalination plant will reach its ultimate capacity of 400,000 m^3/d.

The project is financed by public–private partnership (PPP):

- The private sector contributes 2.42 billion Moroccan Dirhams.
- The public sector contributes 1.86 billion Moroccan Dirhams.
- Farmers with contribute 120 million Moroccan Dirhams.

The contribution of farmers was based on the ratio of 10,000 Moroccan Dirhams/ha.

The exclusive choice of RO technology for the desalination is mainly justified by:

- The excellent performances of RO technology in the field desalination for drinking water or industrial uses.
- RO is the leading desalination technology worldwide.
- The absence of technical feasibility studies, including environmental impact, of competing RO technologies, particularly ED and NF for brackish water desalination.

5 Challenges of Desalination in Agriculture

Many challenges are still a barrier to widespread desalination in irrigation (Martínez-Alvarez et al. 2017), such as the high energy requirements, the associated greenhouse gas emissions, the high cost of desalination on the farming economy, and negative impact of desalinated water on the agriculture performances, on the soil and on the environment.

Indeed, two main negative impacts have been raised by users of RO desalination technology for irrigation:

- Quality of desalinated water: The selection of a suitable desalination technology for agricultural use depends upon the type of crop and its water quality requirement. The recommended quality parameters to be considered when using desalinated water for combined agricultural and municipal uses are electrical conductivity (EC), concentration ranges of Cl^-, Na^+, B, Ca^{2+}, Mg^{2+}, and $SO_4{}^{2-}$, alkalinity, the water stability index in terms of calcium carbonate precipitation potential (CCPP), and pH.
- The lack of essential nutrients in RO desalinated water could have a negative impact on plant growth, which implies, therefore, higher fertilization requirements which will greatly increase the cost. This desalinated water is also characterized by imbalanced chemical composition, quite different from that of conventional water, which could promote the degradation of soil structure.

To face these challenges, some techniques have already been developed in drinking water desalination systems, in particular:

- Chemical re-mineralization of the produced water.
  - The objective of this step is the protection of the equipment downstream of the desalination plant against aggressiveness and corrosiveness of the desalinated water or, if intended for irrigation, the desalinated water can be spiked with nutrients.
  - In case of Brackish water desalination, a partial mixing of desalinated water with pretreated water will enhance the mineralization of the desalinated water.
- The risk of crop toxicity due to the high concentration of boron (B), especially in case of sea water desalination. This problem can be avoided by using specific RO membranes, recently developed to improve the boron removal.
- Fate of brines discharge: A serious challenge in desalination processes is the disposal of brine. Improper disposal would cause serious environmental hazards. In case of SW desalination, it is customary to evacuate the brine discharges to the sea. The problem is more complicated when brackish water to be desalinated is far from the sea side.

Brine is the high-salinity byproduct of the desalination process. Its characteristics and volume depend on the water source and the desalination technology used. For example, BWRO desalination generates a brine stream that is 4 to 10 times more concentrated in salinity as the feed water (Ahdabet al. 2020). Current brine disposal methods negatively impact the environment and are limited by high capital costs (Capex). The cost of brine disposal is 5–33% of the total cost of desalination, with inland brackish desalination plants lying in the upper echelon of this range (Joneset al. 2019; Ahmed et al. 2001). Consequently, cost-effective and efficient brine management is critical to address environmental pollution. A desirable alternative to liquid brine disposal is fully dewatering the brine to a solid product, so as to be close to Zero Liquid Discharge (ZLD).

Current methods for disposing of desalination brine are surface water discharge, sewer discharge, deep-well injection, evaporation ponds, and land application. A method is selected depending on a variety of factors, including brine composition and quantity; geographic location; availability of receiving site (e.g., surface body); production and maintenance costs. Table 7 highlights the disparity in the treatment costs of brine discharges from several desalination plants (Ahdab et al. 2020).

More than 90% of SW desalination plants use surface water discharge back into the ocean, while sewer discharge, deep-injection wells, and land application are almost exclusively used by BW desalination plants.

The most common practice for inland brackish groundwater facilities is to dispose to surface water bodies (47%), sewer discharge (42%), and deep-well injection (9%). The remaining 1% includes other methods, such as evaporation ponds and thermal treatment. Surface water discharge is proving to have very detrimental environmental effects.

To overcome the challenges of the negative impacts of brine discharge and poor desalted water quality, when using reverse osmosis to produce water for irrigation, other Desalination technologies, in case of brackish water with low salinity, such as

Table 7 Methods and cost of brine disposal

Method	Principle	Cost ($/m^3)
Surface water discharge	Discharged into surface water	0.03–0.30
Sewer discharge	Discharged into existing sewage collection system	0.30–0.66
Deep-well injection	Injected into porous subsurface rock formations	0.33–2.65
Evaporation ponds	Evaporated, resulting in salt accumulation at pond bottom	1.18–10.04
Land application	Irrigates salt-tolerant crops and grasses	0.74–1.95
ZLD	Concentrated and evaporated to yield freshwater and solid	0.66–26.41

ED, EDR, and NF may have advantages compared to RO, and are therefore worth exploring.

Thus, in order to select the best brackish water desalination technology, it is suggested to include the brine management as evaluation criteria.

The management of brine discharges and the protection of the environment, according to well-defined standards, must be part of the obligations of any desalination project. Therefore, the actual cost of desalinated water must consider not only the specific cost of producing desalinated water, but also the cost of brine discharge management.

Thus, the real cost of desalinated water would depend on the volume of water discharged and the treatment technology adopted.

We suggest below an equation where both the Capex and Opex of desalted water and management of brine discharge, for a period of 10 years, to be considered:

$$\begin{aligned}\text{Costs to produced water} &= (\text{Capex}_\text{p} + (\text{Opex}_\text{p} \times 10\ \text{years}))_\text{Product}\\ &+ (\text{Capex}_\text{b} + (\text{Opex}_\text{b} \times 10\ \text{years}))_\text{Brine}\end{aligned}$$

where:
Capex_p: Investment cost to produce desalinated water.
Opex_p: Operation cost including membrane replacement for 10 years.
Capex_b: Investment cost to treat the brine (including discharge without any treatment).
Opex_b: Operation cost for treatment of the brine for 10 years.

6 Conclusion

Firstly, the main conclusions of the technologies (ED, NF, and RO) comparison can be summarized as below:

- ED technology presents the best recovery rate, implying the lowest volume of the brine is produced.
- ED ion exchange membranes are more robust than RO membranes. In case of discontinuous operating (seasonal activities) ED is much more suitable than RO.
- NF can achieve a high recovery rate (80 to 85%) for water with TDS in the range up to 10 g/l.
- NF membranes are less selective than RO membranes, and therefore the water product retains a certain salinity, mainly due to the monovalents ions, knowing that most multivalent ions are retained by the membrane.
- NF, requiring less pressure, is therefore less energy consuming compared with RO.

Secondly, it is generally agreed on that resorting to the desalination of SW and BW in agriculture is a very promising option to deal with the scarcity of water resources. RO, as a widely proven technology for the production of drinking and industrial water, should not overshadow the opportunities that other desalination technologies such as ED and NF technologies may be suitable for use in agriculture.

As general conclusion of this paper it's important to highlight that:

- Reverse osmosis technology is best suited for seawater desalination.
- For BW with a TDS less than 7–10 g/l (including drainage and wastewater), NF and ED may have some advantages compared to reverse osmosis, including:
  - Higher recovery rate (reduction of brine volume),
  - The produced water slightly more mineralized, which requires less fertilizer when used for irrigation. (Ahdab et al. 2020)
- For a sustainable development of desalination, the treatment of brine must undoubtedly be taken into account in the choice of technology and in the design of the project.

Finally, to effectively develop the use of desalination for irrigation, particularly in Morocco, certain recommendations should be considered:

- The demineralization of brackish water should be favored over the desalination of seawater, if brackish water resources are available, for several reasons:
  - The cost of demineralization is significantly lower for demineralization compared to desalination.
  - The volume of discharges is lower for demineralization than for desalination.
  - Depending on the salinity of the water to be demineralized, several demineralization options exist: reverse osmosis, electrodialysis, and nanofiltration, which could present specific advantages for crop irrigation.
- Give preference to large demineralization plants for the irrigation of several agricultural areas, rather than small demineralization stations specific to each area.
- Set up specialized technical assistance to support farmers who use desalination technologies,

- Set up a capacity building mechanism for the benefit of users of desalination technologies.

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Index

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